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Research Paper

Effectiveness of slurry wall for lead retention in contaminated soil

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ABSTRACT

This paper examines the hydraulic conductivity and strength properties of several bentonite-cement (BC) mixtures and to delineate the influence of the cementitious material content, bentonite, and curing time upon the strength and hydraulic conductivity of BC barrier materials. The two ratios of cementitious material to bentonite-water slurry used were 7.5%, and 15%. Samples were cured for a period of 7, 14 and 28 days at 100% humidity, after which samples of each mixture underwent permeability and unconfined compression testing. It can be seen that unconfined compressive strength (q_u) of specimen increased as cement content increased due to the hydration products. However, the q_u of specimen decreased as bentonite content increased due to high expansion. Specimens with high cement content form a low permeability material that keeps high lead contaminant in top and middle portion in the specimen. The results shows that q_u increase as cement content and curing period increase while the permeability coefficient decrease as curing period and cement content increase. Moreover, the effectiveness of slurry wall for lead retention contaminated soil can be obtained by using the optimum bentonite-cement proportion of B10C15.

1. Introduction

Vertical barriers are most often constructed of soil-bentonite using the slurry trench method of construction (Evans and Dawson, 1999). In this method, sodium bentonite is mixed with water to form viscous slurry that is pumped into a trench during excavation to maintain the trench stability. The stable trench is then backfilled with a mixture of soil and slurry having a consistency of high slump concrete. These barriers have been designed primarily for low permeability, generally less than 10^{-9} m/s. Some investigations have pointed toward improved performance through the use of admixtures that would both retard the transport of contaminants and provide low permeability (Kaya and Durukan, 2004; Evans et al., 1990; Evans and Prince, 1997). An evaluation of semi-permeable membrane behavior for geosynthetic clay liners (Malusis and Shackelford, 2002) has been extended to soil-bentonite slurry-trench cutoff walls (Yeo et al., 2005b; Henning et al., 2006). Soil-bentonite cutoff-wall backfill materials have been found to behave as semi-permeable membranes restricting the passage of solutes/contaminants (Malusis et al., 2009; Malusis et al., 2011; Hong et al., 2011).

Slurry wall are commonly used as subsurface barriers to lateral flow of ground water and to water-borne

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Note: Discussion on this paper is open until September 2017 pollutants. The major characteristics of slurry wall construction are the use of bentonite and water slurry during excavation to support the excavation without the use of other lateral supports such as shoring. Bentonite clay is montmorillonite clay and the most common amendment in soil-bentonite, soil-cement –bentonite and cement-bentonite slurry walls. Bentonite has the ability to swell as much as 20 times its volume upon contact with water therefore, bentonite slurry walls are the most common type of subsurface wall and are considered baseline barrier technology (Heiser and Dwyer, 1997). If properly designed and constructed, slurry walls can successfully contain waste at contaminated sites (Rumer and Mitchell, 1996). For over 45 years, these walls have been used in the construction industry to contain and direct water, and as a result, the requirements and practices for designing and installing a slurry wall are well established. Slurry walls have been used for pollution control since 1970, and the technology is accepted and regarded as an effective method of isolating hazardous waste and preventing the migration of pollutants. Excavation under a slurry filled trench provides stability and prevents the trench from collapsing.

The application of soil-bentonite slurry walls involves excavation to the desired depth and eventual displacement of the slurry by a permanent backfill, which forms the hydraulic barrier. Varying the composition of the backfill can alter the properties of the barrier to obtain the desired strength or permeability. For example, the addition of plastic fines helps decrease the effect of contaminants on the barrier (Kaya and Durukan, 2004; Montoro and Francisca, 2010; Mishra et al., 2011).

A self-hardening slurry trench is a type of slurry wall that uses cement-bentonite as the permanent backfill. Cement-bentonite walls are advantageous when there is a lack of suitable soil for backfill, insufficient space available for mixing of backfill, a steep slope on site, or a very strong wall is required (shear strength). However, cement-bentonite walls tend to be more permeable than soil-bentonite walls. Permeabilities of cement-bentonite walls range from 10^{-5}-10^{-6} cm/s, and the typical permeability required for site remediation is a minimum of 10^{-7} cm/s (Yeo et al., 2005a). Self-hardening slurries typically consist of mixtures of Portland cement and bentonite clay. The bentonite is blended with water producing hydrated slurry of approximately 6% bentonite by weight. Cement is added just prior to pumping the slurry into the trench. The cement content is usually 100 20% by weight (Mutch et al., 1997). Alternative self-hardening slurries incorporate ground-blast slag in with the cement to increase impermeabilities to 10^{-7}-10^{-8} cm/s. Additions of slag can also increase the chemical resistance and strength of the barrier. Typically, the mixing ratio of Portland cement to slag is 3:1 or 4:1 (Mutch et al., 1997, Opdyke and Evans, 2006; Williams and Ghataora, 2011).

Soil-Cement-Bentonite (SCB) slurry walls are an adaptation of traditional soil- or cement-based walls. Fundamentally, the SCB wall is a soil-bentonite slurry wall with cement added to the backfill (less than 10%). The benefit of the SCB slurry wall is that it is similar to the cement bentonite wall in strength and to the soil-bentonite wall in hydraulic conductivity (Rumer and Mitchell, 1996).

Bentonite slurry walls also known as diaphragm walls are used in construction, where the slurry wall is a trench filled with a thick colloidal mixture of bentonite and water (Gutberle, 1994). A trench that would collapse due to the hydraulic pressure in the surrounding soil does not collapse as the slurry balances the hydraulic pressure. Forms for concrete, and rebar, can be assembled in a slurry-filled trench, and then have concrete poured into the form. The liquid concrete being denser displaces the less-dense bentonite slurry and causes the latter to overflow from the trench. This displaced bentonite slurry is then channeled to a recycling unit from which it can subsequently be reused in a new trench elsewhere on the construction site. In addition, because the colloid is relatively impervious to water, a slurry wall can prevent the seepage of groundwater, which is useful in preventing the further spread of groundwater that has been contaminated by toxic material.

Contamination of toxic waste from sites and landfills can be blocked by slurry cutoff walls (Xanthakos et al./ 1994). The effectiveness of slurry cutoff wall materials is critical to the successful contaminant of these facilities and protection groundwater resources. An attempted has been made to make compatibility determinations but at present there has been little published experience to show which tests produce meaningful results and how these tests can be used to demonstrate compatibility (Fan et al., 2013). The findings obtained can be applied for a preliminary design in waterproofing compound in landfill disposal of waste from industrial sources and can be used as a buffer zone of industry resources to communities that are vulnerable to contaminate by heavy metals. It is expected that these findings can be effectively reduced the contamination to the environment.

Low permeability slurry walls have been widely used as containment for many years to control the migration of contaminants into the subsurface. The goals of this study were to examine the hydraulic conductivity and unconfined compressive strength of bentonite-cement (BC) mixtures and the influence of various mix proportions on the strength and hydraulic conductivity of the resulting mixtures. Moreover, this study aims to

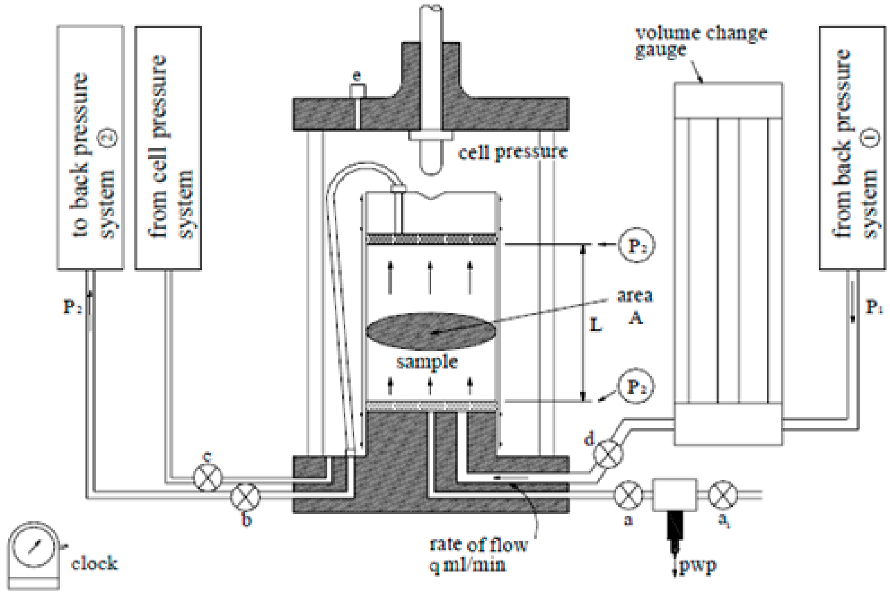
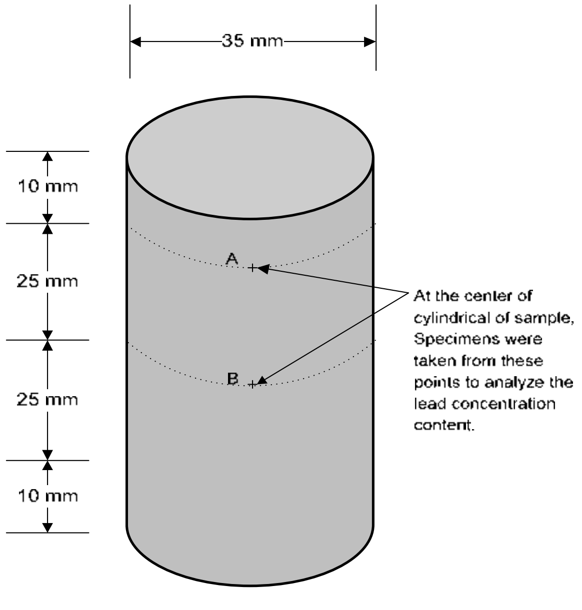


Fig. 1. Lead contamination using triaxial test.



At the center of cylindrical of sample, Specimens were taken from these points to analyze the lead concentration content.

Fig. 2. Collected points for the lead contamination test of soil specimen.

model the performance of slurry wall specimen to prevent the penetration and retention of test solution with high concentration of lead which was assumed as toxic waste. Initially the natural soil was thoroughly mixed by bentonite with percentages of 5%, 10% and 15%. Later, two ratios of cementitious material to bentonite-water slurry were added: 7.5% and 15%. The percentage of cementitious material refers to the percentage of cement by weight of the mixture between natural soil and bentonite. All slurry cutoff samples were cured for a period of 7, 14 and 28 days at 100% humidity. After curing, samples underwent permeability and unconfined compression tests.

2. Materials preparations and investigations

2.1 Lead contamination

This paper examines the hydraulic conductivity and strength properties of several bentonite-cement (BC) mixture contents. The objective of these studies was to delineate the influence of the cementitious material content, bentonite, and curing time upon the strength and hydraulic conductivity of BC barrier materials. The two ratios of cementitious material to bentonite-water slurry used were 7.5% and 15%. Samples were cured for a period of 7, 14 and 28 days at 100% humidity, after which samples of each mixture underwent permeability and unconfined compression testing as recommended by Singkornrum, 2015; Teerawattanasuk, 2015). Moreover, this study aims to model the performance of slurry wall specimen to prevent the penetration and retention of test solution with high concentration of lead which was assumed as toxic waste.

2.2 Sample preparation

Soil samples used in this study is a natural soil located near the water resources of communities around the industrial estate in Rayong Province, Thailand. While bentonite used is the bentonite for wet process bored pile and Portland cement used is Type I Portland cement. Mechanical and physical properties of natural soil were conducted. Grain size distribution was conducted according to ASTM D422. Liquid limit and the plastic limit of the soil samples were conducted according to ASTM D2487. Specific gravity of the soil samples was conducted according to ASTM D854.

Lead contamination in specimen was conducted through permeability testing using triaxial cell permeameters as shown in **Fig**. **1**. Each sample was back pressure saturated to preclude air in the voids of the sample, which might affect the permeability. A back pressure of 390 kPa, applied for a period of 24 hours, was used, after which permeation began. The back pressure was applied using a minimum of 15 min intervals and in increments between 50 and 100 kPa, such that the difference between cell pressure and back pressure was always less than the desired effective consolidating stress to minimize the potential for overconsolidating the sample (Teerawattanasuk, 2015). Ability to detain lead contamination was proof by using artificial waste water with concentration of lead 100 mg/L. After permeability test, two different points of the lead contamination in the top and middle part of soil specimen (point A and B) as shown in **Fig. 2** was collected and analyzed to determine lead (II) nitrate concentration using atomic absorption spectrophotometer.#

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2.3 Preparation of $Pb(NO_3)_2$ solution

To obtain $Pb(NO_3)_2$ solution with concentration of 100 mg/L, lead (II) nitrate powder of 0.1599 gram was put into a 1000 ml volumetric flash and filled with distill water. Gently, the volumetric flash was shook to dissolve lead (II) nitrate with water. Then the pH of the substance $Pb(NO_3)_2$ was measured using a portable pH meter. If the substance was found to be a strong acid, it needed to be adjusted to be a mild acidic of pH equal to 4 by adding NaOH solution to avoid the sedimentation of lead solution due to the high acid condition. On the other hand, if the substance is a strong base, HNO_3 was filled as necessary to adjusted the pH of the lead nitrate solution to the suitable value (pH = 4) before performing the permeability and lead concentration tests.

3. Material properties

3.1 Physical properties

Grain size distribution was conducted as per ASTM D-422 as shown in **Fig. 3**. According to unified soil classification the soil sample can be classified as clayey well graded sand (SW-SC). Specific gravity of natural soil and bentonite is 2.68 and 2.53, respectively. The consistency limit of soil is shown in Table 1.#

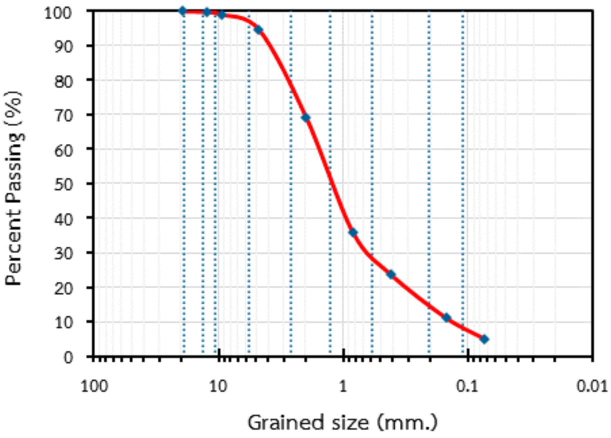

Fig. 3. Grain size distribution of soil.

Table 1. Atterberg's limits of natural soil and bentonite samples.

Atterberg's Limits	Natural Soil	Bentonite
Liquid Limits	23.49%	446.18%
Plastic Limits	11.68%	90.95%
Plastic Index	11.82%	355.22%

3.2 Engineering properties

Unconfined Compression Test according to ASTM D854 was conducted on specimen which composed of natural soil, bentonite, water and Portland Cement Type I was added as an additive. Bentonite was thoroughly mixed with natural soil with content of 5%, 10% and 15% by weight of dry soil. Later, Portland Cement Type I with content of 7.5%, 10%, 15% and 20% by weight of the specimen was then mixed with the mixture between bentonite and natural soil and cured at 3, 7, 14 and 28

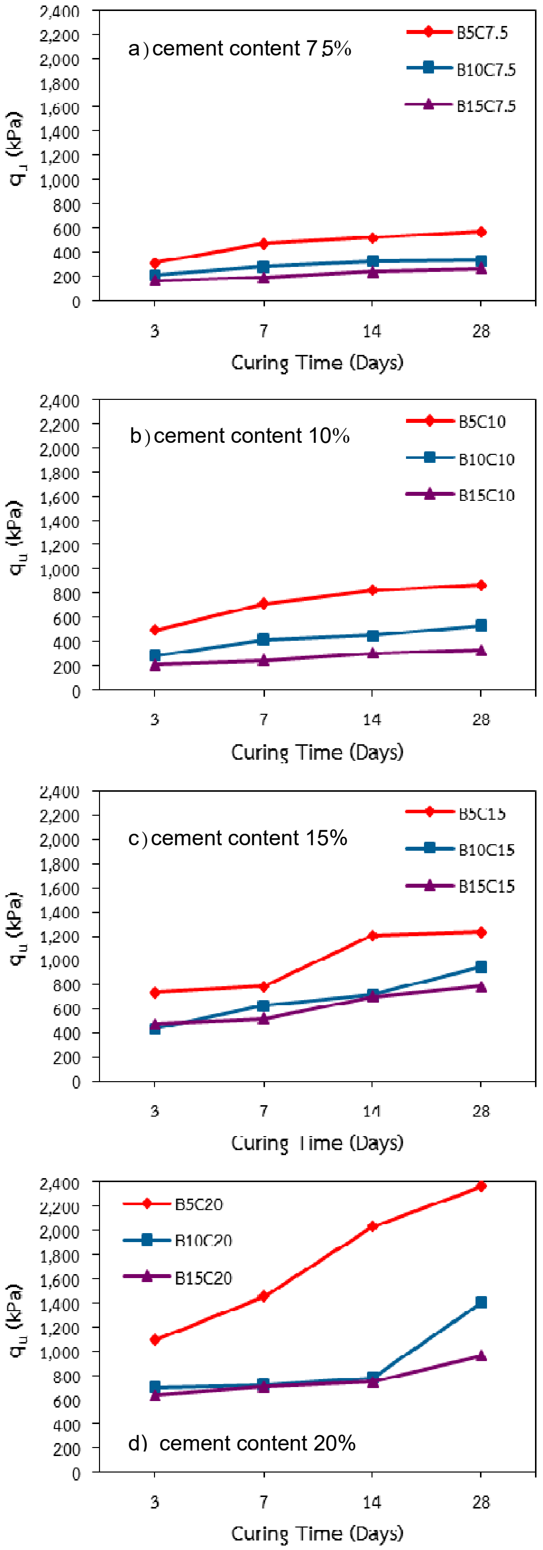

Fig. 4. Relationship between q_u and curing time with various cement contents.

days respectively. In this study there are 2 characters B and C are used. Character B stands for bentonite while C stand for Portland cement. The number written behind the character stand for the percentage of materials used such as B5C7.5 mean the admixture that composed of bentonite 5% and Portland cement 7.5%.

4. Results and discussions

4.1 Influence of Cement Content on Unconfined Compressive Strength (q_u)

The laboratory testing programs revealed a relationship between the unconfined compressive strength of specimen and curing time and cement content varied from 7.5%, 10%, 15% and 20% (**Fig. 4a**). At any given cement content, the unconfined compressive strength decreased with increasing bentonite content. In addition, cement content of 5% had little effect on the unconfined compressive strength, until cement content exceed 10%.

The maximum q_u at 28 days of B5C7.5, B10C7.5 and B15C7.5 was found to be 568.33 kPa, 331.33 kPa and 266.95 kPa, respectively. The maximum q_u at 28 days of B5C10, B10C10 and B15C10 was found to be 871.24, 532.28#kPa, and 330.97 kPa, respectively. The maximum q_u at 28 days of B5C15, B10C15 and B15C15 was found to be 1,233.0 kPa, 943.30 kPa and 782.31 kPa, respectively. The maximum q_u at 28 days of B5C20, B10C20 and B15C20 was found to be 2,365.17 kPa, 1,405.30 kPa and 963.44 kPa, respectively. It can be observed that the q_u of specimen increased as cement content increased due to the hydration products, which are crystalline $Ca(OH)_2$, calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), calcium aluminum silicate hydrates (CASH) and Ettringite. The CSH, CAH, and CASH are regarded as cementitious products which simultaneously enhance the strength of specimen by forming a large number of rigid bonds connecting soil particles.

4.2 Influence of bentonite content on unconfined compressive strength (q_u)

Similar to the demonstrated relationships between q_u and curing time with various cement content, the data also revealed a relationship between q_u and curing time with bentonite content varied from 5%, 10% and 15% (**Figs. 4a to 4d**). The q_u increased as curing period increase for all bentonite content. The maximum q_u at 28 days of B5C5, B5C7.5, B5C10 and B5C15 was found to be 568.33 kPa, 871.24 kPa, 1,233.01 kPa and 2,365.17 kPa, respectively. The maximum q_u at 28 days of B10C5, B10C7.5, B10C10 and B10C15 was found to be 331.33# kPa, 532.28# kPa, 943.30 kPa and 1,405.30 kPa, respectively. The maximum q_u at 28 days of B15C5, B15C7.5, B15C10 and B15C15 was found to be 266.95, 330.97 kPa, 782.31 kPa and 963.44 kPa, respectively. It can be seen that the q_u decreased as bentonite content increased due to high expansion when wet, absorbing as much as several times its dry mass in water. The clay mineral in bentonite is “montmorillonite”, which is the most notorious in the smectite family, can adsorb very large amounts of water molecules between its crystalline sheets. When bentonite becomes saturated, more and more water dipoles are gathered between the crystalline clay sheets, causing the bulk volume of the soil to increase or swell. The incorporation of the water into the chemical structure of the bentonite will also cause a reduction in the capacity or strength of the specimen. Therefore, the increment of bentonite content causes increased water content and void ratio and subsequently decreased unconfined compressive strength.

4.3 Influence of curing time on unconfined compressive strength (q_u)

In addition to the relationship between q_u and various percentage of bentonite and cement content described above, a relationship between q_u and admixture ratio of bentonite-cement was performed (**Fig**. **5**). From the data shown in **Fig**. **5** with 5% of bentonite, the q_u obviously increase as cement content and curing time increase. Considering the B5C20 after 28 days of curing time, it can be seen that the maximum value of q_u is 2,365.17 kPa. The higher the cement contents the higher the cementitous product occurred that affect the strong bonding between the clay particles in the specimen. In contrast It clearly seen that the capacity or strength of the specimen will be reduced as bentonite content increase. The q_u of B10C20 decrease to 1,405.30 kPa. Moreover, the q_u B15C20 decrease to 963.44 kPa which due to water absorption of smectite which can adsorb very large amounts of water molecules between its crystalline sheets.

4.4 Triaxial permeability test with two back pressure system

Permeability testing was conducted using triaxial cell permeameters. Each sample was back pressure saturated to preclude air in the voids of the sample, which might affect the permeability. A back pressure of 275 kPa, applied for a period of 24 hours, was used, after which permeation began. The back pressure was applied using a minimum of 15-min intervals and in increments between 35 and 70 kPa, such that the difference between cell pressure and back pressure was always less than the desired effective consolidating stress to minimize the potential for overconsolidating the sample.

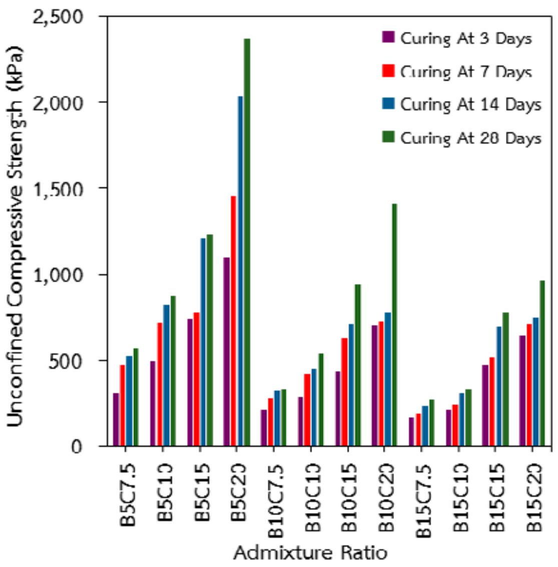

Fig. 5. Relationship between qu and different mixtures.

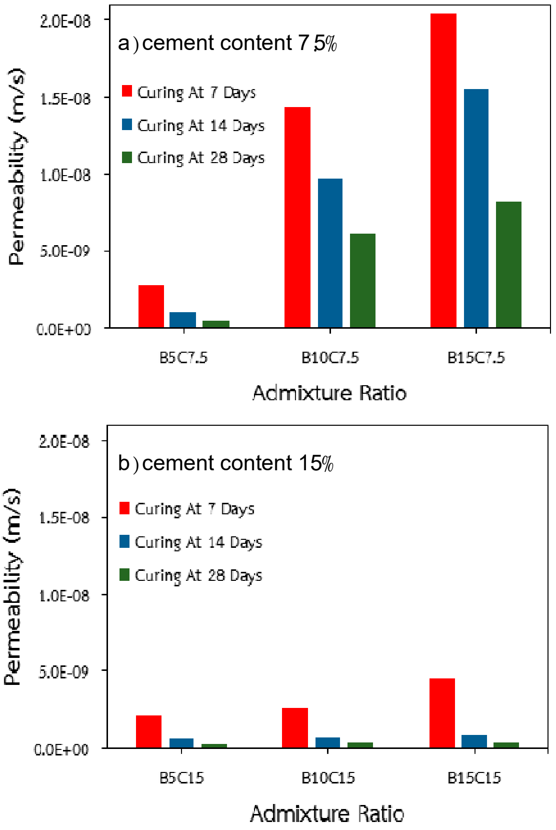

Fig. 6. Relationship between k and admixture ratio.

The permeability test is to measure the flow rate of water through soil. In this test, water is forced by a known constant pressure through a soil specimen of known dimensions and the rate of flow is determined. In order to find permeability coefficient (k) of specimen which composed of natural soil, bentonite, water and Portland Cement Type I. Bentonite was thoroughly mixed with natural soil with content of 5%, 10% and 15% by weight of dry soil. Later, Portland Cement Type I with content of 7.5%, 10%, 15% and 20% by weight of the mixture between bentonite and natural soil was then mixed and cured at 3, 7, 14 and 28 days, respectively. Triaxial Permeability Test with Two Back Pressure System was conducted on saturated specimen and artificial lead solution was used instead of water.

4.5 Influence of the amount of bentonite and cement on the permeability coefficient

The hydraulic conductivity results for samples cured for 7, 14 and 28 days as shown in **Fig**. **6**. These results quantitatively illustrate the influence of the mix proportions (bentonite and Portland Cement Type I) upon the hydraulic conductivity of BC materials. Figure 6a shows the correlation between k of specimen with bentonite content 5%, 10% and 15% and cement content 7.5% and 15%. It can be seen that the k increase with the bentonite content due to the fact that bentonite can absorb large amount of water and void ratio increase as a consequence. For example, specimen with bentonite content 5% after curing period of 7 days exhibits the k of 2.7697×10^{-9} m/s and increase to 1.4361×10^{-8} m/s and 2.0408×10^{-8} m/s as bentonite content increase to 10% and 15% which is 4.18 times and 6.37 times of 5% bentonite. However, the k tends to decrease as curing period increase due to the completion of cement hydration in the specimen that harden and reduce void ratio in the specimen. For example, the specimen with bentonite content 10% and cement content 7.5%, it can be seen that the k decrease from 1.4364×10^{-8} m/s to 6.1548×10^{-9} m/s after 7 days and 28 days respectively which equal to 1.33 times of the 28 days.

Figure 6b shows the correlation between the k of specimen with bentonite content 5%, 10% and 15% and cement content 15%. The result was similar to the case of cement 7.5% that is the k increase as bentonite content increase but the increment rate of k is quite low. In addition, the k tends to decrease as curing period increase. At 7 days of curing periods, if the bentonite increase from 5% to 10% and 15%, the results show that the k of the specimen increase to 24% and 111%, respectively. As expected the addition of cement reduces water permeability. At 7 days of curing period it can be seen that the water permeability coefficient decreases from 2.048×10^{-8} m/s to 4.561×10^{-9} m/s when cement content increases from 7.5% to 15%. This shows that stabilization of the specimen with cement could lead to a better mechanical strength and lower permeability and hence better durability

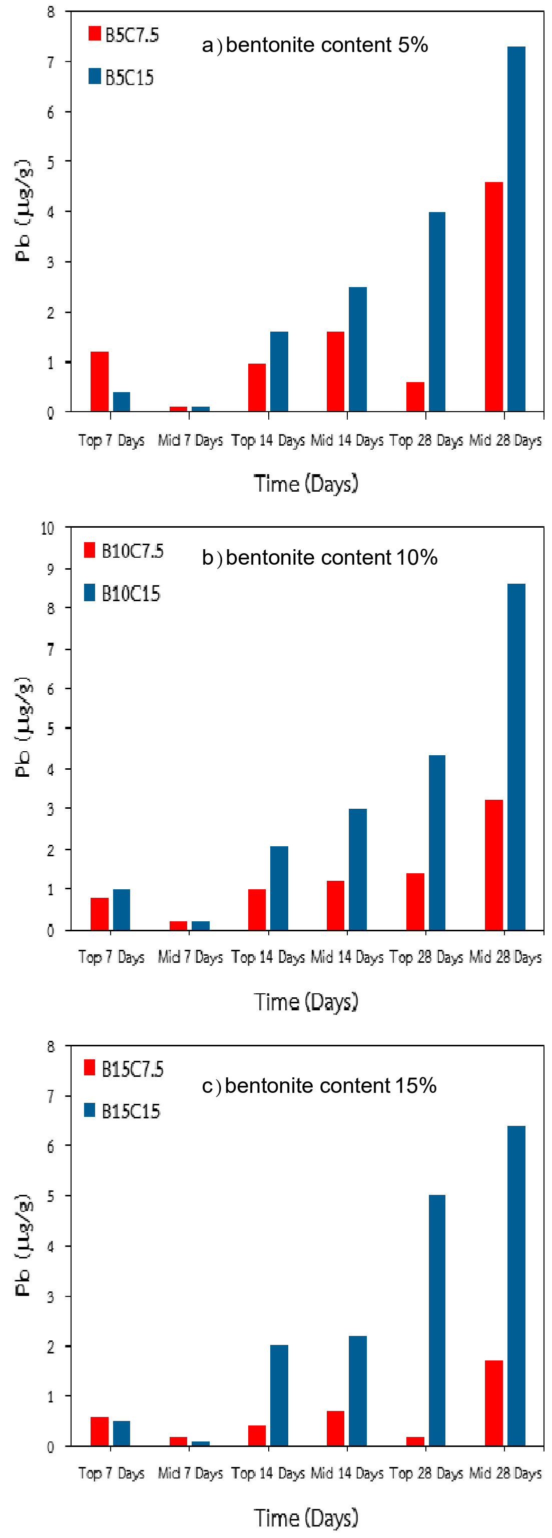

Fig. 7. Relationship between lead concentration and curing period with different bentonite contents.

4.6 Lead concentration in slurry wall

After triaxial permeability test with two back pressure system was conducted on saturated specimen and

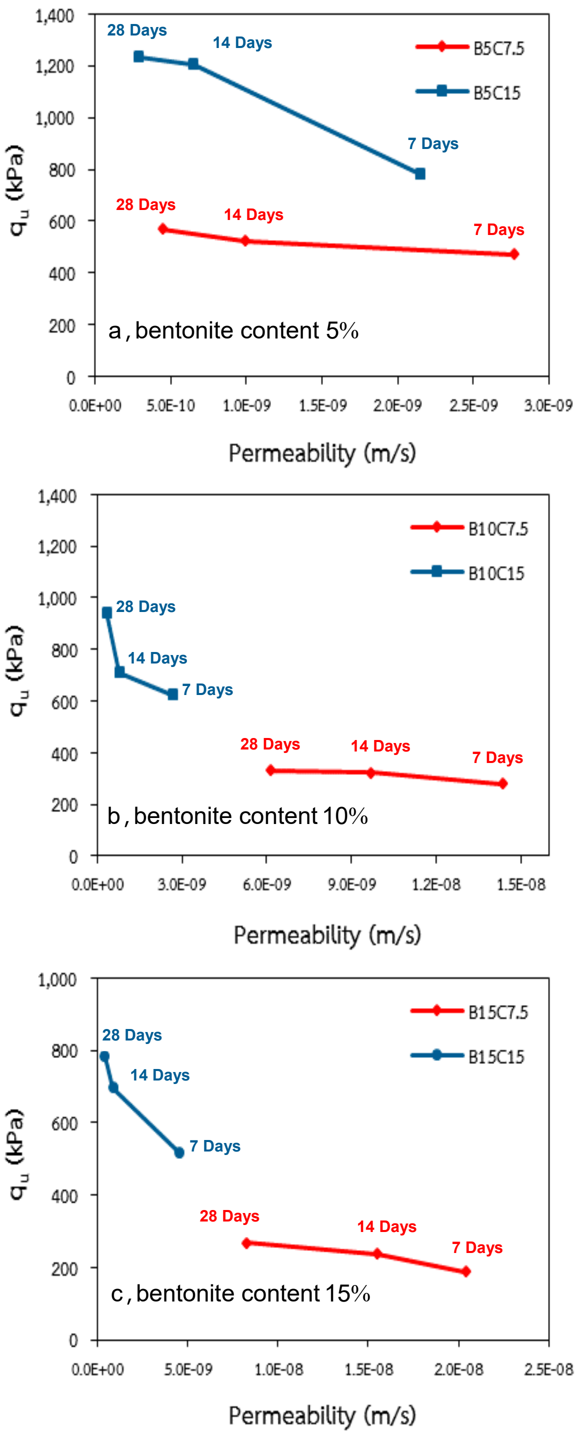

Fig. 8. Relationship between q_u and k of slurry wall specimen with different bentonite content.

artificial lead solution was used instead of water. Lead concentration was investigated by spectrophotometer on top, middle, and exit part of the slurry wall specimens after 7 days, 14 days, and 28 days curing period.#

Figure 7 shows that after 7 days of curing time, lead concentration remaining on the top and middle part of all specimens is quite low due to the incompletion of cement hydration so that the lead ion can easily pass through the void that still continuously contain in the specimen. Besides, it can be observed that the higher the cement content the more the lead was trapped in the specimen. As the reactions proceed, the products of the hydration process gradually bond together the individual soil particle, and other components of the mix, to form a solid mass. Therefore, after 14 and 28 days, high concentration of lead was observed in the middle part of specimen. Lead concentration of 4.0 µg/g and 7.3 µg/g in B5C15 was observed due to high cement content and longer curing period that enhanced solid mass forming in the specimen which simultaneously blocked permeability flow of artificial solution. It clearly seen that the lead concentration in the middle portion of specimen was found to be higher than in the top portion due to longer flow path that cause slower seepage force. Thereafter, the lead was trapped and accumulated in the middle portion. Considering specimen B10C7.5 it can be seen that the lead concentration in top portion is 1.4 µg / g while in the middle portion is 3.2 µg / g which 2.28 times higher than the top portion. In summary, with the proportion of bentonite 5%, 10% and 15% for a curing period of 7, 14 and 28 days. Therefore, the effectiveness of slurry wall for lead retention contaminated soil can be obtained by using the optimum bentonite-cement proportion of B10C15.

4.7 Relationship between q_u and k of slurry wall specimen

There are 6 types of specimen in this study B5C7.5, B5C15, B10C7.5, B10C15, B15C7.5 and B15C15. It can be seen from **Figs**. **8a, 8b** and **8c** that the q_u of the specimen with cement content 7.5% slightly increase as curing time increase. While the permeability decrease in a wide range from 2.7697×10^{-9}, to 9.9424×10^{-10} and 4.4467×10^{-10} m/s at curing period of 7, 14 and 28 days, respectively. It is noted that for the curing period of 28 days the q_u of B5C7.5 is approximately higher than that of B10C7.5 and B15C7.5 of 1.4 times and 1.6 times which due to high bentonite content absorbing large amount of water and as a result the strength of the specimen reduces. In addition, the q_u of specimen with cement content 15% increase rapidly as curing period increase. On the other hand, the q_u at 28 days of B5C15, B10C15, and B15C15 is decrease from 1,233.01 kPa to 943.30 kPa and 782.31 kPa, respectively which due to the increment of bentonite content as previously noted. The permeability coefficient of B5C15 decrease in a wide range compare to B10C15 and B15C15 due to the hydration that slowly developed and void content in the specimen gradually decrease with time. It can be concluded that q_u increase as cement content and curing period increase. On the other hand, the permeability coefficient decrease as curing period and cement content increase.

5. Conclusions

(1) Unconfined compressive strength (q_u) of specimen increased as cement content increased due to the hydration products, which are crystalline $Ca(OH)_2$, calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), calcium aluminum silicate hydrates (CASH) and Ettringite. The CSH, CAH, and CASH are regarded as cementitious products which simultaneously enhance the strength of specimen by forming a large number of rigid bonds connecting soil particles.

(2) Unconfined compressive strength (q_u) of specimen decreased as bentonite content increased due to high expansion when wet, absorbing as much as several times its dry mass in water. The clay mineral in bentonite is “montmorillonite”, which is the most notorious in the smectite family, can adsorb very large amounts of water molecules between its crystalline sheets. When bentonite becomes saturated, more and more water dipoles are gathered between the crystalline clay sheets, causing the bulk volume of the soil to increase or swell. The inorporation of the water into the chemical structure of the bentonite will also cause a reduction in the capacity or strength of the specimen.

(3) The lowest values of hydraulic conductivity of 3.9366×10^{-10} m/s were found from tests on mixtures between 5% bentonite and 15% cement (B5C15) after 28 days curing period due to high cement hydration. While the highest values of hydraulic conductivity of 1.4361×10^{-8} m/s were found from tests on mixtures between 10% bentonite and 7.5% cement (B10C7.5) after 7 days of curing period. This shows that stabilization of the specimen with cement could lead to a better mechanical strength and lower permeability and hence better durability.

(4) After 28 days curing period, the highest lead contamination was found in the middle portion of all specimen mixtures. Specimens with high cement content form a low permeability material that keeps high lead contaminant in the specimen. Therefore, by the addition of varying amounts of cement, it is possible to produce specimens with a wide range of engineering properties.

(5) The q_u increase as cement content and curing period increase. On the other hand the permeability coefficient decrease as curing period and cement content increase. As expected, the more the bentonite was added the more the permeability coefficient can be achieved and the less the q_u was obtained.

(6) Based on the limited of experiment data, the effectiveness of slurry wall for lead retention contaminated soil can be obtained by using the optimum bentonite-cement proportion of B10C15.

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References

Evans, J.C. and Dawson, A.R., 1999. Slurry walls for the control of contaminant migration: A Comparison of United Kingdom and United States Practices. ASCE Specialty Conference on Geo-Engineering for Underground Facilities, ASCE Geotechnical Special Publication No. 90, June: 316-322.

Evans, J.C. and Prince, M.J., 1997. Added effectiveness in minerally-enhanced slurry walls. In Situ Remediation of the Geoenvironment, Geotechnical Special Publication No. 71, ASCE, Reston, VA.: 181-196.

Evans, J.C., Sambasivam, Y. and Zarlinski, S., 1990. Attenuating materials for composite liners. Waste Containment Systems: Construction, Regulation, and Performance. Geotechnical Special Publication No. 26, ASCE, Reston, VA.: 246-263.

Fan, R., Du, Y., Liu, S. and Chen, Z., 2013. Engineering behavior and sedimentation behavior of lead contaminated soil-bentonite vertical cutoff wall backfills. Journal of Central South University, **20** (8): 2255-2262.

Gutberle, 1994. Slurry walls. Virginia Tech. Retrieved 2012-01-05. Available on the website at: http://www.webcitation.org/query?url=http%3A%2F%2Fwww.cee.vt.edu%2Fewr%2Fenvironmental%2Fteach%2Fgwprimer%2Fslurry%2Fslurry.html&date=2012-01-05: 65-69.

Heiser, J.H. and B. Dwyer., 1997. Summary report on close-coupled subsurface barrier technology Initial field trials to full-scale demonstration. Brookhaven National Laboratory, BNL-52531: pp190.

Henning, J.T., Evans, J.C. and Shackelford, C.D., 2006. Membrane behavior of two backfills from field-constructed soil-bentonite cutoff walls. J. Geotech. and Geoenv. Engrg., ASCE, **132** (10): 1243-1249.

Hong, C.S., Shackelford, C.D. and Malusis, M.A., 2011. Consolidation and hydraulic conductivity of zeolite amended soil-bentonite backfills. J. Geotech. and Geoenv. Engrg., ASCE, **138** (1): 15-25.

Kaya, A. and Durukan, S., 2004. Utilization of bentonite-embedded zeolite as clay liner. Applied Clay Science, **25** (1-2): 83-91.

Malusis, M.A., Yeom, S. and Evans, J.C., 2011. Hydraulic conductivity of model soil-bentonite backfills subjected to wet-dry cycling. Canadian Geotech. Journal, **48** (8): 198-211.

Malusis, M.A., Barben, E.J. and Evans, J.C., 2009. Hydraulic conductivity and compressibility of soil-bentonite backfill amended with activated carbon. J. Geotech. and Geoenv. Engrg., ASCE, **135** (5): 664-672.

Malusis, M.A. and Shackelford, C.D., 2002. Chemico-osmotic efficiency of a geosynthetic clay liner. J. Geotech. And Geoenv. Engrg., ASCE*,* **128** (2): 97-106.

Mishra, A.K., Ohtsubo, M., Li, L. and Higashi, T., 2011. Controlling factors of the swelling of various bentonites and their correlations with the hydraulic conductivity of soil-bentonite mixtures. Applied Clay Science, **52** (1/2): 78-84.

Montoro, M.A. and Francisca, F.M., 2010. Soil permeability controlled by particle-fluid interaction. Geotechnical and Geological Engineering, **28** (6): 851-864.

Mutch, R.D., R.E. Ash, and J.R. Caputi, 1997. Contain contaminated groundwater. Chemical Engineering, **104** (5): 114-119.

Opdyke, S.M. and Evans, J.C., 2006. Slag-cement-bentonite slurry walls. J. Geotech. and Geoenv. Engrg., ASCE, **131** (6): 673-681.

Rumer, R.R. and J.K. Mitchell, 1996. Assessment of barrier containment technologies. A Comprehensive Treatment for Environmental Remedial Application. Product of the International Containment Technology Workshop. National Technical Information Service, PB96-180583.

Singkornrum, N., 2015. A study of slurry wall efficient for prevent of contaminated lead solution into soil. M.Eng. Thesis, King Mongkut's University of Technology North Bangkok, Thailand (in Thai unpublished).

Teerawattanasuk, C., 2015. Improvement of slurry wall for the prevention of contaminated heavy metal in soil. Research report, King Mongkut's University of Technology North Bangkok, Thailand (in Thai unpublished).

Williams, M. and Ghataora, G. S., 2011. Effect of fibre reinforcement on the properties of ground granulated blast furnace slag-cement-bentonite slurry. Studia Geotechnica et Mechanica, **33** (4): 63-83.

Xanthakos, P.P., Abramson L.W. and Bruce D.A., 1994 Ground control and improvement. John Wiley & Sons, New York: pp 936.

Yeo, S.S., Shackelford, C.D. and Evans, J.C., 2005a. Consolidation and hydraulic conductivity of nine model soil-bentonite backfills. J. Geotech. and Geoenv. Engrg., ASCE, **131** (10), 1189-1198.

Yeo, S.S., Shackelford, C.D and Evans, J.C. 2005b. Membrane behavior of model soil-bentonite backfill mixtures. J. Geotech. and Geoenv. Engrg., ASCE, **131** (4): 418-429.#