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Reuse of dredged sediments as pavement materials by cement kiln dust and lime treatment

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Abstract. This paper presents an investigation on the properties of two types of cement kiln dust (CKD)-stabilized dredged sediments, silt and clay with a comparison to hydrated lime stabilization. Unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted to examine the optimal stabilizer content and classify the type of highway material. A strength development model of treated dredged sediments was performed. The influences of various stabilizer types and sediment types on UCS were interpreted with the aid of microstructural observations, including X-ray diffraction and scanning electron microscopy analysis. The results of the tests revealed that 6% of lime by dry weight can be suggested as optimal content for the improvement of clay and silt as selected materials. For CKD-stabilized sediment as soil cement subbase material, the use of 8% CKD was suggested as optimal content for clay, whereas 6% CKD was recommended for silt; the overall CBR value agreed with the UCS test. The reaction products calcium silicate hydrate and ettringite are the controlling mechanisms for the mechanical performance of CKD-stabilized sediments, whereas calcium aluminate hydrate is the control for lime-stabilized sediments. These results will contribute to the use of CKD as a sustainable and novel stabilizer for lime in highway material applications.

Keywords: cement kiln dust; dredged sediment; pavement materials; stabilization; strength

1. Introduction

Globally, many hundreds of millions of cubic meters of sediment are dredged every year for the maintenance of harbors and channels. Most of this material is dumped in the sea or stored at land disposal sites (Kamali *et al*. 2008). For example, the Chao Phraya River in Thailand is a main river flowing from the lower northern provinces to the lower central provinces. The length of the river is 372 km, and it flows into the Gulf of Thailand. As this river flows, an alluvial plain is deposited by sediments, creating transportation shipping problems due to the shallow effect in the river. Dredging sediments at a rate of approximately 2.5 million m^3 per year is a typical way to maintain navigable river channels (Thai Marine Department 2015). The large amount of dredged sediments after dredging is a large problem due to the storage area and disposal methods. Most sediments are considered to be marine fine-grained soils, such as silts and clays.

The reuse of the dredged sediments, which is considered for relieving such problems, is encouraged. Several researchers have proposed the reuse of these dredged sediments as backfill materials for pavement structures, including base, subbase, selected material or subgrade. This approach requires chemical stabilization by sediment mixture with various stabilizers to improve the fine-grained sediments' engineering properties, including compressibility, shear strength, bearing capacity and permeability (Houng *et al*. 2010, Oh *et al*. 2011 and Park *et al*. 2014). Since the 1990s, several studies have been performed to evaluate the efficiency of this technique in the case of marine dredged sediment (Dermatas *et al*. 2003, Boutouil and Levacher 2005, Rekik and Boutouil 2009). Similar to soils, the results showed a significant improvement in the mechanical properties of dredged sediments after treatment. The influence parameters affected the stabilized sediment properties in terms of sediment type, stabilizer type, stabilizer content, methodology and curing time (Farouk and Shahien 2013, Yoobanpot and Jamsawang 2014).

One stabilizer normally used in chemical stabilization is lime, which is a locally available and reasonably priced

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material. After lime is admixed with soil and water, the reactions between exchangeable clay ions and calcium ions supplied by lime are immediate. The cation exchange reaction changed the electrolyte content in the water, including flocculation, aggregation and carbonation, which resulted in a decrease in the plasticity of the soil and soil coagulation. This property could increase the soil strength and reduce the soil plasticity and swelling characteristics (Bell 1993, Al-Mukhtar *et al*. 2010, Yaolin *et al*. 2015).

Another interesting cementitious material is cement kiln dust (CKD). CKD is an industrial waste generated in kilns during the cement manufacturing process by electrostatic precipitator machines. The composition of CKD typically includes calcium carbonate and silicon dioxide, similar to the cement kiln raw feed but different in terms of chloride, alkali and sulfate content. The variables in CKD composition and their effects on CKD properties depend on the raw feed material, dust collection methodology, temperature used in the cement kiln, type of fuel used at each factory and operation process. For these reasons, researchers have suggested investigating CKD before using it (Maslehuddin *et al*. 2009, Kumar and Nitish 2013, Khalid *et al*. 2014). The amount of CKD in Thailand could be considered in terms of cement production quantity, which is approximately 30 million t per year (Thai Cement Manufacturers Association, 2015), and 15%-20% of cement becomes CKD (Environmental Protection Agency 1993, Rahman *et al*. 2011); thus, 4.5-6.0 million t per year of CKD is generated.

Researchers have attempted to use CKD in a number of application fields. Najim *et al*. (2014) used CKD as a cement replacement material to produce modified cement mortar. The replacement of CKD with OPC in proportions of 10%, 20% and 30% revealed that mortar strength decreased with increasing CKD content. Higher water quantity was required to achieve the standard consistency of the cement paste. Because CKD contains high amounts of free lime, a quick reaction was formed and led to decrease initial and final setting times of the mortar. At 30% CKD replacement, CKD did not significantly affect pH values (more than 12), which is a positive indicator regarding steel corrosion in concrete. Abukhashaba *et al*. (2014) produced self-compacting concrete (SCC) containing CKD and polypropylene fiber (PPF). It was found that the SCC shrinkage tended to decrease with increasing PPF content and length of PPF at 20 mm, 40 mm and 60 mm. The strength development ratio of C28/C7 decreased from 1.29 to 1.14, 1.09, and 1.12 using PPF content of 0.005, 0.010, and 0.015 kN/m^3, respectively. CKD and PPF could potentially be used for SCC production with a slight negative effect on workability. Moreover, CKD has been found to be satisfactory as a friendly environmental material when used in concrete application work (Kunala *et al*. 2012, Wang *et al*. 2014, Joshua *et al*. 2015). For waste treatment applications, CKD was used to absorb some heavy metal, zinc, manganese, iron, nickel and lead from sewage water. The use of CKD has been demonstrated to be beneficial as an antibacterial agent to kill bio-disease, thereby reducing contamination in sewage water (Mackie *et al*. 2010, Mahmoud 2014, Salem *et al*. 2015). For ground improvement application work, CKD has been mixed with soil as backfill material in retaining wall construction to reduce soil lateral pressure, thereby controlling the construction time and saving costs. It was observed that CKD-mixed soil has a significant effect to reduce the active earth pressure after the layer was set. The CKD-mixed soil method was suggested for backfill materials to compare with the conventional compaction method and gabion technique (Ahmed and Mohie 2014). In addition, the studies revealed that CKD could be used as a stabilizer in geotechnical projects to enhance soil strength, reduce permeability and increase soil durability (Sulapha *et al*. 2009 and Vivek and Rajesh 2015). However, due to the large annually generated volumes of CKD, the investigation of greater quantities of CKD used as road construction materials continues to be of interest.

Utilization of dredged sediments stabilized with lime and CKD as a new material is an interesting solution to the problem of road construction projects due to the lack of high-quality material. Moreover, strength properties, including unconfined compressive strength (UCS), California bearing ratio and microstructure are still limitations. Therefore, the primary objective of this study is to improve dredged sediments as pavement material using the cementitious materials lime and CKD as stabilizers. Based on strength and CBR testing, the results were evaluated in comparison with the pavement material standards for types of materials. The correlation between stabilizer content, water-cement ratio and curing time was analyzed to predict the stabilized sediment strength. X-ray diffraction (XRD) was performed to analyze the reaction products of the cementing hydration process in relation to compressive strength. Observations of the change in the stabilized sediment structure were made by scanning electron microscopy (SEM).

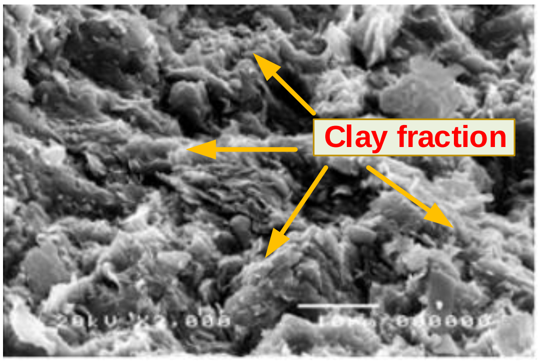
2. Experimental program

2.1 Base sediments

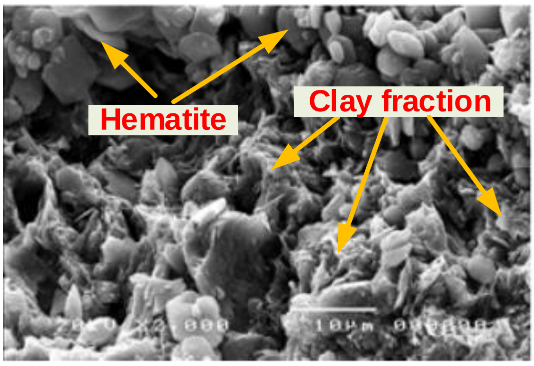
The base sediments utilized in this study are dredged sediments collected from two different locations of the dredged sedimentary project in the Chao Phraya River. Sediment A was taken from the Bangkok vicinity, and Sediment B was sampled from Ayutthaya province, which is approximately 100 km from the construction site of dredged sediment A. The sediment sampling depths were 2 to 5 m and 1 to 4 m from the riverbed for sediment A and sediment B, respectively. The geotechnical engineering properties obtained from laboratory tests for both sediments are listed in Table 1. Sediment A and sediment B were classified as CH and MH, respectively, according to the Unified Soil Classification System (USCS). The initial water contents were 107 and 76% and corresponding void ratios were 2.89 and 2.07 for sediment A and sediment B, respectively, which leads to low strength. Thus, sediment stabilization is introduced as the technique adopted to be used as pavement materials. The maximum dry densities and optimal moisture contents obtained from modified compaction according to ASTM D1557 were 13.4 kN/m^3 and 29.3% and 15.2 kN/m^3 and 22.6% for sediment A and sediment B, respectively. The UCS for compacted sediment A and sediment B before stabilizing were 71 and 88 kPa, respectively. The

Table 1 Geotechnical properties of untreated dredged sediments

Properties	Sediment A	Sediment B
Atterberg's limit		
Liquid limit (%)	87	58
Plastic limit (%)	32	31
Plasticity index (%)	55	27
Grain size		
Sand (%), size 0.475-0.075 mm	2	5
Silt (%), size 0.075-0.002 mm	27	62
Clay (%), size < 0.002 mm	71	33
Specific gravity	2.70	2.72
Natural water content (%)	107	76
Initial void ratio	2.89	2.07
Maximum dry density from modified compaction test (kN/m^3)	13.4	15.2
Optimum moisture content from modified compaction test (%)	29.3	22.6
Unconfined compressive strength of compacted sediment (kPa)	71	88



(a) Dreaded sediments A



(b) Dreaded sediments B

Fig. 1 SEM micrographs of untreated dreaded sediments

mineralogical contents of dredged sediments were determined by X-ray diffraction (XRD). For preparation of the sample used in XRD, dry dredged sediments were ground to powder, passing the U.S. standard sieve No. 200. The XRD patterns were analyzed using a Philips X'Pert diffractometer with energy of 40 kV and current of 30 mA. The scanning of XRD covered the angles between 2° and 70°(2θ). The XRD pattern of untreated sediment as shown in Fig. 7(a) reveals that sediment A has a main crystal phase of quartz combined with common clay

Table 2 Chemical composition of lime and CKD

Compound	Lime (% by weight)	CKD (% by weight)
Silicon dioxide (SiO_2)	0.45	14.05
Alumina oxide (Al_2O_3)	0.23	4.59
Ferric oxide (Fe_2O_3)	0.21	2.32
Calcium oxide (CaO)	73.18	54.47
Magnesium oxide (MgO)	0.45	1.72
Sulfur trioxide (SO_3)	0.14	10.23
Potassium oxide (K_2O)	0.06	3.94
Na_2O + TiO_2 + other	0.51	3.05
Loss on ignition (% by mass)	24.77	5.63

minerals, including montmorillonite, kaolinite and illite. For sediment B (see Fig. 7(b)), the XRD pattern shows the main crystal phase of quartz, and some hematite was found together with montmorillonite, kaolinite and illite. The microstructures of dredged sediments were observed by scanning electron microscopy (SEM) using a JEOL JSM-5600LV series with probe current of 20 mA, accelerating voltage of 20 kA and working distance of 15 mm. The morphology of untreated sediment, as shown in Fig. 1(a), illustrates that sediment A consists of a fine plate of clay fraction with non-uniform shapes, which was packed in an inexact direction. Fig. 1(b) shows that the structure of sediment B comprises a non-uniform shape of clay fraction with a directionless position similar to that found in sediment A. The hexagonal shape of hematite crystal, which corresponds to the detected result by XRD, was also observed in various shapes due to the incomplete crystal structure.

2.2 Stabilizer

Hydrated lime and CKD are the stabilizers used in this study. The chemical composition of the stabilizers was analyzed by X-ray fluorescence (XRF) spectrometry, as listed in Table 2. The results show that lime is primarily composed of calcium oxide (CaO), up to 73%, together with minor oxides such as magnesium oxide (MgO), silicon dioxide (SiO_2), alumina oxide (Al_2O_3) and ferric oxide (Fe_2O_3). CKD was supplied from a cement production factory in Saraburi province, Thailand. The chemical composition of CKD mainly consists of CaO and SiO_2 combined with Al_2O_3 and Fe_2O_3. The specific gravity of CKD is 2.71, and the fineness ranges within 2900-3200 cm^2/g.

2.3 Unconfined compression and California bearing ratio (CBR) tests

Dredged sediments A and B were mixed with lime and CKD to improve the deficient properties. The complete test program by sediment mixture is listed in Table 3. Lime and CKD contents of 1, 2, 4, 6 and 8% by dry weight were added to each ground sample. Water was added to the mixture to achieve the optimal moisture content previously examined by the modified Proctor test. The dredged sediment sample was prepared similarly to the lime

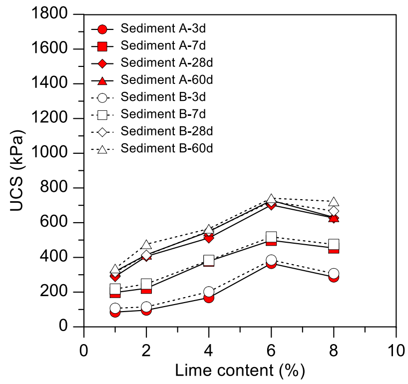
Table 3 Mixture scheme for treated sediment

Designation	Sediment type	Stabilizer (% by dry weight)
AL1, AL2, AL4, AL6, AL8	A	Lime 1, 2, 4, 6, 8
BL1, BL2, BL4, BL6, BL8	B	Lime 1, 2, 4, 6, 8
AC1, AC2, AC4, AC6, AC8	A	CKD 1, 2, 4, 6, 8
BC1, BC2, BC4, BC6, BC8	B	CKD 1, 2, 4, 6, 8

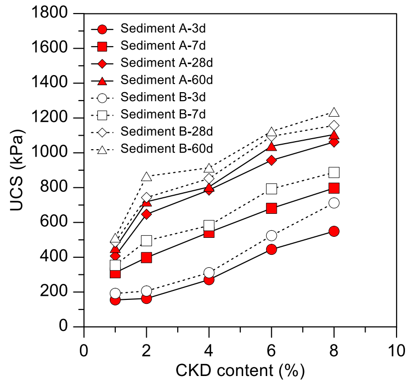
stabilization testing process. Three samples of each specimen were prepared for all testing conditions. After each sediment was mixed with the stabilizer, the treated sediment was prepared for the unconfined compressive strength (UCS) test following the standard of ASTM D2166. The homogeneous sediment mixture was statically compacted in a cylindrical mold of size 50 mm in diameter and 100 mm in length. All specimens were compacted at optimal moisture content with maximum dry density of the untreated material. After de-molding, the specimens were stored in air at ambient temperature and cured for 3, 7, 28 and 60 days prior to strength testing. This storage condition was designed to be consistent with the construction sites where the stabilized sediment is exposed to the climate. According to ASTM D1883, soaked CBR was performed for each stabilized sediment, and the average value was calculated after testing three samples. A sample was compacted in the CBR mold near the optimal moisture content value with maximum dry density, corresponding to the test result of untreated sediment. Specimens were stored in air under ambient temperature and then cured for seven days. This storage condition was applied in a similar way to the specimen preparation for the compressive strength test. After reaching seven days, the specimens were soaked for 96 h before testing.

2.4 Microscopic investigation of stabilized sediment

X-ray diffraction (XRD) analysis of the stabilized sediments was conducted to investigate the reaction products from the hydration process of the stabilized sediments. This method was performed to consider the relation between UCS and the intensity of the reaction product, which was produced based on the failure plan of the treated sediment sample after the UCS test. Scanning electron microscopy (SEM) was applied to observe the changes to the microstructures of the stabilized sediment. After the UCS test, stabilized sediment samples were collected for further observation by SEM.



(a) Lime



(b) CKD

Fig. 2 Effect of stabilizer type on strength development of two stabilized sediments

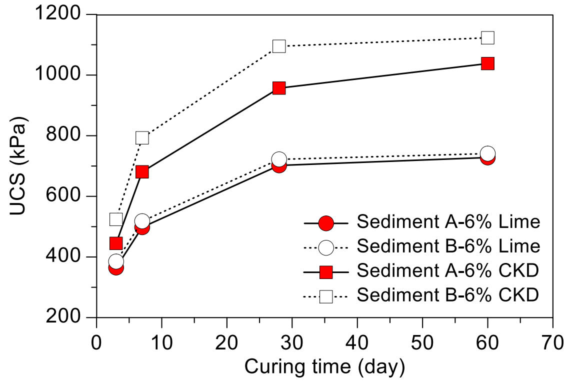


Fig. 3 Compressive strength development with time at 6% stabilizer content

3. Results and discussion

3.1 UCS test

3.1.1 Optimal stabilizer content

The effects of lime content and curing time on UCS of stabilized sediments A and B are presented in Fig. 2(a). The test results reveal that UCS of both sediments for all mixtures increased with increasing curing time and increasing lime content from 1 to 6%. However, UCS of stabilized sediments A and B decreased when the lime content was greater than 6% for all curing times. Thus, it can be considered that lime content of 6% was optimal for stabilized sediments A and B. The optimal lime content found in this study was within common ranges suggested by many researchers. Ramesh *et al.* (2012) attempted to improve red earth clay by adding mine tailings with 1 to 6% lime. The study revealed that using 3% lime exhibited the yield compressive strength of stabilized sediment. Ogundipe (2013) presented the archived CBR for lime-stabilized clay as subgrade material using 8% lime. Wang *et al.* (2013) found that using lime contents of 3 to 9% can enhance the compressive strength of marine sediments. Hashemian et al. (2014) stated that the use of 4% lime can improve the CBR value to meet the standard for airport pavement.

The effects of CKD contents on UCS of stabilized sediments A and B with increasing curing time are presented in Fig. 2(b). Unlike lime stabilization, no optimal CKD content was observed because UCS increased with increasing CKD contents for all curing periods. In addition, the comparative UCS result of sediment B was slightly higher than that of sediment A for all curing periods owing to the higher silt content than sediment A.

3.1.2 Strength development with time

Fig. 3 shows the effects of curing time and 6% stabilizer content on UCS of two stabilized sediments. It was found that lime- and CKD-stabilized sediment exhibits more predominant strength development during the initial 28 days than the subsequent 28 days. For the same sediment, UCS of CKD-stabilized sediments is higher than that of the lime-stabilized sediment. Moreover, it is shown that a higher UCS value was evidenced in sediment B than sediment A. Considering the viewpoint of strength development, the seven day strengths of all stabilized sediments was approximately 0.70, 1.40 and 1.45 times that at the curing time of 3, 28 and 60 days, respectively. The gain in compressive strength for CKD and lime-stabilized sediments increased in the early stage owing to the effect of the integration of sediment particles, whereas the long-term strength is influence by the pozzolanic reactions (Sulapha *et al.* 2008, Umesha *et al.* 2009).

3.1.3 Prediction of strength development

Prediction of the UCS for the stabilized sediments A and B is performed according to the framework developed by Chian *et al.* (2016), which considered the effect of mix proportions and curing duration for cement-treated soft clay. The proposed model equation can be written as

$$UCS = \left[a + b(s/c)\right]\ln t / Y^{w/c} \tag{1}$$

where a, b and Y are empirical constants, which are calibrated from experimental data; s/c and w/c are sediment-cement and water-cement ratios, respectively; and t is curing time in days. The UCS prediction based on Eq. (1) is presented in Eq. (2) to Eq. (5) as follows:

For lime-stabilized sediment A

$$UCS = \left[350 - 1.07(s/c)\right]\ln t / 1.05^{w/c} \tag{2}$$

For lime-stabilized sediment B

$$UCS = \left[200 - 1.25(s/c)\right]\ln t / 1.06^{w/c} \tag{3}$$

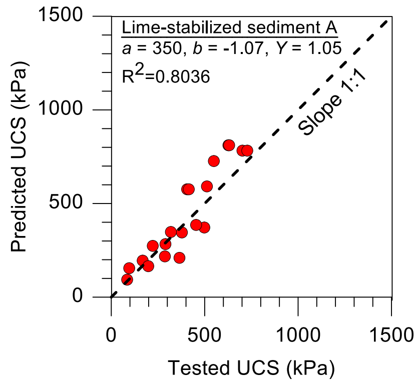
For CKD-stabilized sediment A

$$UCS = \left[320 - 1.45(s/c)\right]\ln t / 1.05^{w/c} \tag{4}$$

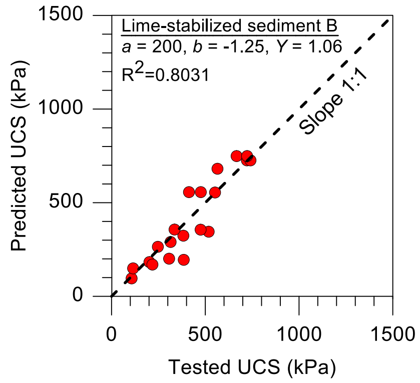
For CKD-stabilized sediment B

$$UCS = \left[220 - 1.35(s/c)\right]\ln t / 1.05^{w/c} \tag{4}$$

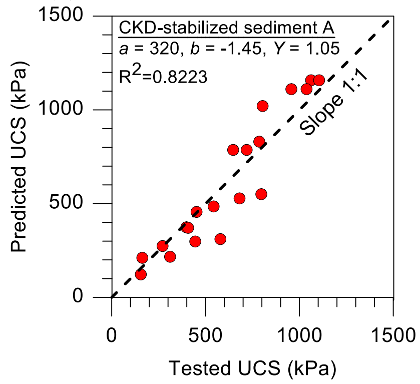
Figs. 4(a)-4(d) illustrate the relationship between predicted and tested UCS for lime-stabilized sediment A,



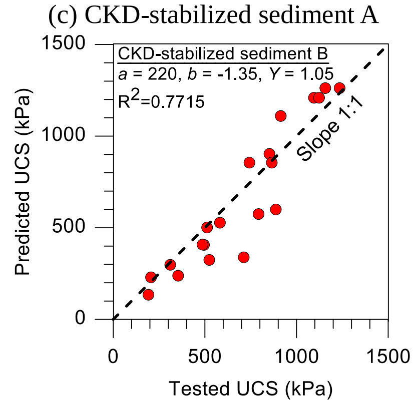
(a) Lime-stabilized sediment A



(b) Lime-stabilized sediment B



(c) CKD-stabilized sediment A



(d) CKD-stabilized sediment B

Fig. 4 Strength comparison of lime- and CKD-stabilized sediment for tested and predicted values

lime-stabilized sediment B, CKD-stabilized sediment A, and CKD-stabilized sediment B, respectively. As indicated by the comparisons (Figs 4(a)-4(d)), for all curing times, the results of the predictions of UCS by Eq. (1) are in a fair level of coefficient of determination (R^2 = 0.7718–0.8223). The values of R^2 obtained from this study are lower than that obtained from work of Chian *et al.* (2016), which ranged between 0.9044 and 0.9960. This finding might indicate that no effects of compaction and stabilizer type were considered in the proposed model. However, it can be said that the predicted UCS, as proposed in Eqs. (2)-(5), are useful for predicting the strength responses of dredged sediments stabilized with lime and CKD, thereby providing the experimenter a better design. It is noted here that only two different base sediments and two different stabilizers were used in this research, which definitely limits possible future use of the proposed equations. Thus, various types of base sediments and stabilizers will be investigated to study the influences of index properties of the based sediments (especially liquid limit and plasticity index), and chemical properties of the stabilizers on stabilized sediments in future

3.2 CBR tested results

Fig. 5 presents the effects of the sediment type and stabilizer content on CBR values. The CBR values of both lime- and CKD-stabilized sediments are higher than that of untreated sediment. For lime-stabilized sediment A, the lowest CBR was presented at 1% lime content, and the highest CBR was presented at 6% lime content. It was found that the CBR value of lime-stabilized sediment A achieved a CBR of between 1.7 and 6.3 times greater than unimproved sediment. The CBR of lime-stabilized sediment B has a similar trend as the CBR of lime-stabilized sediment A. It was found that 1% lime content resulted in the lowest CBR, and 6% lime exhibited the highest CBR.

For CKD-stabilized sediment, CBR increased with increasing CKD content, which showed the difference in the result from lime-stabilized sediment. CKD-stabilized sediment A showed CBR values higher than the original sediment of between 2.3 and 15.7 times greater than 1% to 8% CKD, respectively. For CKD-stabilized sediment B, the CKD values tended to increase with increasing CKD content, which resembles that found in sediment A. Stabilized sediment B established the highest CBR with 8% CKD, BC8, and 18.2 times higher than unimproved sediment. The CBR value of CKD-stabilized sediment increased with increasing CKD content. At two contents, the CBR value exhibited an approximately 40% increase in the CBR when the CKD content increased from 6% to 8%. A dissimilar result was found in lime-stabilized sediment. The CBR value reveals an approximately 25% decrease in the CBR when the CKD content increases from 6% to 8%. Similar to the unconfined compression test results, the compressive strength of CKD-stabilized sediment increased with increasing CKD content, whereas the strength of lime-stabilized sediment increased with 6% lime content and decreased with 8% lime content. This result is consistent with that obtained by Tutumluer and Al-Qadi (2009), confirming that CKD stabilization presents more potentiality for CBR in stabilized soil relative to lime.

3.3 Correlation between UCS and CBR

The correlation between compressive strength and CBR

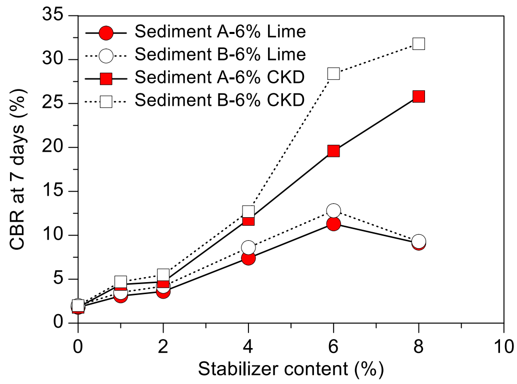


Fig. 5 Effect of sediment type and stabilizer content on CBR

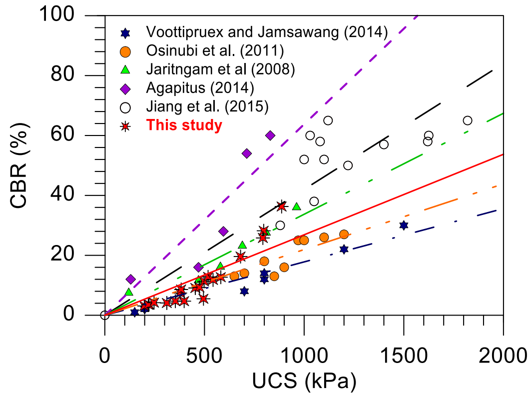


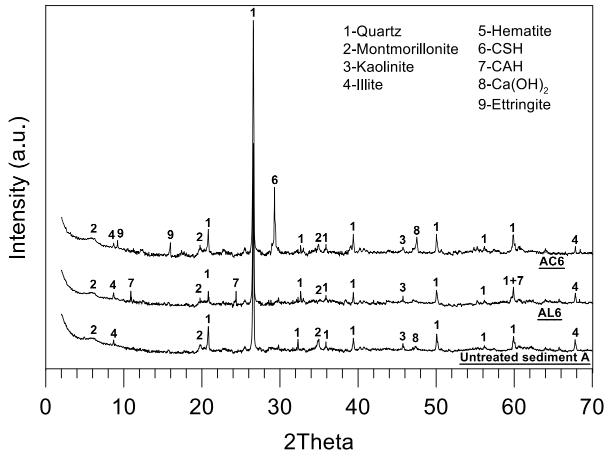
Fig. 6 Correlation between compressive strength and CBR for various types of stabilized sediment

value of stabilized sediment found in this study is illustrated in Fig. 6. This correlation for various types of stabilized soil has also been studied by other researchers. Jaritngam *et al.* (2008) attempted to improve soft clay with cement to reduce the post-construction settling of road construction on soft clay. The study revealed that *CBR* = 0.034*UCS* approximately. Osinubi *et al.* (2011) improved black cotton soil with cement mixed with locust bean waste ash, and the result of the correlation was CBR = 0.022*UCS*. Agapitus (2014) enhanced the durability of quarry fine-modified black cotton sediment subgrade with cement kiln dust and illustrated that *CBR* = 0.064*UCS*. Voottipruex and Jamsawang (2014) attempted to improve expansive soils in Northern Thailand with cement and fly ash and the study showed that *CBR* = 0.018*UCS*. Jiang *et al*. (2015) stabilized soft highway subgrade soil with calcium carbide residue by evaluating in a multiscale laboratory the physical, mechanical and microstructural properties. These researchers' results exhibited that *CBR* = 0.042*UCS*. Therefore, the correlation between UCS and CBR of stabilized sediment in this study was also plotted, and it was shown that *CBR* = 0.027*UCS* is the within range of general cementitious material-stabilized soil.

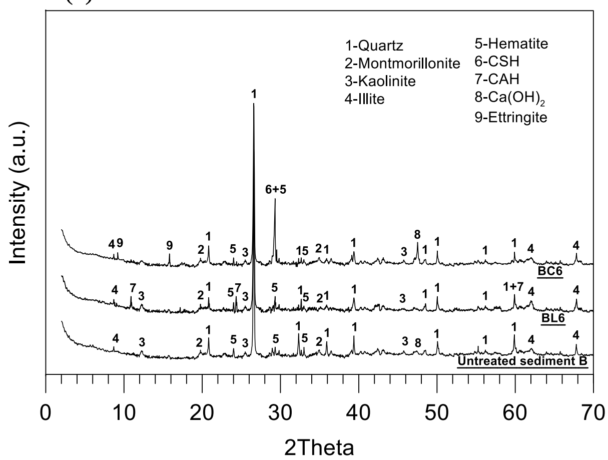
3.4 Microscopic investigation of stabilized sediment

3.4.1 X-ray diffraction (XRD) analysis

The hydration reaction product of stabilized sediment was analyzed by XRD, focusing on the phase change



(a) Sediment A stabilized with lime and CKD



(b) Sediment B stabilized with lime and CKD

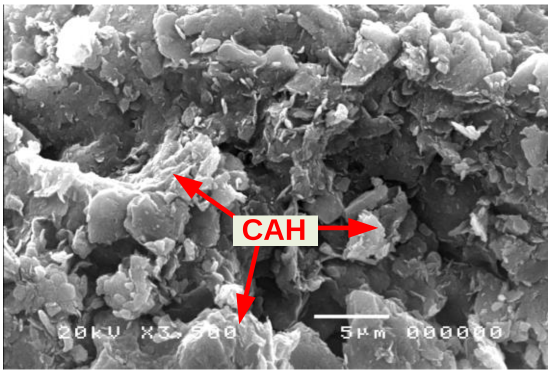
Fig. 7 XRD pattern of stabilized sediment after 7 days of curing

analysis of the products compared with the compressive strength test results. The XRD pattern of sediment A stabilized with lime and CKD, with the same 6% stabilizer content, at seven days is shown in Fig. 7(a). CKD-stabilized sediment AC6 reveals that sediment A consists of the major reaction products calcium silicate hydrate (CSH), calcium hydroxide ($Ca(OH)_2$) and ettringite associated with quartz and clay minerals (montmorillonite, kaolinite and illite). According to the products found, CSH exhibited higher intensity than the other products, so it was considered as the main product for CKD-stabilized sediment. At this stage, CSH was formed at 7 days along with compressive strength; therefore, it is believed that CSH contributed to the strength development. The mechanism explanation of CKD strength development in stabilized sediment could be considered. After the sediment was filled with CKD, a hydration reaction was formed and worked to change the sediment properties. The primary hydration reaction produced hydrated calcium silicates and calcium hydroxide. The secondary hydration reaction called the “pozzolanic reaction,” which formed between calcium hydroxide and clay minerals, sediment silica and sediment alumina, was continuously produced as CSH and $Ca(OH)_2$ with curing time. According to both results of that reaction, the sediment property was changed, becoming denser and stronger and resulting in increased sediment strength with time (Bell 1993, Hesham 2013). Furthermore, the benefit of the formation of ettringite crystal to enhance concrete strength was suggested by a previous researcher (Xu *et al.* 2012, Carmona-Quiroga and Blanco-Varela 2013).

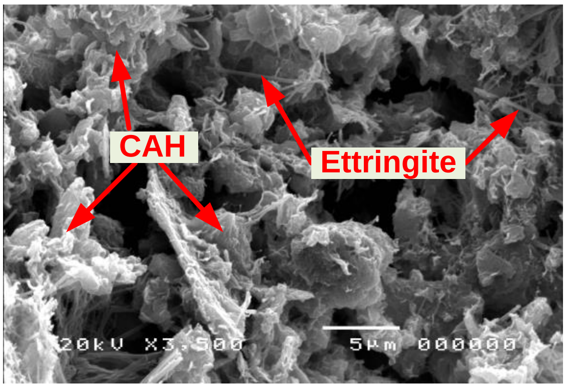
Fig. 7(a) presents the lime-stabilized AL6 sample of sediment. It reveals that sediment A consists of the major reaction products calcium aluminum hydrate (CAH) combined with quartz and clay minerals such as montmorillonite, kaolinite and illite. At this time, the difference can be observed in the different products to compare CKD-stabilized sediment. Because CAH appeared after 7 days of curing, it corresponds to the development of the compressive strength result. Therefore, it is believed that the product CAH played an important role to enhance the strength of lime-stabilized sediment. Based on the relationship between UCS and lime content, the mechanism of sediment lime could be explained. When lime was added to the sediment, the three processes of primary reaction—namely, cation exchange, flocculation and carbonation—were performed. The cation exchange, generated between the metallic ions on the surface of clay particles and surrounded by a water double layer, modified the capacity of calcium ion by an electrical charge around the clay particles as a consequence of the flocculation of sediment particles. This process has a major effect in improving the engineering properties of sediments that utilize lime. The carbonation reaction process is normally not considered because it has a few effects on the sediment lime reaction process. The pozzolanic reaction is a secondary reaction formed during sediment lime mechanism activity. It has long-term changes owing to pozzolanic reactions encouraged by lime, which increase the alkalinity of the sediment. This phenomenon can dissolve silicon and aluminum in sediment. The dissolved material reacts with the calcium ions and forms cementitious material properties, resulting in enhanced shear strength and reducing permeability. Although lime stabilization can be used to improve sediment properties, lime content is a function of clay content, so there is a limitation for using lime in sediment (Cardoso and Maranha 2012, Selvi 2015). The optimal limit of 6% lime content found in this study was consistent with previous studies (Aldaood *et al.* 2014, Zhang *et al.* 2015).

The XRD pattern of sediment B stabilized with the same 6% stabilizer content, lime and CKD is shown in Fig. 7(b). It can be observed that at 7 days, the CKD-stabilized sediment BC6 presents the main reaction products CSH, $Ca(OH)_2$ and ettringite associated with quartz, hematites and clay minerals. This reaction product is similar to those found in AC6, as shown in Fig. 8(a). For lime-stabilized sediment BL6, the main reaction product is CAH with a resemblance to the reaction product of AL6. From the similar result of both, it is shown that CSH and ettringite formed by CKD and CAH generated by lime are the main reaction products responsible for enhancing the strength of stabilized sediment. Because of the CSH, high intensity, and ettringite, the strength of CKD-stabilized sediment was relatively higher than that of lime-stabilized sediment, whose only product is CAH.

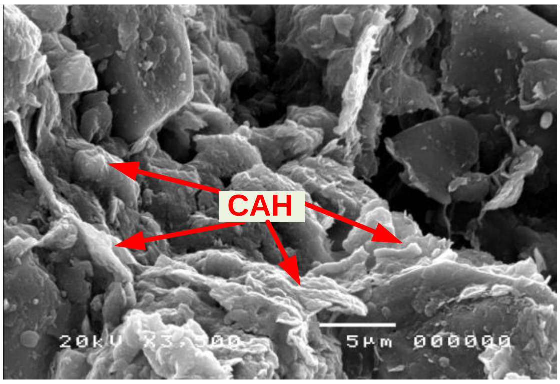
Furthermore, the XRD pattern of untreated sediment A,



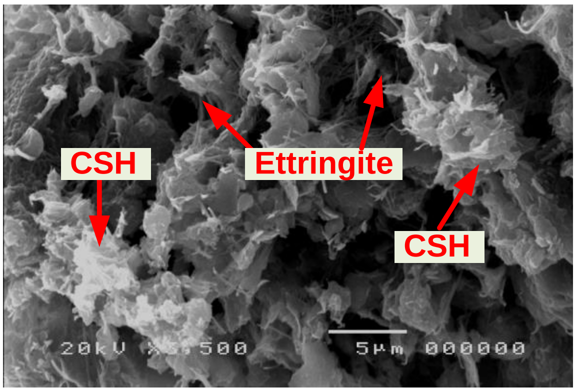
(a) AL6



(b) AC6



(c) BL6



(d) BC6

Fig. 8 SEM micrographs of stabilized sediment after 7 days of curing

clay, and sediment B, silt, in relation to the original strength was discussed. The difference in the mineral identified in sediment B was clearly observed as a greater majority of quartz and hematite than that found in sediment A. Sediment B was given a strong diffraction pattern with a sharp reflection of quartz for both the intensity and magnitude of the peak. Quartz is composed of silica tetrahedral groups and has a high-stability structure and high-hardness mineral composition. These factors influence the strength behavior of the sediment. In other words, sediment strength increases with increasing percentage of quartz (Tenando 2004, Haque *et al.* 2013). Furthermore, hematite is a metallic mineral also found in sediment B, which has the advantage of increasing sediment strength due to the effect of the solid crystal properties. For the above reason, sediment B presented more strength characteristics than sediment A, which agrees well with the results of XRD analysis.

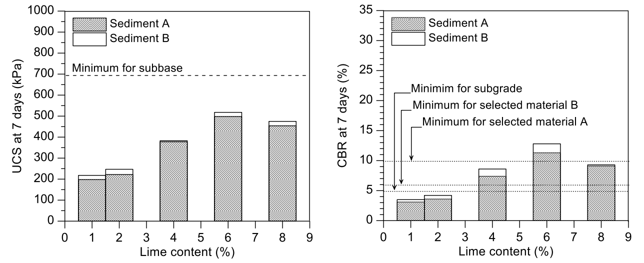
3.4.2 Scanning electron microscopy (SEM) observations

Changes in the microstructure of stabilized sediment was observed by scanning electron microscopy (SEM), as shown in Fig. 8. The samples of each sediment type cured for seven days with the same content of 6% stabilizer were selected for SEM observation to compare with XRD analysis and compressive strength testing. The SEM micrograph of sediment A stabilized with lime (AL6) is shown in Fig. 8(a). It was found that the CAH products, confirmed through XRD analysis in Fig. 7(a), formed to cover the sediment surface. According to the SEM micrograph of untreated sediment in Fig. 1(a), a clay sheet was laid in an inexact direction with a simple touch of contact between sheets effected in low strength. After lime was added, the cation exchange reaction with the electrolyte content in the water, gel or slurry occurred and effected chemical bonding of the sediment particles. The subsequent phenomenon indicated that the lime addition increased the content of $Ca(OH)_2$. Increasing Ca^{2+} and OH^- ions increased the adsorption exchange, which caused the adsorbed layer to spread over the colloid to be slender and larger in the sediment particles. During the curing time, the crystallization reaction of $Ca(OH)_2$ generated a water matrix or water lattice ($Ca(OH)_2$.nH2O), viscous fluid such as slurry or gel, and co-crystallization with sediment particles (Stoltz *et al.* 2012). This phenomenon changed the sediment to coarser aggregates and formed large groups of sediment particles. Those groups led to the formation of sediment lumps, which resulted in increased sediment strength with increasing curing time. A similar study was reported by Kassim (2009), who presented that the reaction products formed after adding 5% lime for sediment stabilization.

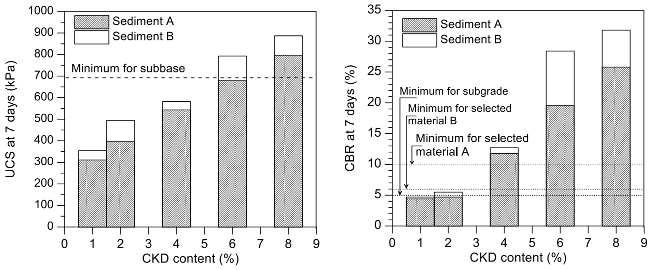
The SEM micrograph of sediment A stabilized with CKD (AC6) is presented in Fig. 8(b). The main hydration products CKD, CSH and ettringite, which were detected by XRD in Fig. 7(a), were found in stabilized sediment clusters. The cementitious product CSH was formed as a fabric with a heterogeneous distribution on the sediment surface. The enlargement of CSH filled the pore space between sediment particles, causing the sediment structure to be denser, which resembled a study by Pourakbar *et al.* (2015). The other major cementitious product is ettringite.

Table 4 Requirement of pavement material

Material	Standard No.	7-day strength (kPa)	CBR (%)
Soil cement base	DH-S 204/2533	1724	
Soil cement subbase	DH-S 206/2532	689	
Selected material A	DH-S 208/2532		10
Selected material B	DH-S 209/2532		6
Subgrade material	DH-S 102/2532		5



(a) Lime stabilization



(b) CKD stabilization

Fig. 9 Consideration of stabilized sediment as pavement material

Needle-like ettringite crystals were formed in the sediment clusters and CSH fabric. The abundantly formed ettringite crystals, rigid crystal property, and intercrossing with CSH and sediment clusters caused the stabilized sediment to become stiffer, resulting in increased stabilized sediment strength similar to that found by Bahmani *et al.* (2016**)**. Additionally, Horpibulsuk *et al.* (2010) stated that the benefit of the growth of cementitious products is to enhance the inter-cluster bonding sediment strength and fill the pore space. This effect on the volume of pores, smaller than 0.1 μm, significantly decreases with increasing strength.

The structure of lime-stabilized sediment B (BL6) is shown in Fig. 8(c). The CAH product, which was confirmed by XRD analysis in Fig. 7(b), formed a cover on the sediment surface similar to AL6. CAH bonding gel linked the sediment particles in a lump, resulting in increased stabilized sediment strength. CKD-stabilized sediment B is presented in Fig. 8(d). The cementitious products CSH and ettringite (detected by XRD analysis) were spread as a cover over the sediment surface, similar to AC6. The growth of those reaction products caused the stabilized sediment to become denser and stiffer, thus increasing the stabilized sediment strength. The difference in the microstructure of lime- and CKD-stabilized sediment could be considered. Although the CAH bonding gel can form sediment lumps, leading to increased sediment strength, this finding is due only to the effect of CAH, which linked the sediment as nearer particles. For CKD-stabilized sediment, not only can CSH fabric fill the pore space between sediment particles, increasing the sediment density, but also the intercrossing of ettringite crystals with CSH and sediment clusters increases the sediment stiffness. For the above reason, CKD-stabilized sediment significantly increased sediment strength more than lime treatment, which agrees with the result of the strength test.

3.5 Summary of tests as pavement material

The criteria of suitable pavement materials based on the Department of Highways (DOH) of Thailand classify highway materials into five categories: soil cement base, soil cement subbase, selected material A, selected material B and subgrade material, as listed together with the corresponding standard designations in Table 4. It is shown that the specifications of soil cement base and soil cement subbase require the minimum UCS of treated soil at seven days to be 1,724 and 689 kPa, respectively. If the UCS at seven days is unsatisfied, the stabilized soil is classified as selected material A, selected material B and subgrade material by considering only CBR values.

A consideration of stabilized sediment as pavement material is presented in Fig. 9. It should be noted that at 1% and 2% lime content, the sediment is unsuitable for use as pavement material because the UCS and CBR values are lower than the minimum requirement of the standard. For CKD-stabilized sediment, 1% and 2% content of CKD-stabilized sediment A and 1% content of CKD-stabilized sediment B are unsuitable for use as pavement material because the UCS and CBR values also do not meet the standard requirement. The following are summaries of the sediments as pavement material.

A. Soil cement subbase (required UCS 689 kPa)

(1) Sediment A; CKD = 8% where UCS = 797 kPa

(2) Sediment B; CKD = 6% and 8% where UCS ranges from 793 kPa to 887 kPa

B. Selected material A (required CBR 10%)

(1) Sediment A; CKD = 4% and 6% where CBR ranges from 11.8% to 19.6% and lime = 6% where CBR = 11.3%

(2) Sediment B; CKD = 4% where CBR = 12.7% and lime = 6% where CBR = 12.8%

C. Selected material B (required CBR 6%)

(1) Sediment A; lime = 4% and 8% where CBR ranges from 7.4% to 9.1%

(2) Sediment B; lime = 4% and 8% where CBR ranges from 8.6% to 9.3%

D. Subgrade material (required CBR 5%)

(1) Sediment A; -

(2) Sediment B; CKD = 2% where CBR = 5.5%

Based on the laboratory test results, the use of lime-stabilized sediment can improve dredged sediments only for selected material A and selected material B, whereas CKD can improve untreated sediment as sediment cement subbase, selected material A, selected material B and subgrade material. It can be stated that CKD has higher potential than lime for use as a stabilizer in pavement material for road work. This result of the study agrees with those found by Miller and Zaman (2000), who presented that CKD can be more effective than lime as a stabilizing agent applied for soil improvement on road construction projects. In addition to the pavement materials, the CKD-stabilized soils can be used for a wide range of applications in many fields such as road subgrade and embankment materials, (Zhang *et al*. 2015) or concrete mat for underground structures (Shen *et al*. 2015, Wu *et al*. 2015). Moreover, the CKD blend is able to be a useful binder for traditional ground improvement techniques, including deep mixing, grouting and jet grouting, as reported by Ni and Cheng (2011, 2014), Modoni and Bzòwka (2012), Modoni *et al*. (2012), Shen *et al.* (2013a, b, c, 2017), Wang *et al*. (2013).

4. Conclusions

The study was focused on the stabilization of dredged sediments with lime and cement kiln dust (CKD) as pavement material, and the following conclusions were drawn:

• For lime stabilization, UCS of sediment A (CH) and sediment B (MH) increased with increasing lime content up to 6% with curing time. The suggested optimal lime content for both sediments is 6%, which improves sediment in selected material A and selected material B.

• The strength of CKD-stabilized sediments increased with increasing CKD content with curing time. Focusing on sediment cement subbase materials, the use of 8% CKD was suggested as the optimal content for sediment A, whereas 6% content of CKD was recommended for sediment B. The compressive strength of lime- and CKD-stabilized sediment agreed with the CBR test results.

• The prediction of UCS for using proposed model of Chian *et al*. (2016) provided fair results, which are useful for predicting the strength responses of dredged sediments stabilized with lime and CKD.

• The correlation between compressive strength and CBR found in this study, $CBR = 0.027UCS$, is within the general range of cementitious stabilized sediment.

• Reaction products CSH and ettringite from CKD and CAH from lime, generated by the hydration process obtained by XRD analysis, can be observed by the SEM technique to cause the sediment structure to be harder than the untreated sediment, resulting in increasing strength with time.

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