Journal of Soils and Sediments (2020) 20:3807–3823
https://doi.org/10.1007/s11368-020-02635-x

SEDIMENTS, SEC 5 • SEDIMENT MANAGEMENT • RESEARCH ARTICLE

Sustainable reuse of dredged sediments as pavement materials by cement and fly ash stabilization

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Received: 7 July 2019 / Accepted: 19 April 2020 / Published online: 9 May 2020

Abstract

Purpose The process of removing sediments from the bottom of dams generates large amounts of dredged sediments, which are considered waste. The purpose of this research was to present the results of testing conducted on dredged sediment stabilized with ordinary Portland cement (OPC) and fly ash (FA) for reuse as pavement materials.

Materials and methods The base sediment was high plasticity silt (MH) based on the Unified Soil Classification System (USCS). The experiments in this study consisted of unconfined compression (UC), California bearing ratio (CBR), and resilient modulus (M_r) tests on stabilized dredged sediment. A combination of scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) was used to investigate the microstructures of the stabilized specimens. Finally, a simple comparative cost analysis between roads using conventional earthen materials and stabilized dredged sediment was performed.

Results and discussion The results showed that the unconfined compressive strength (q_u), CBR, and M_r improved the pavement materials from unsuitable to suitable, and a 10% FA content provided the optimal strength enhancement. The SEM images showed that the calcium silicate hydrate (CSH) product, which was formed by hydration and pozzolanic reactions, attached to the clay clusters and filled the pore spaces between clay particles, resulting in a denser sediment structure. The EDX analyses showed that the calcium weight proportion and the silica-aluminum ratio were important factors in improving the strength of the dredged sediment treated with OPC and FA. These EDX results agreed with the q_u, CBR, and M_r results. For the studied situation, roads using stabilized sediment were 1.5 times more economical than roads using conventional earthen pavement materials.

Conclusions Dredged sediments treated with OPC and FA can be sustainably reused as pavement materials based on the Department of Highways of Thailand standard, as well as the recommendations of Austroads (2017). Thus, for suitable sediments, reuse in road and pavement construction may be considered with appropriate treatment and conditioning.

Keywords Dredged sediment · Pavement materials · Resilient modulus · Reuse · Treatment

1 Introduction

Sediments may be characterized as a combination of loose particles consisting of clay, silt, and sand produced by the erosion and weathering processes of soils, rocks, and organics and by human activities (Dubois et al. 2011). The deposition of sediments in many water sources creates problems in transportation and shipping due to river shoaling; almost a billion cubic meters of sediments are dredged yearly to maintain navigable river channels and sufficiently deep harbors in Thailand. These dredged sediments, which are considered waste materials, are dumped in the sea or at a land disposal site (Kamali et al. 2008). A large amount of sediment has accumulated behind the Mae Sab hydropower dam, which is located in Samoeng District, Chiang Mai, Thailand, reducing

Responsible editor: Victor Magar

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the water storage capacity of the reservoir. Sediments are dredged to maintain the water storage capacity of the reservoir. However, the large amount of dredged sediments removed is a major problem because it is difficult to identify proper storage sites and disposal methods.

To relieve such problems, the reuse of dredged sediments as pavement materials, such as subgrade, selected material subbase and base courses, is considered and highly encouraged. However, most of the dredged sediments are classified as fine-grained materials such as silts and clays with high void ratios and compressibilities, weak strengths, and low bearing capacities. Consequently, dredged sediments that do not undergo stabilization cannot be reused directly as pavement materials. Chemical stabilization with type I ordinary Portland cement (OPC) is one of the most traditional techniques for improving the properties of problematic soils in various applications, resulting in high unconfined compressive strengths (q_u), high bearing capacities and low compressibilities (Horpibulsuk et al. 2010; Horpibulsuk et al. 2011; Mohammadinia et al. 2015; Tongwei et al. 2014; Voottipruex and Jamsawang 2014; Güllü et al. 2017; Jamsawang et al. 2017; Yoobanpot et al. 2017).

Ordinary Portland cement can also be mixed with waste material from the coal combustion process of power plants, such as fly ash (FA), to reduce costs (via the replacement of OPC) and environmental problems (because a high level of CO_2 is released during cement production) associated with the use of OPC alone (Wen et al. 2010; Güllü 2014). Class C FA has been shown to be effective for soil stabilization in civil engineering works (Horpibulsuk et al. 2009; Jongpradist et al. 2010; Wen et al. 2010; Tastan et al. 2011; Kogbara et al. 2013; Shaheen et al. 2014; Suksiripattanapong et al. 2015). Fly ash is able to increase the performance of the soil stabilization process by increasing the reactive surface area (Horpibulsuk et al. 2009) for hydration and pozzolanic reactions.

The resilient modulus (M_r) and California bearing ratio (CBR) are important factors in the determination of pavement thickness and the selection of pavement construction materials, as explained in the AASHTO (1993) Guide for the Design of Pavement Structures and Austroads (2017). Over the last decade, several studies have focused on evaluating the factors affecting the M_r and CBR of OPC-stabilized subgrade soils (Osinubi et al. 2011; Solanki et al. 2011; Tastan et al. 2011; Agapitus 2014; Voottipruex and Jamsawang 2014; Abu-Farsakh et al. 2015; Jiang et al. 2015). These factors include the stress state, additive content, curing time, curing temperature, moisture content, compaction delay, and soil properties. In general, M_r of stabilized soil increases as the binder content increases, whereas the permanent deformation of stabilized soil decreases as the binder content increases (Solanki et al. 2011; Abu-farsakh et al. 2015).

Scanning electron microscopy (SEM) has been widely used to investigate the microstructural changes resulting from the stabilization process (Shaheen et al. 2014; Kang et al. 2015; Ahmed 2015; Jiang et al. 2015; Jamsawang et al. 2017; Yoobanpot et al. 2017). Scanning electron microscopy is commonly coupled with energy-dispersive X-ray spectroscopy (EDX) to describe the microstructural changes in stabilized samples. Most previous studies focused on the mechanical and microstructural properties of subgrade soils stabilized with cementitious materials. However, a limited number of studies focused on the reuse of dredged sediments stabilized with OPC and FA as pavement materials.

This paper investigates the development of q_u, CBR and M_r of dredged sediment stabilized with OPC and FA. The microstructural changes in the stabilized dredged sediment were observed via SEM, whereas the changes in chemical composition were investigated using EDX. The prediction of the stabilized dredged sediment M_r was determined via the q_u and CBR values. Finally, the properties of dredged sediments stabilized with OPC and FA were assessed for reuse as pavement materials based on the Department of Highways of Thailand standards and Austroads (2017) recommendations, and a road construction site was evaluated to compare the costs between roads using stabilized sediment and roads using conventional earthen pavement materials.

2 Materials and methods

2.1 Dredged sediment and admixtures

The studied sediments were dredged from the Mae Sab hydropower dam in Samoeng District, Chiang Mai, Thailand. The basic physical and engineering properties of the untreated dredged sediment were assessed in accordance with the ASTM standards. The raw sediment was sieved through sieve no. 40 (finer than 0.425 mm) and then tested using three samples for each test. Therefore, the test results were presented in terms of an average value. The specific gravity of the dredged sediments is 2.55, and the natural moisture content of the dredged sediments, which is defined as the ratio of the weight of the water to the weight of the dry sediment and presented as a percentage, is 55%. The liquid and plastic limits are 57 and 39%, respectively. The dredged sediment is classified as inorganic high plasticity silt (MH) according to the Unified Soil Classification System. The maximum dry unit weight and the optimum moisture content were obtained from a modified Proctor compaction test according to ASTM D1557 (2015) and were found to be 16.6 kN m^{-3} and 18.5%, respectively. The SEM images in Fig. 1a show that the dredged sediment comprises a nonuniform distribution of silt and clay fractions with large pores. The OPC particles have rough surfaces and sharp corners and are nonuniformly shaped, whereas most of the FA particles are spherical, as shown in Fig. 1b and c, respectively.

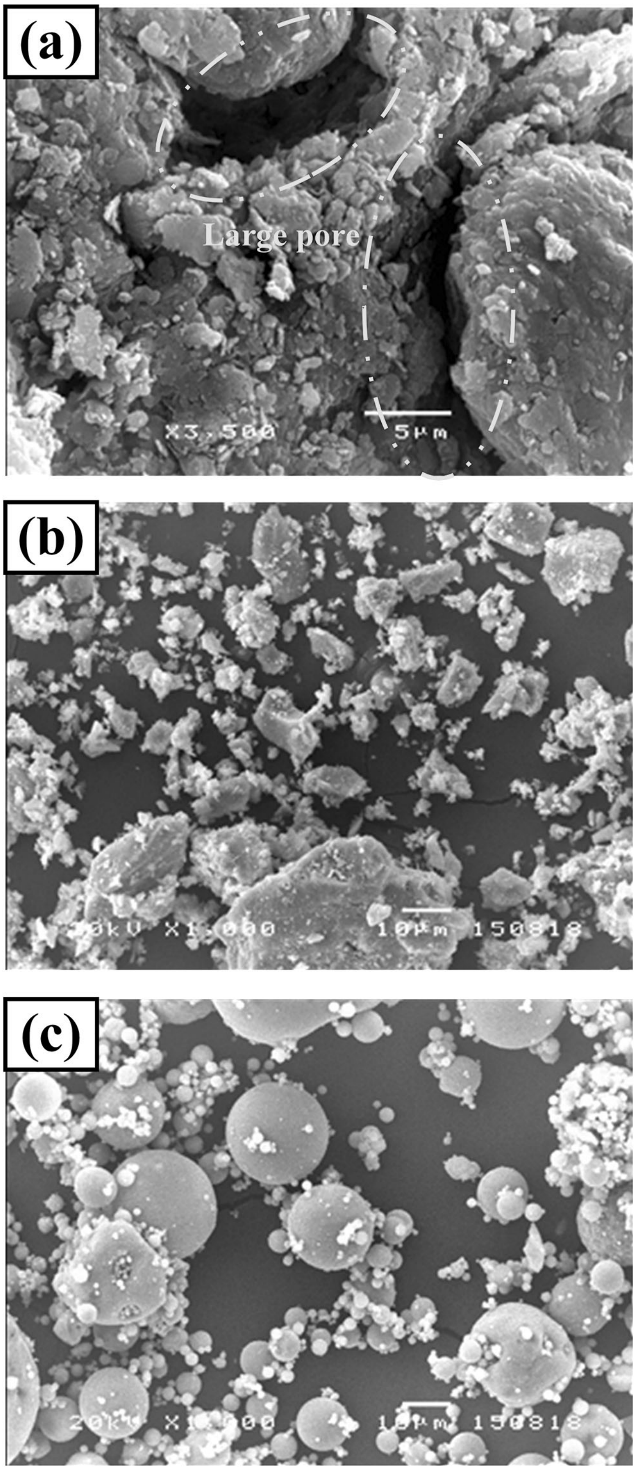


Fig. 1 SEM images of the **a** dredged sediment, **b** ordinary Portland cement (OPC), and **c** fly ash (FA)

Based on the X-ray fluorescence analysis presented in Table 1, the untreated dredged sediment consisted of 66.20% silicon dioxide (SiO_2), 19.30% aluminum oxide (Al_2O_3), 6.67% ferric oxide (Fe_2O_3), 1.01% calcium oxide (CaO), and 0.91% magnesium oxide (MgO). All the components of the dredged sediments are considered to be relatively inert and unreactive relative to OPC and FA. The cement utilized in this study was type I OPC with a specific gravity of 3.15, fineness of 2900 $cm^2\ g^{-1}$, and high CaO content of 62.81%. The FA was from the Mae-Moh power plant in northern Thailand. The total amount of the three main components (SiO_2, Al_2O_3, and Fe_2O_3) in the FA is 69.14%, which is between 50 and 70%. Thus, the FA used in this study is classified as class C based on ASTM C 618 (2012).

Table 1 Chemical composition of dredged sediment, OPC, and FA

Compound	Dredged sediment (%)	OPC (%)	FA (%)
SiO_2	66.20	21.20	37.34
Al_2O_3	19.30	4.95	18.63
Fe_2O_3	6.67	2.82	13.17
Na_2O and K_2O	3.98	0.30	4.94
MgO	0.91	4.00	3.92
CaO	1.01	62.81	17.85
SO_3	0.19	2.63	3.51
Other	1.74	1.29	0.64

2.2 Molding and curing of the specimens

Cylindrical specimens 50 mm in diameter and 100 mm in height were used for the unconfined compression (UC) and M_r tests, whereas cylindrical specimens 152 mm in diameter and 116 mm in height were used for the CBR tests. The raw dredged sediment was sieved (passing 0.425 mm) and then dried in an oven for 24 h to ensure that its initial moisture content was zero before mixing with OPC, FA and additional water. A series of UC, CBR, and M_r tests was performed using exclusively OPC, exclusively FA, and a combination of OPC and FA. In this study, OPC contents of 1.5, 2.5, 5, and 7.5% (by dry weight of sediment) and FA contents of 5, 10, 15, and 20% (by dry weight of sediment) were mixed with the sediment. The water content in the mixture achieves the optimum moisture content of 18.5%, as determined by modified Proctor tests. The descriptions of all the mixture proportions are shown in Table 2.

The unstabilized and stabilized compacted specimens used in the tests were prepared by hand-mixing dry sediment, OPC, FA, and water. The uniformity and homogeneity of the specimen were satisfied by visual observation, and three samples of the mixtures were taken to determine the moisture content. For the UC and M_r tests, each specimen was contained in a cylindrical mold, which could split into two parts and was greased by lubrication oil and was then statically compacted in three layers using a compression machine so that each layer attained the specified dry unit weight. The top of each layer was slightly scarified. After the molding process was

Table 2 Mixture proportion and results of the UC, CBR, and M_r tests on dredged sediment stabilized with OPC and FA

Symbol	OPC content	FA content	q_u (kPa)					CBR (%)					M_r (MPa)				
			Curing time (days)					Curing time (days)					Curing time (days)				
	(%)	(%)	7	14	28	60	120	7	14	28	60	120	7	14	28	60	120
C0F0 (control)	0	0	387	387	387	387	387	6	6	6	6	6	52	52	52	52	52
C0F5		5	483	665	732	846	1123	12	15	16	21	28	99	109	112	138	201
C0F10		10	531	620	752	906	1245	13	14	16	23	31	103	104	127	153	212
C0F15		15	569	580	831	1085	1368	14	17	18	27	34	90	92	128	174	225
C0F20		20	616	690	846	1027	1454	19	20	20	26	36	107	119	131	165	246
C1.5F0	1.5	0	624	818	988	1313	1652	14	16	19	33	41	111	138	161	197	235
C1.5F5		5	712	850	1095	1405	1932	17	20	22	35	48	132	147	174	211	275
C1.5F10		10	879	1082	1277	1600	2265	23	26	27	40	57	142	166	189	229	312
C1.5F15		15	752	854	1143	1430	2089	18	22	23	36	52	129	140	174	208	287
C1.5F20		20	739	892	1099	1351	1967	17	19	21	34	49	113	135	164	193	264
C2.5F0	2.5	0	807	1012	1138	1470	1999	21	24	25	37	50	142	183	207	226	255
C2.5F5		5	855	1089	1231	1588	2028	25	28	29	40	51	163	192	210	247	293
C2.5F10		10	1047	1169	1413	1714	2602	28	30	32	43	65	188	201	228	255	334
C2.5F15		15	960	1008	1256	1604	2365	24	28	31	40	59	155	165	218	249	315
C2.5F20		20	858	982	1110	1506	2108	21	25	25	38	53	162	182	202	231	276
C5F0	5	0	1073	1221	1406	1802	2084	30	33	34	45	52	172	193	219	294	347
C5F5		5	1293	1432	1561	1927	2437	31	35	38	48	61	201	227	251	315	403
C5F10		10	1561	1639	1645	2271	3163	38	42	43	57	79	226	269	273	337	428
C5F15		15	1381	1320	1621	2059	2541	36	38	41	51	64	211	199	259	333	414
C5F20		20	1256	1314	1396	1986	2353	33	36	39	50	59	191	210	236	314	363
C7.5F0	7.5	0	1417	1525	1866	2126	2519	40	46	47	53	63	209	224	271	334	430
C7.5F5		5	1698	1798	2120	2364	3180	42	47	49	59	79	241	252	285	325	457
C7.5F10		10	1856	2154	2365	2917	3529	46	51	52	73	88	273	294	308	396	494
C7.5F15		15	1722	1985	2226	2658	3227	43	48	50	66	81	257	277	295	372	473
C7.5F20		20	1608	1633	2044	2405	2993	40	47	49	60	75	227	230	284	342	437

completed, the specimen was instantly demolded. The specimen was considered appropriate for testing when it met the following criteria: dry unit weight, moisture content, diameter, and height within 1, 0.5%, 0.5 mm, and 1 mm of the design values, respectively. The specimens passing these criteria were covered with a plastic sheet to avoid moisture loss from the sample (Güllü 2014) and were then cured for 7, 14, 28, 60 and 120 days inside a controlled room with a temperature of 25 ± 2 °C and humidity of 95 ± 5%.

For this study, the CBR values of the unstabilized and stabilized compacted specimens were determined at the maximum dry unit weight and optimum water content obtained from the modified Proctor tests, which were the same values used for specimen preparation for the UC and M_r tests. The specimen was contained in a standard cylindrical steel mold and was compacted in five layers. Each layer was given 56 blows with a 44.5 N metal hammer falling 457 mm according to ASTM D1557 (2012). The criteria for considering the appropriate specimen and curing condition for the CBR test are similar to those for the UC and M_r tests.

2.3 Unconfined compression test

The unconfined compressive strength (q_u) of pavement material is an important parameter used in pavement design (Silitonga et al. 2009). The UC tests were conducted in accordance with ASTM D 2166 (2016a) to illustrate the influences of the OPC and FA contents on the strength development in the stabilized sediment. When the assigned curing time of the specimen was achieved, the UC tests were then performed on the specimen using an automatic loading machine with a capacity of 50 kN under a strain rate of 0.01 min^{-1} until the specimen failed. q_u was taken to be the maximum compressive stress or the compressive stress at 15% axial strain, whichever occurred first during the test. The acceptance criterion of this study was designated as follows: a deviation of each q_u result of three specimens with the same mixture proportion must be less than 10% from the mean q_u.

2.4 California bearing ratio test

The CBR value is extensively used in designing pavement courses, and the CBR test is the most traditional test utilized to evaluate pavement materials. All CBR tests in this study were conducted based on ASTM D1883 (2016b). After the required curing time of the specimen was reached, the surcharge with a weight of 44.5 N was placed on the top of the specimen in the mold. The mold with surcharge was immersed in water, allowing water to access the top and bottom of the specimen to soak the specimen for 96 h. After soaking, the CBR tests were then performed on the specimen using an automatic loading machine with a capacity of 50 kN. The load on the penetration piston with a cross-sectional area of 1935 mm^2 was applied with a penetration rate of approximately 1.27 mm min^{-1}. The stress values at penetrations of 2.54 and 5.08 mm were recorded. The bearing ratios were calculated for each specimen by dividing the stresses at penetrations of 2.54 and 5.08 mm by the standard stresses of 6900 and 10,300 kN m^{-2}, respectively, and multiplying by 100. The CBR value reported is normally the one at 2.54 mm penetration. When the CBR at 5.08 mm penetration is greater than the CBR at 2.54 mm penetration, the CBR test was repeated. If the repeated test provides the same result, the CBR at 5.08 mm penetration is reported.

2.5 Resilient modulus test

The resilient modulus (M_r) of unstabilized and stabilized soils is a significant factor in determining the pavement thickness and material selection. The M_r values of the pavement materials were determined using the M_r test conducted in accordance with the AASHTO T307 (2012) standard test method. The specimens were initially conditioned by the application of five hundred stress cycles with a cyclic stress of 23.1 kN m^{-2} and a confining stress of 103.4 kN m^{-2}. When the conditioning stage was completed, a series of steps was performed that consisted of the application of one hundred cycles with a haversine-shaped stress pulse under various levels of confining pressures and deviatoric stresses. In this study, the stress pulse had a load duration of 0.1 s and a rest period of 0.9 s. M_r was determined from the cyclic stress divided by the recoverable strain. The equipment of the M_r test included two vertical electric displacement transducers that were symmetrically placed on top of the sample to measure the vertical displacements. The applied axial stress was measured by a load cell with a capacity of 10 kN attached on the loading plunger. The air pressurized chamber (which provided a confining pressure) was utilized to accommodate the sample during the test. The samples used in the M_r tests were similar to those used in the UC tests. The M_r tests were performed on the specimens after curing. Before testing, the plastic wrap was removed from the samples, and the dimensions and unit weights of the samples were measured. The acceptance criteria for the CBR and M_r values were similar to that for the q_u value.

2.6 Scanning electron microscopy and energy-dispersive X-ray spectroscopy

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) were performed to investigate the microstructural changes in the stabilized dredged sediments caused by the stabilization process. Small block-shaped samples were collected from the failure plane of the tested specimens after the UC tests were completed. The collected samples were approximately 3 to 7 mm long and were placed in a box with desiccant to dry. A selected sample was coated with platinum for 30 s at a current of 50 mA before SEM micrographs were obtained with a Do SEM JSM-5410 LV scanning electron microscope, and the EDX analysis was performed with a Do SEM Link ISIS300.

3 Results and discussion

3.1 Unconfined compressive strength

The increase in the strength of dredged sediment due to stabilization with OPC and FA can be simply explained by using chemical equations of the OPC hydration reaction and the pozzolanic reaction, as presented in Eqs. 1 and 2, respectively.

$$\text{OPC hydration reaction}: CaO + H_2O \Rightarrow CSH + \underbrace{Ca(OH)_2}_{\text{byproduct}} \quad (1)$$

$$\text{Pozzolanic reaction}: \underbrace{Ca(OH)_2}_{\text{byproduct from OPC hydration}} + \underbrace{SiO_2}_{\text{compound in FA}} \Rightarrow \underbrace{CSH}_{\text{new product}} \quad (2)$$

Once the OPC, FA, and water are mixed with the dredged sediment, the OPC hydration reaction occurs immediately. High concentrations of CaO dissociating from the OPC and FA dissolve SiO_2 and Al_2O_3, producing cementitious calcium silicate hydrate, CSH, gel and calcium hydroxide, $Ca(OH)_2$. $Ca(OH)_2$ can be considered a byproduct of the OPC hydration reaction. Then, the pozzolanic reaction occurs. SiO_2, which is a compound in FA, slowly sequesters $Ca(OH)_2$ from the OPC hydration reaction, creating a new pozzolanic reaction product or new CSH induced by the pozzolanic reaction. The increase in strength depends on the type and quantity of reaction products induced by the OPC hydration reaction products (e.g., CSH improves the short-term strength at curing times of 7, 14 and 28 days), and the pozzolanic reaction products (e.g., CSH improves the long-term strength at curing times of 60 and 120 days) (Horpibulsuk et al. 2009; Shon et al. 2010; Tastan et al. 2011; Kang et al. 2015). The rate of reaction and the strength contribute to the consumption of $Ca(OH)_2$. Principally, the pozzolanic process is rather slow and is slowed further by the creation of a crust of CSH gel around particles of FA (Kang et al. 2015). This phenomenon can be observed via SEM.

The mean values of q_u obtained from the UC tests are shown in Table 1. q_u of the unstabilized specimen was 386 kN m^{-2}, and the q_u values of the stabilized specimens for all the mixture proportions increased steadily with the curing time. The q_u of the specimens stabilized with exclusively OPC and exclusively FA increased with the OPC and FA contents, respectively. Unlike for stabilization with a combination of OPC and FA, q_u increased as the content of exclusively FA increased from 5 to 10%, and q_u decreased as the content of exclusively FA increased above 10%. Considering the short-term strength of the curing period of 28 days, the q_u values of the specimens stabilized with exclusively 7.5% OPC (C7.5F0), exclusively 20% FA (C0F20) and a combination of OPC and 10% FA (C7.510) were 1866, 846 and 2365 kN m^{-2}, respectively. When the curing time increased to 120 days, the long-term strengths increased to 2519, 1454 and 3529 kN m^{-2} for C7.5F0, C0F20 and C7.510, respectively.

It can be concluded that the use of a combination of OPC and FA was the most effective for dredged sediment stabilization, followed by the use of exclusively OPC and exclusively FA. Most of the CSH was induced from only the OPC hydration reaction due to the lack of SiO_2 from FA, as expressed in Eqs. 1 and 2. The utilization of FA exclusively provided the lowest strength due to the lack of CaO from OPC, which is the main chemical component in CSH, causing the lowest amount of CSH to form (e.g., lowest strength). For specimens stabilized with a combination of OPC and FA, the total amount of CSH was the sum of the portions of CSH products induced by OPC hydration and pozzolanic reactions due to the existence of SiO_2 in the FA, resulting in a greater amount of CSH than using exclusively OPC or exclusively FA.

However, the 10% FA content provided the highest q_u for all samples (C1.5FA10, C2.5FA10, C5FA10, and C7.5FA10), as the 10% FA content provided the most suitable proportions of SiO_2 and $CaOH_2$ from the FA and the OPC hydration reaction, respectively, yielding an optimal performance of the pozzolanic reaction caused by the increased formation of CSH. q_u tended to decrease when the FA content was greater than 10%. An FA content in excess of 10% may occlude the OPC grains and prevent the chemical reaction between water and OPC, which reduces the degree of the hydration reaction, resulting in a decrease in the amount of hydration products (Horpibulsuk et al. 2011).

Figure 2a presents the q_u values of the dredged sediments stabilized with OPC and FA after 7, 14, 60, and 120 days of curing versus those at 28 days of curing. The correlation

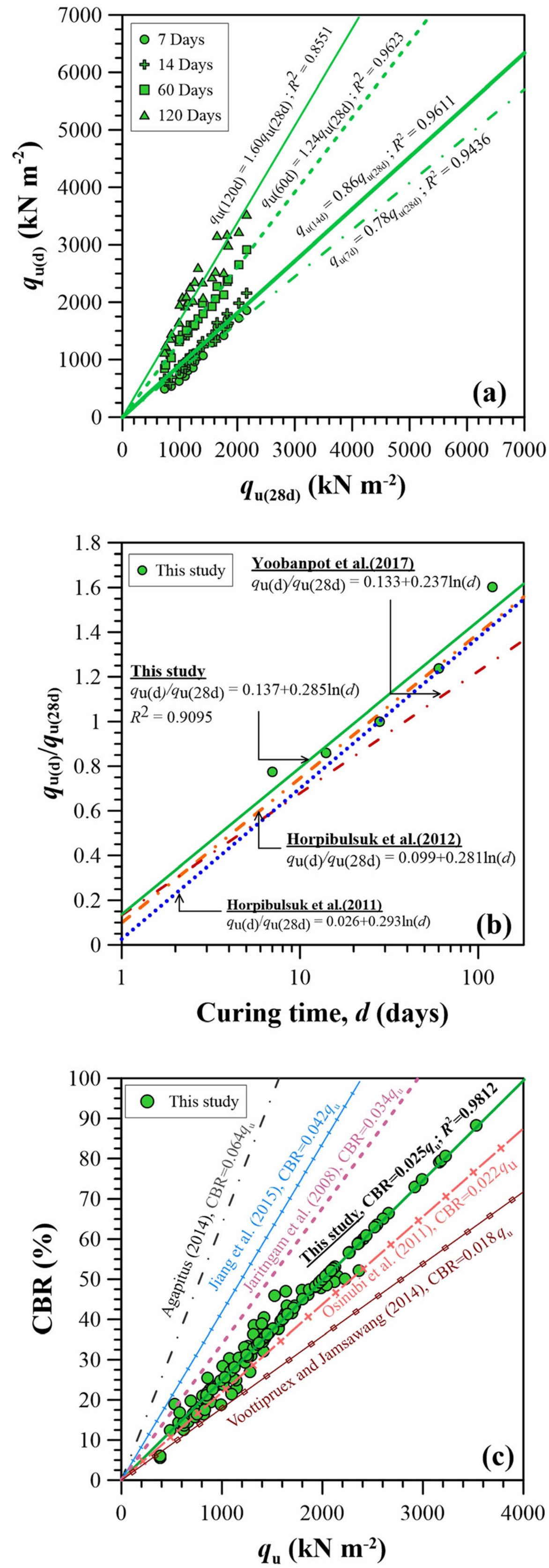


Fig. 2 **a** q_u at any curing time with respect to the 28-day q_u. **b** General equations for strength development in stabilized dredged sediments. **c** Correlation of the CBR with q_u

between q_u at d days, $q_{u(d)}$, and q_u at 28 days, $q_{u(28d)}$, was represented by a fitting curve determined through a linear regression. This correlation indicated that the q_u values of the stabilized sediments at 7, 14, 60, and 120 days were approximately 0.78, 0.86, 1.24, and 1.60 times the $q_{u(28d)}$, respectively. The $q_{u(28d)}$ was used to calculate normalized strength, $q_{u(d)}/q_{u(28d)}$, as was suggested by Horpibulsuk et al. (2009, 2011, 2012). Figure 2b shows the $q_{u(d)}/q_{u(28d)}$ with respect to the curing time, d, for the stabilized specimens. The generalized strength development for the stabilized dredged sediment can be expressed on a natural logarithmic scale as a linear variation, as shown in Eq. 3; the correlation coefficient (R^2) of this equation is 0.9095. The equation determined in this study is close to the previously reported equations for cement kiln dust (CKD) and FA residue mixed with soft clay (Yoobanpot et al. 2017), OPC mixed with soft Bangkok clay (Horpibulsuk et al. 2011) and OPC mixed with saline clay (Horpibulsuk et al. 2012) due to similar strength development characteristics caused by the hydration and pozzolanic processes, which were major and minor reactions, respectively.

$$\frac{q_{u(d)}}{q_{u(28d)}} = 0.137 + 0.285\ln(d), R^2 = 0.9095 \quad (3)$$

3.2 California bearing ratio

The results derived from the CBR tests conducted on the unstabilized and stabilized dredged sediment specimens were similar to the UC test results, as presented in terms of the mean CBRs in Table 1. The CBR for the unstabilized dredged sediment was 6%. At a curing time of 28 days, the CBRs of the stabilized specimens C7.5F0, C0F20, and C7.5F10 increased to 47, 20, and 52%, respectively. For the curing time of 120 days, the CBR increased to 63, 36, and 88% for C7.5F0, C0F20, and C7.510, respectively. Thus, the unstabilized specimens could be improved via 8-, 3-, and 9-fold CBR increases at a short-term curing time of 28 days and via 11-, 6-, and 15-fold CBR increases at a long-term curing of 120 days for C7.5F0, C0F20, and C7.510, respectively. The CBR values of C7.5F10 were higher than those of C0F20 and C7.5F0, similar to the results of the UC tests, as discussed in Sect. 3.1. For specimens stabilized with a combination of OPC and FA, when the FA content increased from 10 to 20%, the CBR values of C7.5F20 decreased to 49 and 75% after 28 and 120 days, respectively. Thus, 10% FA is also optimal for improving the CBR of unstabilized sediment.

The correlation between CBR and the q_u value of dredged sediment stabilized with OPC and FA found in this study is illustrated in Fig. 2c and was modeled by a linear equation, as expressed in Eq. 4. This correlation has been studied by other researchers for various types of stabilized soil. Jaritngam et al. (2008) attempted to improve soft clay with OPC to reduce the postconstruction settlement of road construction on soft clay and found that the CBR was approximately $0.034q_u$. Osinubi et al. (2011) improved black cotton soil with OPC mixed with locust bean waste ash, and the result was a CBR of $0.022q_u$. Agapitus (2014) enhanced the strength and durability of soil subgrade with cement kiln dust and presented that CBR = $0.064q_u$. Voottipruex and Jamsawang (2014) studied OPC and FA stabilization of expansive soils and showed that CBR = $0.018q_u$ for both 3–7% exclusively cement and a combination of 1% cement and 10–20% FA. Jiang et al. (2015) used calcium carbide residue as a stabilizer to improve soft subgrade soil highway materials and investigated the subgrade at the microscale and macroscale in the laboratory. Their results showed that CBR = $0.042q_u$. The correlation between q_u (in kPa) and CBR (in %) of stabilized sediment in the current study is within range of general cementitious material-stabilized soil.

$$CBR = 0.025q_u, R^2 = 0.9812 \quad (4)$$

3.3 Resilient modulus

Various types of prediction models have been proposed to estimate M_r. To reduce the cost and time of advanced laboratory experiments used for determination of the M_r, M_r predictions for stabilized sediments were performed in this study. Figure 3a shows examples of the M_r values at each cycle for C7.5F0, C7.5F5, C7.5F10, C7.5F15, and C7.5F20 at curing times of 7, 28, and 120 days. Table 1 shows the mean values of M_r after 15 cycles for all the specimens used in this study at curing times of 7, 14, 28, 60, and 120 days. The results showed that the M_r results of the stabilized dredged sediment exhibited similar trends to those of the q_u and CBR values. The M_r value of the unstabilized dredged sediment was 52 MN m^{-2}. After stabilization with OPC and FA, the M_r values increased to 271, 131, and 308 MN m^{-2} at a curing time of 28 days and increased to 430, 246, and 494 MN m^{-2} at a curing time of 120 days for C7.5F0, C0F20, and C7.510, respectively. The M_r values of the unstabilized specimens could be improved 5-, 3-, and 6-fold at short-term curing of 28 days and 8-, 5-, and 10-fold at long-term curing of 120 days for C7.5F0, C0F20, and C7.510, respectively. C7.5F10 was most effective in developing M_r. However, the M_r values of C7.5F20 increased to 284 and 437 at curing times of 28 and 120 days, respectively.

Figure 3b shows the relationship between M_r and q_u. The trend could be modeled by linear regression. Based on the linear regression equation, M_r of the stabilized dredged sediment is 149 times q_u, as expressed by Eq. 5. The similar linear M_r–q_u relationship reported in previous studies is compared to the results proposed in this study, as shown in Fig. 3b. Kang et al.

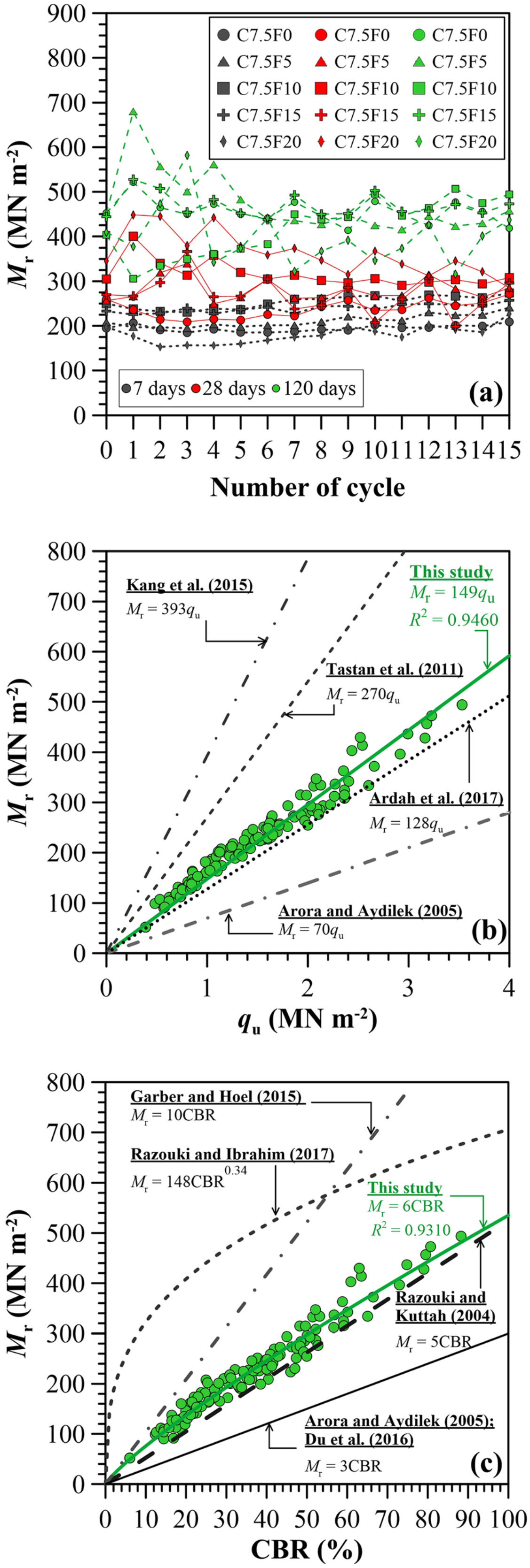


Fig. 3 **a** Typical relationship between M_r of the stabilized dredged sediment and the number of cycles. **b** Correlation of M_r with q_u. **c** Correlation of M_r with the CBR of the stabilized dredged sediment

(2015) utilized 10–20% FA and 4–20% lime kiln dust for stabilizing soft clay used in roadbase construction, whereas Tastan et al. (2011) studied the effect of various types of FA (10–20% FA contents) on the stabilization of three soft organic soils with different organic contents. Kang et al. (2015) and Tastan et al. (2011) found that M_r–q_u correlations could be expressed as $M_r = 393q_u$ and $M_r = 270q_u$, respectively, which overestimates the M_R values obtained from this study by approximately 1.8–2.6 times. However, the proposed linear relationship (M_r = $70q_u$) by Arora and Aydilek (2005) for silty soils stabilized by 2–8% quick lime for use in highway subgrade underestimates the M_r–q_u correlation of this study by 2.1 times. The correlation ($M_r = 128q_u$) reported by Ardah et al. (2017) for clayey soils treated by 2–8% OPC, 2–11% lime and 10–15% FA is close to that derived from the current study.

$$M_r = 149q_u, R^2 = 0.9460 \quad (5)$$

Figure 3c shows the M_r–CBR results of this study. The trend of the correlation was modeled by a linear equation, as expressed in Eq. 6. The M_r–CBR relationships suggested by other researchers are also illustrated in Fig. 3c for comparison purposes. Garber and Hoel (2015) proposed the linear equation M_r = 10CBR for subgrade soils, which overestimates the M_R values obtained from this study by approximately 1.7 times. However, the suggested linear relationship (M_r = 3CBR) by Arora and Aydilek (2005) for silty soils stabilized by 2–8% quick lime underestimates the M_r-CBR correlation of this study by half. The linear M_r-CBR correlation (M_r = 5CBR) proposed by Razouki and Kuttah (2004) for clayey gypsiferous soil is very close to that obtained from this study. However, the nonlinear M_r-CBR correlation (M_r = 148CBR$^{0.34}$) reported by Razouki and Ibrahim (2017) for a gypsum sand roadbed improved by an increased degree of compaction significantly overestimates the M_R values found in this study.

$$M_r = 6CBR, R^2 = 0.9310 \quad (6)$$

3.4 Microstructural analyses

3.4.1 Scanning electron microscopy

Figure 4a–f show the microstructural changes in the samples. The observation of C7.5F0 depicted in Fig. 4a, b illustrated that after 28 days of curing, many hydration products were present, including CSH gels and ettringite crystals (Jamsawang et al. 2017), and rough surfaces of the specimens were found. The pozzolanic reaction products, which are cementitious compounds, improve the intercluster bonding strength and fill the void spaces. After 120 days of curing, the CSH products form a fabric on the sediment clusters and filled the void spaces between particles of the sediments,

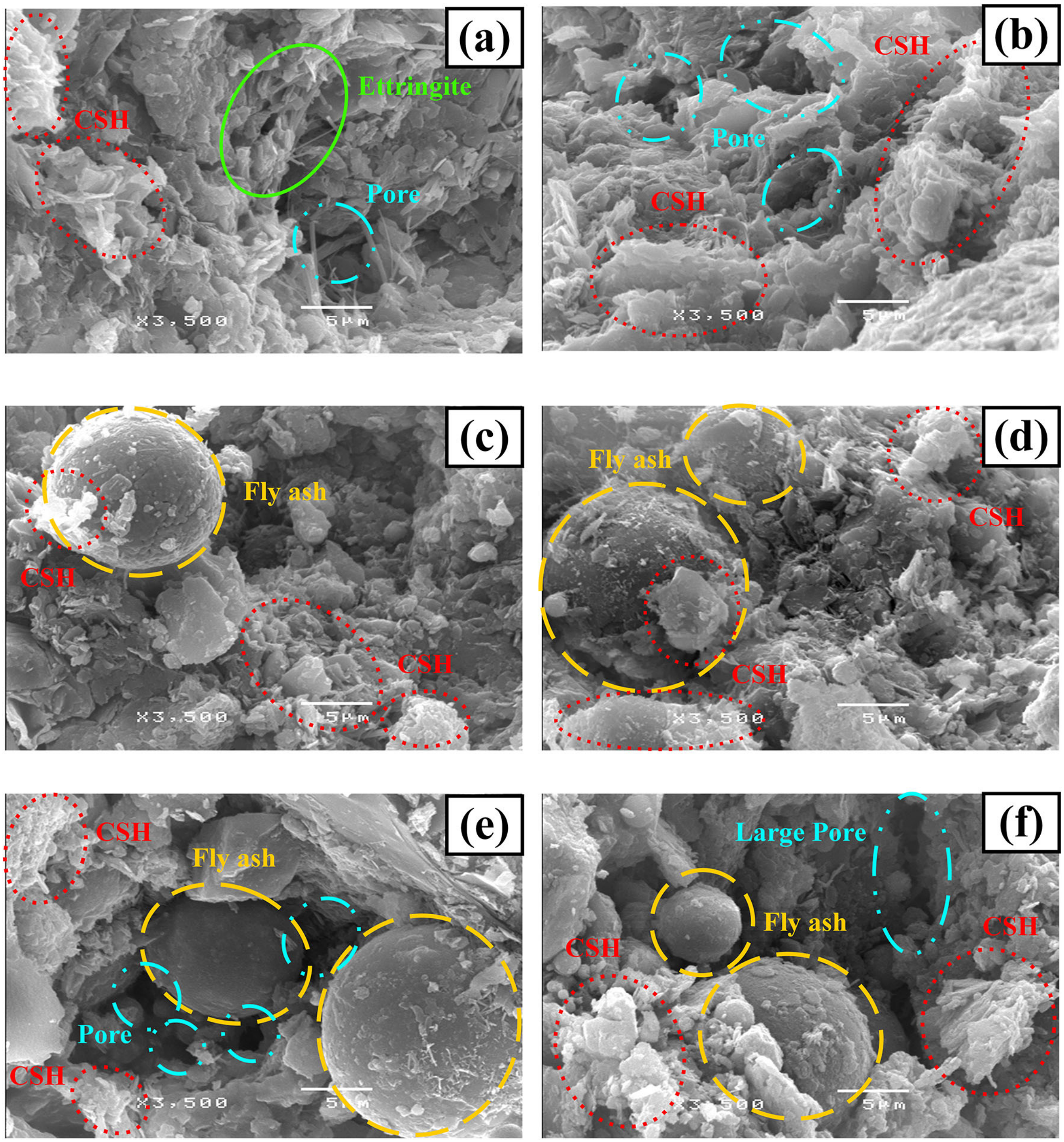
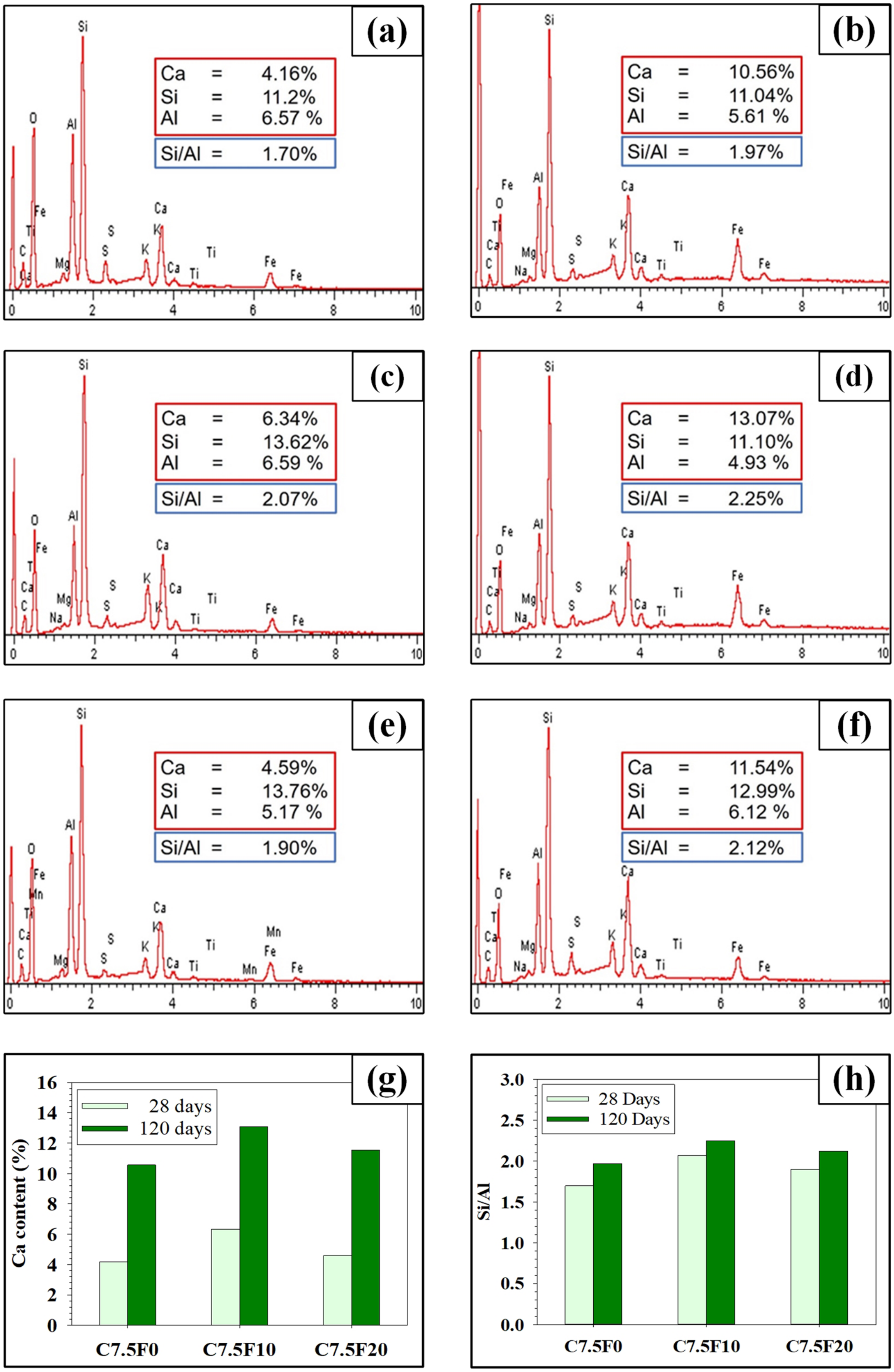


Fig. 4 SEM images of the stabilized samples. **a** C7.5F0 at 28 days. **b** C7.5F0 at 120 days. **c** C7.5F10 at 28 days. **d** C7.5F10 at 120 days. **e** C7.5F20 at 28 days. **f** C7.5F20 at 120 days

causing the sediment structure to densify. Cementitious products were also detected on the surfaces of the sediment particles.

Figure 4c and d illustrate SEM images of C7.5F10. The particles of FA interspersed with the CSH fabric and filled the voids between the particles of the sediments. Consequently, this impact reduced the void volume in the sediment structure, resulting in an increase in the overall density. In general, SEM revealed that the FA particles were hollow spheres of various sizes, and most of the FA particles were smooth. After 120 days of curing (Fig. 4d), some glassy irregularly shaped pieces can be seen among the FA particles. When FA added to the sediment, the mixture started setting, and the hydration products around the particles of FA could be easily detected via SEM. As the curing period increased, a crust of hydration gel formed that tightly bound the sediment particles and adjacent FA particles. Eventually, the hydration crust connected the sediment and FA particles, and the strength of the mixture was improved by the curing time. The products obtained from the hydration and pozzolanic reactions filled the voids in the mixture, and the particles aggregated and connected. The connection and aggregation of the stabilized dredged sediments improved the stress-strain behavior at the macroscale. The stabilized dredged sediments had smaller pores and denser microstructures than those of the unstabilized dredged sediments (Fig. 1a). Thus, the stabilized sediments had high q_u,


(a)
Ca = 4.16%
Si = 11.2%
Al = 6.57 %
Si/Al = 1.70%
(b)
Ca = 10.56%
Si = 11.04%
Al = 5.61 %
Si/Al = 1.97%
(c)
Ca = 6.34%
Si = 13.62%
Al = 6.59 %
Si/Al = 2.07%
(d)
Ca = 13.07%
Si = 11.10%
Al = 4.93 %
Si/Al = 2.25%
(e)
Ca = 4.59%
Si = 13.76%
Al = 5.17 %
Si/Al = 1.90%
(f)
Ca = 11.54%
Si = 12.99%
Al = 6.12 %
Si/Al = 2.12%
(g)
28 days
120 days
Ca content (%)
C7.5F0
C7.5F10
C7.5F20
(h)
28 Days
120 Days
Si/Al
C7.5F0
C7.5F10
C7.5F20

◀ **Fig. 5** EDX analyses of samples. **a** C7.5F0 at 28 days. **b** C7.5F0 at 120 days. **c** C7.5F10 at 28 days. **d** C7.5F10 at 120 days. **e** C7.5F20 at 28 days. **f** C7.5F20 at 120 days. **g** Ca content and **h** Si/Al ratio of samples C7.5F0, C7.5F10, and C7.5F20

CBR and M_r properties and low compressibilities (low plastic strain) (Kang et al. 2015). The advantage of including FA to produce cementitious products has been previously suggested, and former studies have found that FA is beneficial for reducing the void spaces in sediment particles and enhancing sediment strength in long-term curing conditions (Wang et al. 2013; Shaheen et al. 2014; Yoobanpot et al. 2017).

The SEM images of C7.5F20 in Fig. 4e, f are similar to those of C7.5F10, but C7.5F20 has a larger void space than that of C7.5F10 because C7.5F20 produced less CSH that could fill the voids in the mixture. Moreover, some FA particles in C7.5F20 were only partially covered by a crust of CSH gels, unlike the FA particles found in C7.5F10, which were fully encased by CSH.

3.4.2 Energy-dispersive X-ray spectroscopy

The chemical composition of the stabilized dredged sediment was investigated by EDX analysis of C7.5F0, C7.5F10, and C7.5F20 after 28 and 120 days of curing; the results are shown in Fig. 5a–f. The observations show that calcium (Ca), silica (Si), aluminum (Al), iron (Fe), and oxygen (O) are present in all the specimens (Al-Homidy et al. 2017; Li and Poon 2017; Bilondi et al. 2018). High amounts of Ca, Si, O, and Al, especially Ca, provided suitable conditions for the formation of CSH gel in the stabilized specimens, whereas the Si/Al ratio is significantly important to the bond strength of the stabilized specimens. Therefore, the main parameters affecting the strength of the stabilized specimens were both the weight proportion of Ca and the ratio of Si/Al; additionally, an increase in the Si/Al ratio, which is expected to control the amount of Ca, increases the strength of the stabilized specimens due to the associated increase in the formation of the CSH gels and bond strength (Bilondi et al. 2018).

Figure 5a shows the analysis of C7.5F0 after 28 days of curing. The weight proportion of Ca and the Si/Al ratio were 4.16 and 1.70, respectively, and these parameters increased with curing time due to the hydration and pozzolanic reactions to 10.56 and 1.97 after 120 days of curing, respectively (Fig. 5b). Similar results were observed for C7.5F10 and C7.5F20, as shown in Figs. 5c, d and e, f, respectively. The weight proportion of Ca and the Si/Al ratio for C7.5F10 were 6.34 and 2.07 at a curing period of 28 days and 13.07 and 2.25 at a curing period of 120 days, respectively, and for C7.5F20, these results were 4.59 and 1.90 at a curing period of 28 days and 11.54 and 2.12 at a curing period of 120 days, respectively. The trend of the Ca content and Si/Al ratio versus FA content charts, as shown in Fig. 5g and h, respectively, is similar to results of the q_u, CBR and M_r, and the maximum weight proportion of Ca and the maximum value of Si/Al ratio were exhibited by C7.5F10, which can be explained by C7.5F10 having the greatest amount of CSH gel formation and highest bond strength compared to those of C7.5F0 and C7.5F20. The findings obtained from SEM and EDX confirmed that 10% FA is optimal for improving the performance of sediment stabilized with a combination of OPC and FA and suggested that an excessive amount of FA may block the interaction between the water and OPC, decreasing the degree of cement hydration reaction and the amount of cementitious products. These results confirm the finding of the highest q_u for specimens stabilized with a combination of OPC and FA at an optimal content of 10% in Sect. 3.1. Therefore, FA could effectively stabilize dredged sediments in terms of enhancing its strength and resilience characteristics as an effect of pozzolanic reactions, which improve the properties and bonding between the sediments and FA particles (Horpibulsuk et al. 2009; Shon et al. 2010).

3.5 Summary of the potential use of dredged sediments as pavement materials

The criteria of suitable pavement materials based on the Department of Highways of Thailand classify highway materials into four categories: soil cement base, soil cement subbase, selected material and subgrade material. These classifications are listed together with the corresponding standard designations in Table 3. The specifications of the soil cement base and soil cement subbase require the minimum q_u of stabilized soil at 7 days to be 1724 and 689 kN m^{-2}, respectively. If the q_u requirement at 7 days is not met, the stabilized soil is classified as selected material or subgrade material by considering only the CBR values. A consideration of stabilized sediment as a pavement material for all mixture proportions is presented in Fig. 6a and b. Note that the unstabilized dredged

Table 3 The criteria of suitable pavement materials based on the Department of Highways of Thailand

Materials	7-day q_u (kN m^{-2})	7-day CBR (%)	Optimum mixture proportion
Soil cement base	1724		C7.5F10
Soil cement subbase	689		C1.5F5
Selected material		8	C0F5
Subgrade material		4	C0F0 (unstabilized sediment)

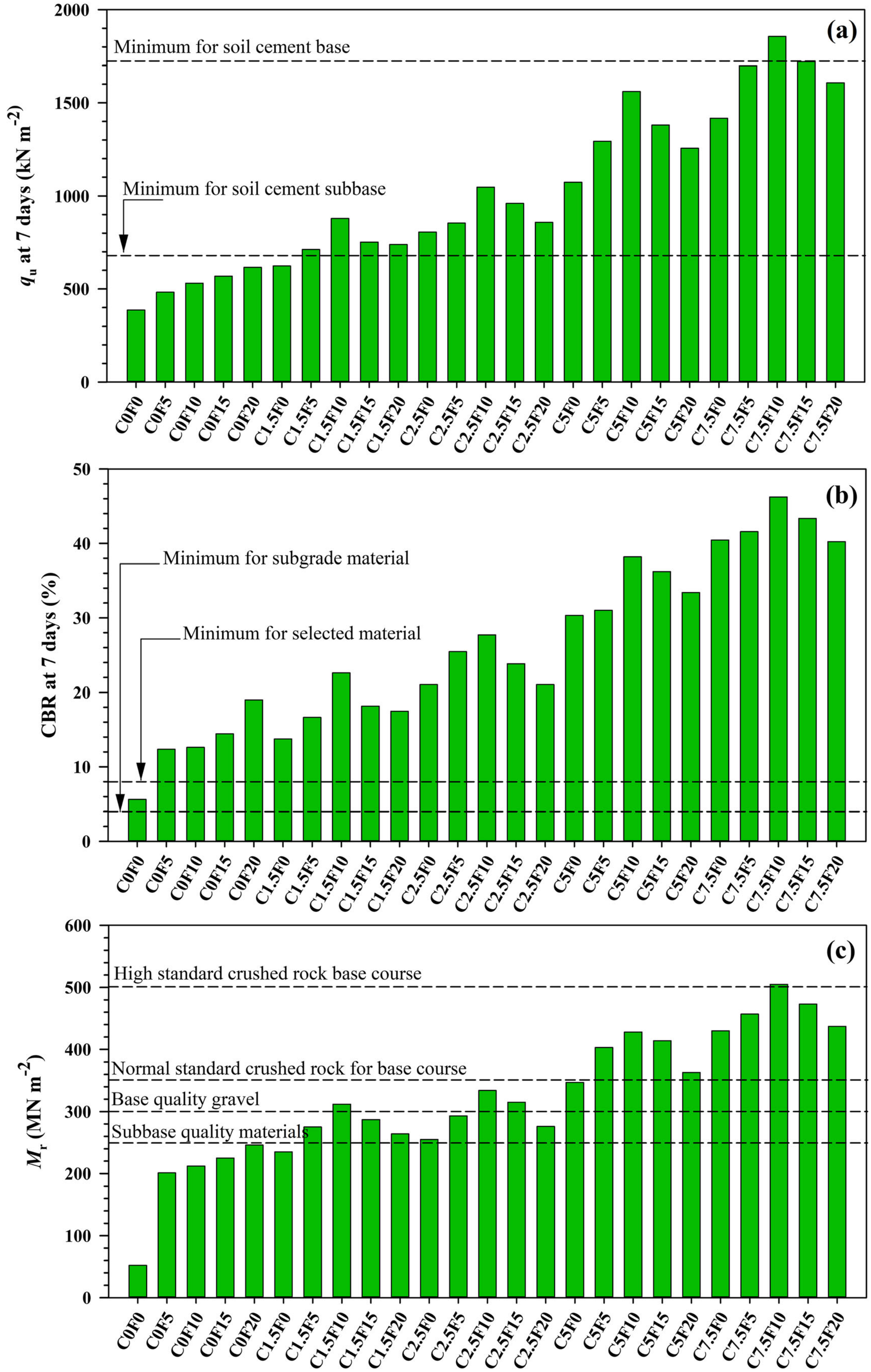


Fig. 6 Consideration of stabilized sediment for all the mixture proportions of the pavement materials based on **a** q_u, **b** CBR, and **c** M_r values

Table 4 Presumptive values of M_r for unbound materials under thin bituminous surfacing (Austroads 2017)

Materials	Typical value (MN m^{-2})	Optimum mixture proportion
High standard crushed rock base course	500	C7.5F10
Normal standard crushed rock base course	350	C5F5
Base quality gravel	300	C1.5F10
Subbase quality gravel	250	C1.5F5

sediment is suitable for use as only a subgrade material because the CBR values exhibited by the unstabilized dredged sediment are higher than the subgrade material requirement but lower than the requirements for other materials listed in the standard. Table 3 also summarizes the optimum mixture proportions of the tested stabilized dredged sediments in this study for potential use as soil cement base, soil cement subbase, selected material and subgrade material based on the Department of Highways of Thailand.

Alternatively, Austroads (2017) also provided presumptive values of M_r for unbound granular materials under thin bituminous surfacing, as shown in Table 4; these values should be considered by pavement designers. Thus, the results in this study, as presented in Fig. 6c, compared to Table 4, also show that the stabilized dredged sediment with the optimum mixture proportions can be used as pavement materials, including high standard crushed rock base course, normal standard crushed rock base course, base quality gravel, and subbase quality materials.

Notably, the results in this study were based on the stabilization of dredged sediment without contaminants; thus, only the strength of the stabilized dredged sediment was considered for use as pavement materials. However, OPC and FA can also stabilize highly contaminated dredged sediment, but in addition to the strength, the leachability rate of heavy metals is primary concern regarding the final judgment of the use of stabilized dredged sediment as pavement materials. Previous studies by Dermatas and Meng (2003), Yin et al. (2006), Scanferla et al. (2009), Tomasevic et al. (2013), Wang et al. (2015), and Gupta et al. (2017) confirmed that highly contaminated soil and sediment stabilized by OPC and FA exhibited high strength and low leachability that never exceeded regulatory limits due to the existence of hydration and pozzolanic reaction products, similar to the findings in this study.

The results obtained by this study are generally applicable in all climes. However, the application of stabilized sediment for road materials in cold climes and tropical wet–dry climes requires additional test results of the freeze–thaw durability and wetting–drying durability, respectively, to ensure that the stabilized sediment has a sufficient residual strength for maintaining the service life of the road, as recommended by COE (2004) and Tripathy and Rao (2009). Previous studies by Tebaldi et al. (2016), Wang et al. (2018) and Yilmaz and Fidan (2018) confirmed that stabilized pavement materials can resist freeze–thaw cycles, whereas Tang et al. (2011), Kampala and Horpibulsuk (2013) and Kampala et al. (2014) reported that stabilized soils exhibit durability against wetting–drying cycles and can thus be considered durable pavement materials, resulting in reduced maintenance costs.

3.6 A comparative cost analysis

Typical sections of pavement structures using conventional earthen materials and cement-stabilized soil materials in accordance with the standard of the Department of Highways of

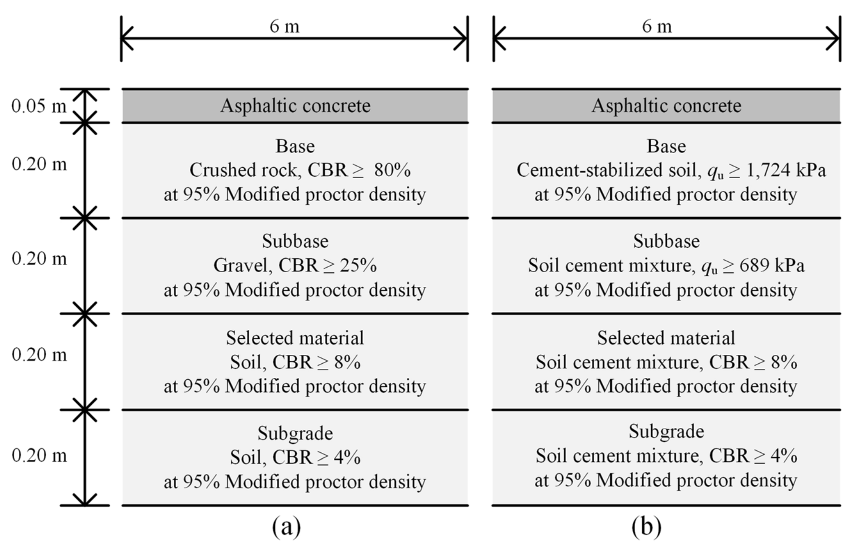


Fig. 7 Typical sections of the pavement structures using **a** conventional earthen material and **b** cement-stabilized soil

Table 5 Details of comparative cost analysis between road using conventional earthen pavement materials and road using dredged sediment stabilized with OPC and FA

Layer	Material	Volume (m^3)	Distance from material source to construction site (km)	Material cost per unit volume ($)	Hauling cost per unit volume ($)	Transportation cost per unit volume ($)	Total material cost ($)	Total hauling cost ($)	Total transportation cost ($)	Total cost ($)
Conventional earthen pavement materials										
Wearing course	Asphaltic concrete	300	60	233.33	–	1.00	70,000	–	18,000	88,000
Base course	Crushed rock	1200	30	10	–	1.00	12,000	–	36,000	78,000
Subbase course	Gravel	1200	30	1.33	–	1.00	1600	–	36,000	37,600
Selected material	Soil	1200	10	1.00	–	1.00	1200	–	12,000	13,200
Subgrade	Soil	1200	10	0.67	–	1.00	800	–	12,000	12,800
						Grand total	85,600	–	114,000	199,600
Dredged sediment stabilized with OPC and FA										
Layer	Material	Volume (m^3)	Distance from material source to construction site (km)	Material cost per unit volume ($)	Hauling cost per unit volume ($)	Transportation cost per unit volume ($)	Total material cost ($)	Total hauling cost ($)	Total transportation cost ($)	Total cost ($)
Wearing course	Asphaltic concrete	300	60	230.33	–	1.00	70,000	–	18,000	88,000
Base course	Dredged sediment	1200	1	–	0.67	1.00	–	800	1200	2000
Subbase course	Dredged sediment	1200	1	–	0.67	1.00	–	800	1200	2000
Selected material	Dredged sediment	1200	1	–	0.67	1.00	–	800	1200	2000
Subgrade	Unstabilized dredged sediment	1200	1	–	0.67	1.00	–	800	1200	2000
	Total OPC	130	30	100.00	0.00	1.00	13,000	–	3900	16,900
	Total FA	300	30	3.33	0.00	1.00	2000	–	18,000	20,000
						Grand total	85,000	3200	44,700	132,900

Thailand, as shown in Fig. 7a and b, respectively, were used for the comparative cost analysis. The typical pavement structures consisted of wearing surface (asphaltic concrete), base, subbase, selected material, and subgrade layers. The dredged sediments stabilized with OPC and FA in optimum mixture proportions, as shown in Table 4, were used instead of cement-stabilized soil materials, as shown in Fig. 7b, to perform a simple comparative cost analysis between roads using conventional earthen pavement materials and roads using dredged sediment stabilized with OPC and FA, considering the material, hauling, and transportation costs only. The detailed comparative cost analysis is summarized in Table 5. The road construction site was near the Mae Sab hydropower dam in Samoeng District, Chiang Mai, Thailand, at the future site of a 1-km-long rural road connecting the dam and the local community center. The costs of the asphaltic concrete were the same for the roads with conventional earthen pavement materials and stabilized sediment. There was no material cost for the dredged sediment, but a hauling cost was required to obtain the dredged sediment for the roads using stabilized sediment. Although the hauling cost for the road using earthen materials was zero, the material cost of earthen materials was high. The distance from the material source to the construction site for the road using stabilized sediment was only approximately 1 km, whereas that for the road using earthen materials was approximately 10 to 30 km. However, the additional costs of the road using stabilized sediments compared to the costs of conventional roads were attributed the material and transportation costs of the FA and OPC. The material cost of the FA was lower than that of the OPC by approximately 30 times, and the distance from the supply source of the OPC and FA was 30 km. The summarized comparative cost analysis in Table 5 indicates that the use of dredged sediment stabilized with OPC and FA as pavement materials in a roadway application has a clear advantage over the use of conventional earthen pavement materials. The main factor affecting the total cost is the distance from the material source to the construction site. In this study, the total transportation cost of roads using stabilized sediment was 2.5 times cheaper than that of roads using conventional earthen pavement materials, resulting in a total cost of using stabilized dredged sediment that was 1.5 times more economic than using conventional earthen materials.

4 Conclusions

This research evaluated the engineering properties of dredged sediments stabilized with OPC and FA for use as road construction materials. The laboratory testing program included UC, CBR, and resilient modulus tests. Correlations used for estimation of M_r from CBR and q_u were proposed. The changes in the microstructure and chemical composition due to hydration and pozzolanic reactions of cement and FA were investigated via SEM and EDX analyses. An assessment of the stabilized dredged sediments for reuse as pavement materials was performed. Finally, the cost between roads using conventional earthen materials and stabilized dredged sediment was analyzed. Based on the results of this study, the following conclusions can be drawn:

1. The developments of q_u, CBR and M_r of the stabilized dredged sediment were similar. The stabilization of dredged sediments with a combination of OPC and FA is most effective because of the highest amount of CSH products induced via the sum of the CSH products from the hydration reaction (induced by the presence of OPC during short-term curing) and the CSH products from the pozzolanic reaction (induced by the presence of SiO_2 in FA during long-term curing). Utilization of exclusively OPC creates CSH products from only the hydration reaction due to the absence of SiO_2 from the FA. The use of exclusively FA is the least effective due to the absence of CaO from the OPC, creating the lowest amount of CSH.
2. An FA content of 10% was the most effective for increasing the q_u, CBR, and M_r results of the samples using a combination of OPC and FA because 10% FA provided the most suitable proportions of SiO_2 and $CaOH_2$ for creating the greatest amount of CSH products. When the FA content exceeded 10%, q_u, CBR and M_r gradually decreased. An excess FA content of 10% may occlude the OPC grains and hinder the interaction between the water and OPC, which significantly reduces the degree of the hydration reaction, leading to a reduction in the cementitious products.
3. The correlations between M_r and q_u and between M_r and CBR were represented by linear regression equations, which can be expressed as $M_r = 149q_u$ and $M_r = 6$CBR, respectively. The correlations are useful in terms of cost and time reduction for determining the parameter M_r by using advanced laboratory experiments.
4. The SEM results confirmed that samples stabilized with a combination of OPC and 10% FA had a larger amount of CSH products than samples stabilized with either a combination of OPC and 20% FA or exclusively OPC. A larger amount of CSH products can enhance the intercluster bonding strength and can fill more pore spaces in the sediment. This effect reduces the void volume in the sediment structure, thereby increasing the overall structural densification and increase in strength, which agreed well with the results of the UC, CBR and M_r tests.
5. The EDX analysis showed that the samples stabilized with a higher weight proportion of Ca and a high Si/Al ratio had greater strengths due to the more suitable conditions for the formation of the CSH gel and higher bond strength. The EDX analysis also confirmed that the sediment stabilized with a combination of OPC and 10% FA exhibited the optimal performance because it had the highest weight proportion of Ca and Si/Al ratio. Therefore, the pozzolanic reactions induced by the existence of FA can enhance the strength and resilience characteristics by improving the bonds between the sediments and FA particles.
6. Based on the q_u and CBR values according to the standard of the Department of Highways of Thailand, unstabilized dredged sediment was determined to be suitable for use as a subgrade material. The inclusion of only 5%FA with improved the dredged sediment enough to meet the requirements of selected material. To meet the requirements of soil cement subbase and soil cement base, combinations of 7.5% OPC with 10% FA and 1.5% OPC with 5% FA were required.
7. Based on the M_r value according to recommendations of Austroads (2017), stabilization with the combinations of 7.5% OPC with 10% FA and 5% OPC with 5% FA improved dredged sediment to meet the requirements of high standard crushed rock base course and normal standard crushed rock base course, respectively. In addition, the use of 1.5% OPC with 10% FA and 1.5% OPC with 5% FA stabilized the dredged sediment to meet the requirements of base quality gravel and subbase quality materials, respectively.
8. A simple cost comparative analysis showed that the road using dredged sediment stabilized with OPC and FA was approximately 1.5 times more economic than the road using conventional earthen materials because the total transportation cost of materials used in the road using stabilized sediments was 2.5 times cheaper than that of the road using conventional earthen pavement materials.

Funding information This research was funded by King Mongkut's University of Technology North Bangkok under Contract No. KMUTNB-61-KNOW-008 and King Mongkut's University of Technology Thonburi (KMUTT) under Research Grant No. CE-KMUTT 6401. The last author would like to acknowledge the Ratchadapisek Sompoch Endowment Fund (2019), Chulalongkorn University (762003-CC).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human participant and/or animal rights and informed consent None.

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