Geotechnical Engineering Journal of SEAGS & AGSSEA

https://ph01.tci-thaijo.org/index.php/seags_agssea_journal

Strength Development in Cement and Fly Ash Admixed Bangkok Clay with Considering Shear Wave Velocity

Wungsumpow C.[1], Pochalard S.[2], and Piriyakul K.[3,*]

[1]*KMUTNB Techno Park, King Mongkut's University of Technology North Bangkok, Thailand*

[2]*Building and Landscape Division, Suan Dusit University, Bangkok, Thailand*

[3,*]*Center of Excellence in Structural Dynamics and Urban Management, Science and Technology Research Institute, and Department of Civil and Environmental Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand*

E-mail: keeratikan.p@cit.kmutnb.ac.th

ABSTRACT: This paper aims to investigate the strength development in ordinary Portland cement (OPC) and Fly ash (FA) admixed Bangkok clay. The role of cement is to stabilize and enhance the compressive strength of Bangkok soft clay. The OPC is replaced by FA which is a sustainable method since FA is an industrial waste product from Mae Moh power plant in the northern of Thailand. Bangkok soft clay was mixed with OPC content of 20% by weight and varied FA content from 0, 10, 15, 20, 25 to 30% by weight, after curing time for 7, 14, 28 and 90 days. The initial shear modulus (G_0) was determined from the shear wave velocity (V_s) measured by a non-destructive bender element testing. For comparison and ensuring the results, the strength development of the tested clay samples was also determined by destructive unconfined compression test (UCS). From the results, it was found that the optimum of replacement fly ash is about 15-20% and showed that the strength development of this Bangkok clay admixed with OPC and FA is increased with increasing the curing time. Moreover, the research found the linear relationship between G_0 (MPa) and q_u (MPa) as $G_0=27.57q_u$. Last but not the less, the linear relationship between the normalized $G_0/G_{0(28)}$ and the q_u/q_{28} was noted as $G_0/G_{0(28)} = 0.9073\ q_u/q_{28}$.

KEYWORDS: Bangkok Clay, Fly Ash, Shear Wave Velocity, Shear Modulus, and Unconfined Compressive Strength.

1. INTRODUCTION

Bangkok is the economic center and the capital city of Thailand. It is located on a very soft clay layer known as Bangkok clay. Mairaing and Amonkul (2010) studied the floodplain area of the river basin from the lower Chao Phraya River to the mouth of the river. Using data from 4,000 exploration boreholes, it was found that the soft clay is thicker than along the Gulf of Thailand coast, and its thickness decreases with distance to the north. In the Bangkok area, the thickness of this soft Bangkok clay layer ranges from 10 to 20 meters. Due to soft clay soil characteristics, Bangkok clay has a high moisture content near the liquid limit, resulting in high settlement and low shear strength. There are several studies on these issues. For example, a group of soil mechanical researchers, Horpibulsuk et al. (2007), evaluated several engineering characteristics of Bangkok soil and found that the compaction lines of the newly molded Bangkok clay were real and based on clay minerals and porous fluids. It was concluded that the liquid limit increases with its compressibility. So, there is a need to improve clay properties by increasing its strength for various civil engineering applications. A group of civil engineers, El-Kassasa et al. (2020), compared two case studies of the Sukhumvit subway station in Bangkok, Thailand, and the Chicago subway station in Chicago, United States of America. It was found that the shrinkage of the supporting slabs affected by thermal shrinkage affected the walls of the subway station, causing deformation and subsidence of the soft soils at all stages of the construction of the subway station.

Cement stabilization of clay soils, namely “soil-cement”, can be used to enhance soil strength properties and reduce the ground settlement. The deep mixing method (DMM) is a popular soil improvement method that involves mixing Ordinary Portland Cement (OPC) into soft soils. However, the use of OPC results in carbon emissions, as described by Suksiripattanapong et al. (2022).

A group of soil engineers, Madhyannapu et al. (2010), studied the improvement in the quality of Bangkok soft clay by stabilizing it with calcium Fly Ash (FA) geopolymer in soil-cement columns. It was noted that the undrained compressive strength of the treated geopolymer sample increased significantly with the increase in OPC for the design of the soil-cement column. Naweena et al. (2013) studied strength development of stable sandy clay with high water content. The clay to water/additive ratio was found to be important for strength development. Whenever the liquidity index was between 1 and 2. A group of researchers, Saadeldin et al. (2013), examined the characteristics of the soil-cement mixing and developed a general tendency for clay-cement mixtures. It was found that the reduction of the plasticity index was effective in demonstrating stability in cementitious soil strength. Firoozi et al. (2017) investigated the properties of soils with different additives and identified the stabilized soil as a composite material, whose properties can be obtained by mixing and optimizing the additives. It was noted that the treatment of clay with cement can reduce volume change. However, it is not suitable for clay with a high plasticity index in developing soil strength. Several predictive models have been proposed in recent decades. A group of researchers, Tsuchida and Tang (2015), assessed the compressive strength of cement-treated marine clays with varying initial values and water content. Using the gel-space ratio theory, a new formulation was proposed based on the results of six Japanese marine clays. Moreover, Kang et al. (2015) studied the mobilization of cement-treated Japanese soils during the early stages of curing times. Four samples of Japanese clay were examined by boundless compression and shear tests. It was found that the mobilization process can be divided into 2 phases, before and after 3 days of curing time, introducing useful predictive equations based on the initial water content and specific volume ratios. Yao et al. (2019) proposed a general hyperbolic formula to calculate the power and magnitude of

https://doi.org/10.14456/seagj.2026.2 Published on 24 June 2026

stabilized soil-cement hardening. This model works with different cement types, soil types and curing times. A group of engineers, Correia et al. (2013), studied the Unconfined Compressive Strength (UCS) of chemically stabilized soft soils using wet and dry methods. It was noted that this method was successful for a wide range of soils.

Miura et al. (2001) studied the influence of cement mixed with high tide content of Bangkok clay. It was found that the cement-clay-water ratio is important in controlling the characteristics of soil-cement, especially when the liquidity index ranges from 1 to 2. The water to cement ratio of 1 is also quoted for the Bangkok soft clay wet mix method. Por et al. (2017) found that the addition of cement significantly reduced the spatial and vertical contractile strain stress free swelling. In addition to the obvious improvement in the strength and hardness of expanded clay (a mixture of Na-montmorillonite, bentonite and non-expanding Bangkok clay), the cement had a greater vertical reduction effect on the swelling pressure than the lateral pressure during one-dimensional swelling.

Pozzolan is used as a substitute for cement recently and it has a chemical appearance similar to cement. Ahmed et al. (2019) found that pozzolanic materials rely on secondary reactions with free calcium hydroxide to form the calcium silicate hydrate (C-S-H) phase, which is an important factor in increasing the compressive strength of concrete. Pozzolan materials take 91 days to form and have a strong capacity from mixing and casting. Li et al. (2012) evaluated the strength improvement of cement-based organic soils containing a stabilizer called GX07. This compound is a mixture of gypsum, lime, water glass, sodium hydroxide, super plasticizer and triethanolamine. It was noted that GX07 improves soil-cement strength and is cheap. A group of civil engineers, Liu et al. (2019), verified the performance of soil-cement, metakaolin, and slag at different clay fractions, water content, and curing times. The strength of the newly developed material was found to be as good as that of soil-cement. A group of geologists, Nakayenga et al. (2021), investigated the influence of rock content, powder content, and particle size of different granite powders on the strength of soil-cement. It was found that the compressive strength of the geosynthetic material containing granite particles was higher than that of the control sample, owing to the increased surface area and pozzolanic reactivity of the rock powder. This new material can reduce cement consumption by 28.6% using stone powder. A group of material researchers, Chindaprasirt et al. (2021), studied the rejuvenating properties of recycled soil-cement with FA. It was noted that the optimum fly ash content was between 20% and 25%, corresponding to a prediction model. A team of geotechnical researchers, Cong et al. (2014), investigated the strength improvement of soil-cement by UCS and SEM. The data showed that binder enrichment was effective in promoting pozzolanic reactions and could improve the UCS of soil-cement. Vichan and Rachan (2013) used calcium carbide residue and biomass ash to stabilize the soft clay soil of Bangkok. It was found that the pozzolanic reaction occurred at a high pH and resulted in higher strength than the fly ash cementitious clay (FA) and biomass (BA) soil-cement mixture after 28 days of curing. A group of researchers, Jamsawang et al. (2017), studied the improvement of the properties of Bangkok soft soil mixed with cement and bagasse ash (BA), a waste product (obtained from the sugar industry). It was found that replacing cement with 20% BA was the most suitable proportion to increase strength. The finding confirms the use of industrial waste materials to replace ordinary Portland cement. A group of engineers, Tural et al. (2024), studied an eco-friendly material using Ground Granulated Blast Furnace Slag (GBS), fly ash, and silica fume. It was found that greenhouse gas emissions were reduced from 13% to 43%.

Fly ash (FA) has played an increasing role in sustainable soil-cement mixtures over the past few decades. Much research has used FA to improve the strength of soil-cement. For example, two studies by Horpibulsuk et al. (2009 and 2010) investigated the strength and microstructure in soil-cement mixtures. It was found that fly ash in soil-cement causes large soil-cement clusters to disperse into smaller clusters. It was noted that the maximum strength was found at 10% FA. Horpibulsuk (2012) studied the effect of curing time, cement and fly ash content on the strength and microstructure of soil-cement. It was stated that the development of the force consists of three zones: active area, inertial area and decomposition area. In the active area, the pore area with diameters less than 0.1 μm is reduced by increased cement content, resulting in higher strength. In the inertial area, the pore area and cement products will gradually change with increasing cement content. As a result, the rigidity changes slightly. In the degraded area, there is no moisture due to a lack of water, resulting in a decrease in strength. Chompoorat et al. (2022) studied the improvement of mechanical properties and shrinkage cracking characteristics of Bangkok soft clay in deep mixing with ordinary Portland cement (OPC) and fly ash (FA). The UCS tests were performed after 7 and 28 days of curing time, together with consideration of the effect of wet/dry spinning on the admixture durability based on the preliminary test of deep mixing with OPC. It was recommended to replace 15% FA content in the binder with the proposed water ratio of 0.4. A group of soil mechanical researchers, Chompoorat et al. (2021), have shown that cement and lime are effective in improving swelling behavior and other engineering properties of naturally expanded clay. The scanning electron microscopy analysis revealed an increase in the formation of particle clusters with curing time, and X-ray diffraction patterns showed moisture and pozzolanic chemical particle products. A group of material engineers, Wungsumpow et al. (2018), used the electrical resistivity tomography measurement in a landfill. The waste left over from these industrial plants needs to be mined in landfills by mining to dig landfills, some of which can be used to make recyclable materials as FA. Nowadays, industrial waste and synthetic fibers are commonly used in soil-cement mixing, as described by Pochalard et al. (2024a) and Pochalard et al. (2024b).

Bender Element (BE) testing has been using to determine the strength of geomaterials for many years. There are many advantages to this technique, as it is a Non-Destructive Testing (NDT) method. Piriyakul and Pochalard (2012) studied the strength development of Bangkok clay mixed with cement and fly ash by using the BE test. It was noted that the optimum fly ash content was approximately 15–20%. A group of environmental engineers Iamchaturapatr et al. (2021) studied on the bio-cement reaction in sand by using BE test. It was found that BE technique can be used to monitor the strength development of bio-cemented sand. Iamchaturapatr et al. (2022a) and Iamchaturapatr et al. (2022b) used the BE technique to determine the shear modulus of geomaterials.

The aforementioned reviews reveal that cement's role is to stabilize soft Bangkok clay. FA, on the other hand, is a waste by-product from power plants, so replacing cement with it serves a sustainable purpose. This study uses BE test to measure the initial shear modulus of Bangkok soft clay stabilized with OPC and FA replacement. The shear wave velocity is recorded at 7, 14, 28, and 90 days after the curing time. UCS tests are another method used to determine the strength development of tested clay samples for comparisons. In addition, the UCS and shear modulus of stabilized Bangkok clay are examined and correlated.

2. MATERIALS

2.1 Bangkok Clay

All soft Bangkok clay materials were sampled in the northern part of Bangkok, near King Mongkut's University of Technology North Bangkok (KMUTNB) Bangkok Campus, at a depth of about 10-12 m, where the material was near the liquid limit and formed a homogeneous, thick clay layer. Tables 1 and 2 show the basic properties of those Bangkok clay samples and the main chemical composition. This Bangkok clay has the unit weight of 1.47 T/m^3, the specific gravity of 2.68, the liquid limit of 88% and the plastic limit of 34%. It is noted that the natural moisture content of this Bangkok soft clay is about 81%, whereas the liquidity index of clay near the soil surface is about 1.0, but it decreases with depth. The Engineering properties of Bangkok clay were investigated by Horpibulsuk et al. (2007).

2.2 Portland Cement and Fly Ash

In this research, Ordinary Portland Cement (OPC) was used to stabilize all Bangkok soft clay samples. The main chemical compositions of Ordinary Portland Cement are shown in Table 1. It consists mainly of CaO, SiO2, Al2O3, and Fe_2O_3. The specific gravity of OPC is about 3.14. In addition, Fly Ash (FA) is an industrial waste from the Mae Moh Power Plant in Lampang Province, which is located in the north of Thailand. This FA is classified as Type F according to ASTM C 618. Figure 1 shows the SEM image of this FA and its main chemical compositions are listed in Table 1. Additionally, the specific gravity of the FA is approximately equal to 2.3; the average grain size (D50) of the Portland cement is around 0.6 mm, and the fly ash is about 0.08 mm.

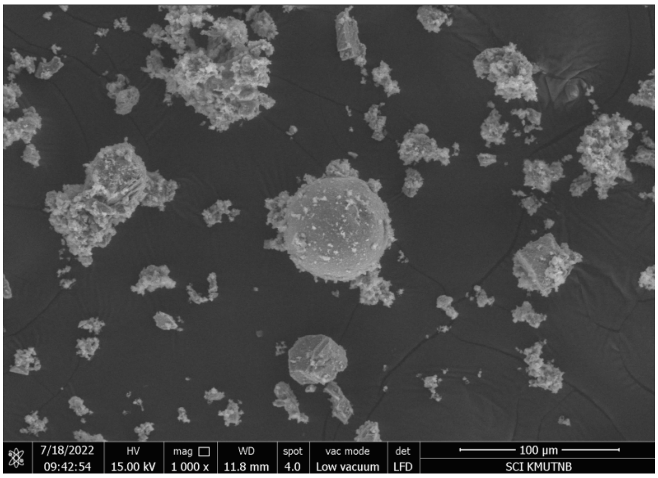

Figure 1 Enlarged SEM image of Mae Moh fly ash type F

Table 1 Chemical compositions of Bangkok clay, Portland cement and Fly ash (class F)

Comp.	OPC [%]	FA [%]	Bangkok clay [%]
SiO_2	20.90	37.34	62.5
Al_2O_3	4.76	18.63	18.4
Fe_2O_3	3.41	13.17	8.49
CaO	65.41	17.85	1.07
MgO	1.25	3.92	2.35
SO_3	2.71	3.51	1.86

Table 2 Properties of Bangkok soft clay

Unit weight [t/m^3]	UCS [kPa]	Specific gravity [-]	Liquid limit [%]	Plastic limit [%]	Moisture content [%]
1.47	14.5	2.68	88	34	81

2.3 Soil Cement Preparation

To prepare all Bangkok clay samples, water content 20% Ordinary Portland cement (OPC) was mixed with water at a limiting fluid of 88% (Horpibulsuk et al., 2010; Jamsawang et al., 2017; DOH, 1998) and then separated with FA at various contents (0%, 10%, 15%, 20%, 25% and 30% FA) and cured for 7, 14, 28 and 90 days according to Table 3. Each test consisted of 3 samples. For example, 12 samples were mixed with 0% FA for 7-, 14-, 28- and 90-day curing times, so there were 72 samples in total. Representative mean for further calculations. It is noted that each test is performed with 3 samples, and all data are averaged with deviations not greater than ± 10%.

3. METHODS

3.1 Bender Element Test

According to ASTM D8295–19, the bender element test measures the shear wave velocity, Vs, which is used to determine the stiffness of Bangkok clay samples in terms of the initial shear modulus, G_0. This method was used to determine strength development, considering V_s, for all Bangkok clay samples containing a mixture of ordinary Portland cement and fly ash that underwent a pozzolanic reaction, as determined by shear modulus measurements. Figure 2 depicts the shear wave test method by arranging the device to generate a shear wave signal. The function generator converts the analog signal into a sine pulse signal, which is sent to the transmitter bender element via a signal cable installed with a Bangkok specimen. The signal will travel through the clay sample. Entering the receiver bender element, the signal travels into the oscilloscope and one more line is connected directly to the oscilloscope to convert the signal back into the computer to form a pattern of the signal traveling through the clay sample.

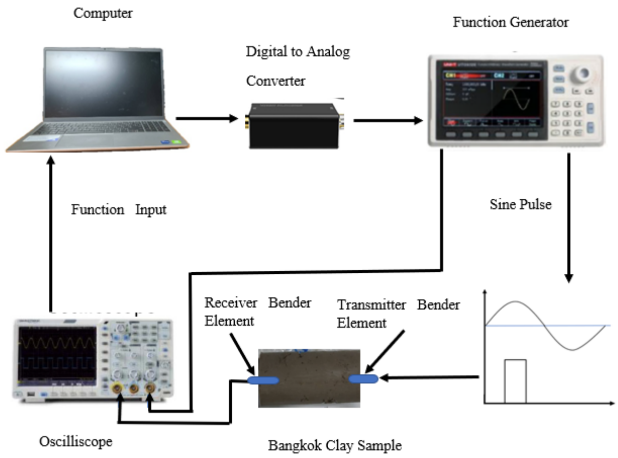

Figure 2 Bender element test set-up

Figure 3 shows an example shear wave measurement. Pattern of sine pulse signals transmitted through an oscilloscope transmitter transmitting a sine pulse shear wave frequency generated by the travel of sine waves through clay samples back to the signal originating computer. The computer transmits a 10 V amplitude signal at a frequency of 10 kHz through a digital-to-analog converter, as recommended by the manufacturer. Once the wave travels through the clay sample, the receiver bender element detects the shear wave signal. In the shear wave journey, the time it takes for the wave to travel from the transmitter to the receiver is measured. Checking the travel duration of the shear wave. From Figure 3, the wave entering the highest point of wave 1 is used as the starting point for counting the travel time from sending to the peak of wave 2 as the end of the journey of the receiving wave. Therefore, V_s (expressed as V_s-V_h) can be found together (ASTM D1633–17 and ASTM D8295–19) using the following Equation (1).

$$V_s = (L_i - L_b)/(T_s - T_c) \tag{1}$$

Where V_s is the shear wave velocity, measured in (m/s). L_i is the length of the Bangkok clay sample used for testing (m). L_b is the overall length of the bender element test measured between the transmitter and receiver (m). T_s is the measured time of the shear wave travel through the object from the wave emission unit to the wave receiver unit. T_c is the delay correction factor. Initial shear modulus (G_0, MPa) of clay samples corresponding to measured V_s Further calculations can be made as Equation (2).

$$G_0 = (\rho)(V^2{}_s)/10^6 \tag{2}$$

where ρ is the stable soft soil density (kg/m^3) as shown in Table 3.

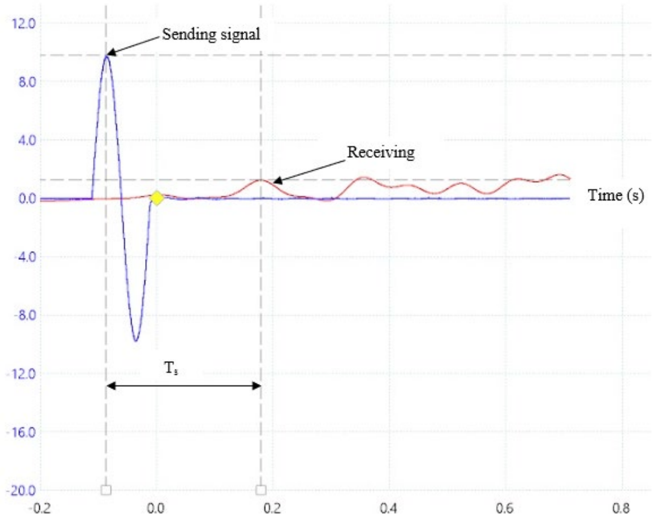

Figure 3 Examples of shear wave measurement

3.2 Unconfined Compression Test

According to ASTM D1633–17, the Unconfined Compressive Strength Test (UCS) is an execution of the unconfined compressive strength method. The purpose is to compare the ability of unconfined compressive strength to shear wave velocity, whose duration determines strength. It means that shear waves travel well in hard objects. Unconfined compressive strength testing has advantages, such as saving testing time and knowing test results quickly. The procedure for testing is simple. However, unconfined compressive strength testing destroys the tested sample. In the experiment with the Bangkok clay samples used in this study, the Bangkok clay samples were packed in cylinders with a diameter of 38 mm and a height of 76 mm, and then incubated by encapsulating them in a plastic membrane to prevent moisture loss. Samples were stored in plastic containers with sealed lids, with curing times of 7, 14, 28, and 90 days. At the end of each curing period, samples are tested using the UCS method according to ASTM D1633–17. The ratios used for soil-cement mixing are shown in Table 3 and Figure 4.

Table 3 Mixing proportions of Bangkok clay samples

Dry clay [g]	Unit Weight [t/m^3]	OPC [g]	FA [g]	Water [%]	Curing Time (days)
101.36	1.4799	20.27	0	88	7, 14, 28, 90
101.36	1.5732	18.24	2.027	88	7, 14, 28, 90
101.36	1.4999	17.23	3.040	88	7, 14, 28, 90
101.36	1.4765	16.21	4.054	88	7, 14, 28, 90
101.36	1.4984	15.20	5.067	88	7, 14, 28, 90
101.36	1.5749	14.18	6.081	88	7, 14, 28, 90

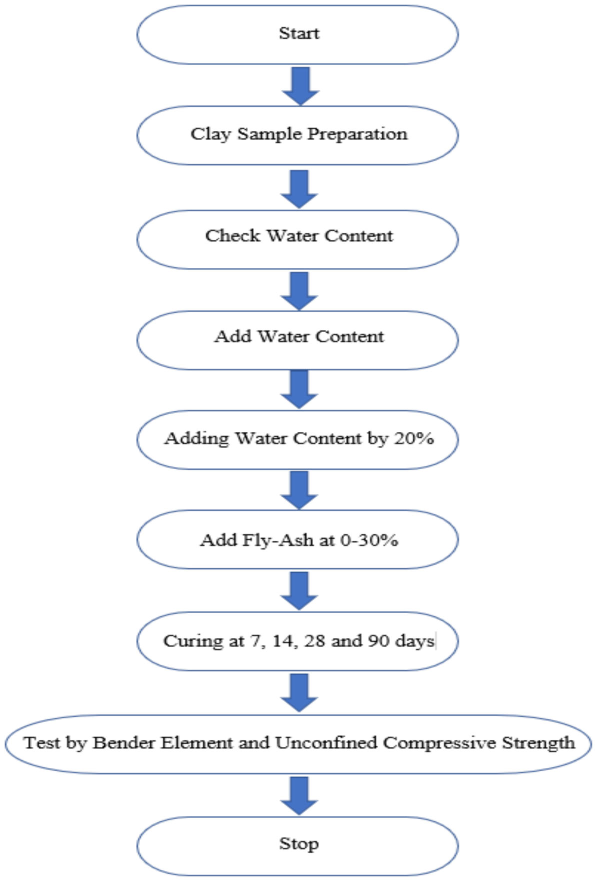

Figure 4 Flow chart for sample preparation

4. RESULTS AND DISCUSSIONS

4.1 Effect of Aging

Figure 5 shows the initial shear modulus, G0, varied with FA content between 0% (controlled sample), 10%, 15%, 20%, 25% and 30%, and the curing time at 7, 14, 28 and 90 days. It was again found that the G_0 has the tendency to increase with increasing the curing time. At 7 days, the G_0 results were 123.55, 142.74, 91.66, 104.82, 146.33 and 113.68 MPa, respectively. It was noted that the replacement of Ordinary Portland Cement with 25% FA resulted in a maximum of 146.33 MPa. Then at 14 days, G_0 data were 165.97, 145.51, 154.47, 145.40, 144.08 and 107.93 MPa. The controlled sample showed the maximum G_0 of 165.97 MPa. However, the replacement of 10%, 15%, 20% and 25% FA data also presented their good results of 145.51, 154.47, 145.40 and 144.08, respectively which was as good as the results of the controlled sample. Later, at 28 days, G0 results of 197.00, 149.26, 157.91, 159.69, 148.59, and 111.44 MPa were calculated, respectively. It was observed that the controlled sample had a G0 value of 197.00 MPa, the maximum value. However, the replacement of 10%, 15%, 20%, and 25% FA also showed good results of 149.26, 157.91, 159.69, and 148.59 MPa, respectively. Lastly, at 90 days, the G0 results were 213.00, 213.89, 328.93, 438.11, 211.26, and 214.98 MPa, respectively. It was noted that samples with FA replacement of 15-20% showed the greatest improvement, reaching 328.93 and 438.11 MPa, which were also higher than the data for the control samples. It seems the hydration reaction of the controlled sample ended at 28 days, resulting in no significant change in G_0.

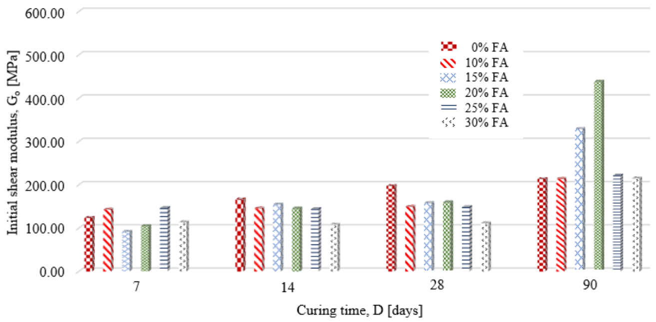

Figure 5 Development of G_0 with curing time of FA stabilized Bangkok soft clay

In the same way, Figure 6 presents the Unconfined Compressive Strength, UCS, varied with FA content between 0% (controlled sample), 10%, 15%, 20%, 25% and 30% and the curing time at 7, 14, 28 and 90 days. This UCS test revealed the compressive strength development behavior of the samples cured for 7-90 days. Again, it was found that, in general, UCS tends to increase with increasing curing time. At 7 days, the UCS results were 539.53, 267.73, 417.66, 319.02, 311.93 and 267.53 kPa, respectively. It was noted that the maximum UCS result of 539.53 kPa was found at the controlled sample, while the replacement Ordinary Portland Cement with 15% FA had the second UCS data of 417.66 kPa. Then, at 14 days, UCS values were 632.55, 303.33, 623.27, 443.05, 451.06, and 345.95 kPa. The controlled sample showed the maximum UCS of 632.55 kPa. However, the replacement of 15% and 25% FA also yielded good results of 623.27 kPa, respectively, which were as good as the controlled sample. Later at 28 days, UCS results of 703.23, 455.33, 676.69, 522.80, 370.77, and 409.21 kPa were calculated, respectively. It was observed that the controlled sample had a UCS result of 703.23 kPa and was the maximum value. However, the replacement of 15% FA data also showed good results of 676.69 kPa, which was as good as the results of the controlled sample. Lastly, at 90 days, the G_0 results were 1300.00, 681.41, 1249.87, 973.09, 1019.58, and 690.15, respectively. It was noted that samples with FA replacement of 15% had the UCS of 1,249.87 kPa, which was as good as the UCS data of the controlled samples, which was 1,300 kPa. Therefore, it was recommended to use a 15% FA replacement in the mix.

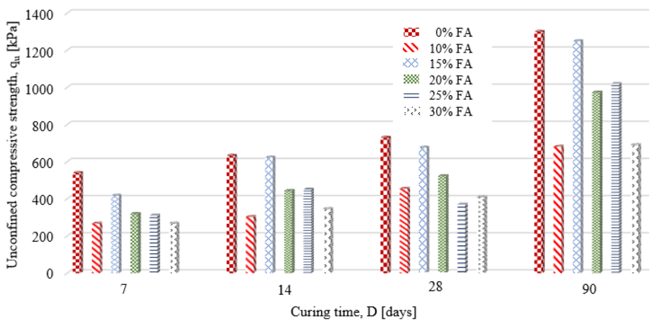

Figure 6 Development of q_u with curing time of FA stabilized Bangkok soft clay

4.2 Effect of FA Content

Figure 7 reveals the effect of a replacement of FA content with curing time and the change of V_s and G_0 on the Bangkok soft clay mixed with the 20% OPC and varied replacement FA content of 0 (controlled sample), 10, 15, 20, 25 and 30%. Figure 8 depicts the V_s with FA content. It was observed that at 90 days the maximum V_s result of 534.1 m/s was found at 20% replacement FA. The second Vs test data of 468.3 m/s was found at 15% replacement FA. So, it is recommended that 15-20% replacement FA should be used for the soil-cement mixing. Similarly, Figure 9 shows G_0 with FA content. It was noted that at 90 days, the maximum G_0 result of 534.1 MPa was found at 20% replacement FA. The second G_0 test data point of 468.3 MPa was observed at 15% FA replacement. Therefore, it was confirmed that 15-20% replacement FA should be used for the soil-cement mixing, which is in good agreement with the studies of Horpibulsuk et al., 2010 and DOH, 1998.

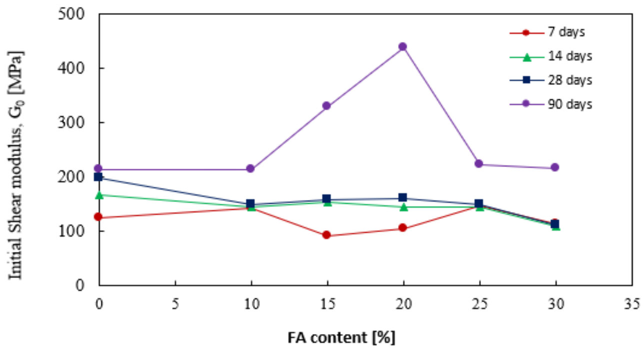

Figure 7 Variation of G_0 and FA contents of stabilized Bangkok soft clay

In the same way, Figure 8 presents the UCS data vs FA content, showing the UCS data with different curing time of the Bangkok soft clay mixed with the 20% OPC and varied replacement FA content of 0 (controlled sample), 10, 15, 20, 25 and 30%. It was noted that the UCS data at 15% FA content were as good as those for the controlled sample. It was recommended to use this replacement with 15% FA content for soil-cement mixing, and this was agreed with the work of A. Ahmed et al. (2019).

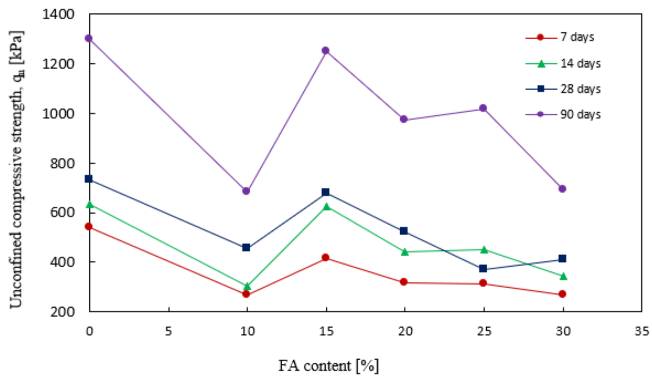

Figure 8 Variation of q_u and FA contents of stabilized Bangkok soft clay

4.3 Relationship between G_0 and q_u

Figure 9 shows the regression analysis of the experimental data to establish the relationship between G_0(MPa) and q_u(MPa). Kim's et al. (2017) data were used to compare the relationship between the normalized $G_0/G_{0(28)}$ and q_u/q_{28}, modeled as the natural logarithmic function. Equation (3) and Equation (4) were compared in the form of a linear natural logarithmic function with slopes of 0.287 and 0.8972, respectively. However, it was observed that the inconsistency of the linear natural logarithmic function to the experimental data is not suitable, as shown by R^2 of 0.5436. Therefore, it is necessary to revise this equation. So, Equation (4) was revised into Equation (5), showing the R^2 value of 0.9073 as shown in Figure 11.

$$\frac{G_0}{G_{0(28)}} = \left\{0.287 \ln\left[\frac{q_u}{q_{28}}\right] + 1\right\} \tag{3}$$

$$\frac{G_0}{G_{0(28)}} = \left\{0.8972 \ln\left[\frac{q_u}{q_{28}}\right] + 1\right\} \tag{4}$$

$$\frac{G_0}{G_{0(28)}} = \left[0.9526 \frac{q_u}{q_{28}}\right] \tag{5}$$

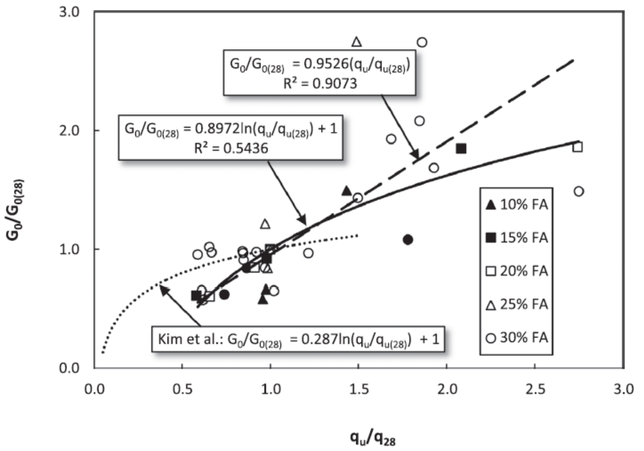

Figure 9 Relationships between $G_0/G_{0(28)}$ and $q_u/q_{u(28)}$

Although consistency of the three relationships is achieved, there may be discrepancies due to different soil-cement mixture ratios. Kim et al. (2017) also tested two materials from Busan clay and Ulsan clay. Using additives to increase soil stability, Kim et al. (2017) proposed that Ordinary Portland Cement (OPC) of 10–16% was used for Busan clay and 16–22% OPC for Ulsan clay together with blast furnace slag (BFS). However, Bangkok clay used an additional admixture of 20% Ordinary Portland Cement (OPC), mixed with different replacement cements including coal fly ash (FA). A group of concrete experts, Chindaprasirt et al. (2021), proposed the relationship between the deformation modulus, E_{50}, in MPa and the Unconfined Compressive Strength, q_u, in MPa for recycled clay from Nakhon Ratchasima Province (Thailand) with Ordinary Portland cement (OPC) and fly ash (FA) at a curing time of 28 days. Equation (6) can be written as follows.

$$E_{50} = 50\, q_u \tag{6}$$

The bender elements were used for testing in this study, where the shear velocity could be set and later converted to G_0 using Equation (2), and in an unconfined compression test, q_u could also be given. Figure 10 shows a regression of experimental data, establishing a relationship between G_0 (MPa) and q_u (MPa). This study will show that linear functions are used to optimize the data obtained from the experiment, which can be expressed in Equation (7) as follows.

$$G_0 = 27.57\, q_u \tag{7}$$

The relationship between the elastic modulus E and the initial shear modulus G_0 can be found using Equation (7), which can be rewritten as Equation (8) as follows.

$$\frac{E}{2(1+\vartheta)} = G_0 = 27.57 q_u \tag{8}$$

The Poisson ratio of ϑ is equal to 0.3–0.5. When we substitute the values into Equation (8), we obtain the following equation.

$$E = [71.68\ to\ 82.71] q_u \tag{9}$$

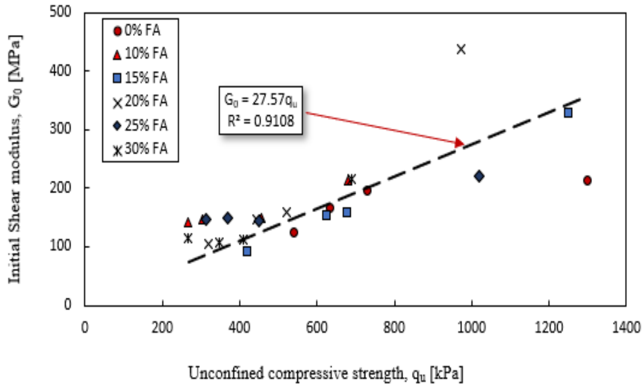

Figure 10 Relationships between G_0 and q_u

5. CONCLUSIONS

Bangkok soft clay was stabilized with 20% OPC and varied replacement FA content between 0%, 10%, 15%, 20%, 25% and 30% and curing time at 7, 14, 28 and 90 days. Based on the shear wave velocity data from the bender element test and the UCS test results, the research can be summarized as follows:

1. It was recommended to use the replacement FA content of 15-20% in the soil-cement mixing since the bender element and the UCS data confirmed the optimum and maximum results.
2. When FA content was added to the soil-cement mixing, it was noted that at 90 days, the maximum Vs and G0 results were obtained. This confirms that 15-20% FA replacement improves the soil-cement strength in the long term, which was also higher than the data of the controlled samples. It seems the hydration reaction of the controlled sample was over at 28 days; there was no significant increase in V_s and G_0.
3. Regression analysis is performed with experimental data to establish the relationship between G_0(MPa) and q_u(MPa). It was noted that the relationship between G_0 (MPa) and q_u (MPa) was G_0=27.57q_u which is a linear function that fits the experimental data this time. Moreover, the relationship between the normalized $G_0/G_{0(28)}$ and the q_u/q_{28} relationship of the natural logarithmic function. It was addressed that it is a linear relationship with a slope of 0.9073 and R^2 = 0.9073 which was in good agreement with Kim's et al. (2017).
4. A linear relationship between the normalized G_0 and the normalized UCS is instead suggested due to the error in curve fitting with the experimental data and is equal to 0.8972.
5. It is recommended that the findings of this study be applied to construction practice and compared to other sustainable materials, specifically waste and recycled materials.

6. ACKNOWLEDGEMENTS

This research was funded by National Science, Research and Innovation Fund (NSRF), and King Mongkut's University of Technology North Bangkok with Contract no. KMUTNB-FF-66-33.

7. REFERENCES

Ahmed, A., Kamau, J., Pone, J., Hyndman, F., & Fitriani, H. (2019). Chemical Reactions in Pozzolanic Concrete. Mod. Approaches Mater. Sci, 1, 128–133.

ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.

ASTM D1633–17, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders.

ASTM D8295–19, Standard Test Method for Determination of Shear Wave Velocity and Initial Shear Modulus in Soils Specimen Using Bender Elements.

Chindaprasirt, P., Daprom, P., Jitsangiam, P., & Horpibulsuk, S. (2021). Role of Fly Ash on Strength Properties of Rejuvenated Soil Cement for Pavement Materials. Civil and Environmental Engineering, 17(2), 583–596.

Chompoorat, T., Likitlersuang, S., Sitthiawiruth, S., Komolvilas, V., Jamsawang, P., & Jongpradist, P. (2021). Mechanical Properties and Microstructures of Stabilised Dredged Expansive Soil from Coal Mine. Geomechanics and Engineering, 25(2), 143–157.

Chompoorat, T., Likitlersuang, S., Thepumong, T., Tanapalungkorn, W., Jamsawang, P., & Jongpradist, P. (2021). Solidification of Sediments Deposited in Reservoirs with Cement and Fly Ash for Road Construction. International Journal of Geosynthetics and Ground Engineering, 7(4), 85.

Chompoorat, T., Thanawong, K., & Likitlersuang, S. (2021). Swell-Shrink Behaviour of Cement with Fly Ash-Stabilised Lakebed Sediment. Bulletin of Engineering Geology and the Environment, 80, 2617–2628.

Chompoorat, T., Thepumong, T., Khamplod, A., & Likitlersuang, S. (2022). Improving Mechanical Properties and Shrinkage Cracking Characteristics of Soft Clay in Deep Soil Mixing. Construction and Building Materials, 316, 125858.

Cong, M., Longzhu, C., & Bing, C. (2014). Analysis of Strength Development in Soft Clay Stabilized with Cement-Based Stabilizer. Construction and Building Materials, 71, 354–362.

Correia, A. A. S., Venda Oliveira, P. J., & Lemos, L. J. L. (2013, September). Prediction of the Unconfined Compressive Strength in Soft Soil Chemically Stabilized. In Proc., 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering (pp. 2457–2460). Paris: Presses des Ponts.

Department of Highways of Thailand (DOH) & Japan International Cooperation Agency (JICA). (1998). Manual for Design and Construction of Cement Column Method. DOH, pp. 75.

El-Kassasa, M. R., Ahmedb, S. M., & Srouorc, T. M. Geotechnical Aspects of Deep Excavation in Soft Clay. Al-Azhar University Civil Engineering Research Magazine (CERM) Vol. (42) No. (1) January, (2020).

Firoozi, A. A., Olgun, C. G., Firoozi, A. A. & Baghini, M. S. Fundamentals of Soil Stabilization., 2017, 8. DOI: https://doi.org/10.1186/s40703-017-0064-9, 26.

Horpibulsuk, S. (2012). Strength and Microstructure of Cement Stabilized Clay. In Scanning Electron Microscopy. IntechOpen.

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of Strength Development in Cement-Stabilized Silty Clay from Microstructural Considerations. Construction and Building Materials, 24(10), 2011-2021.

Horpibulsuk, S., Rachan, R., & Raksachon, Y. (2009). Role of Fly Ash on Strength and Microstructure Development in Blended Cement Stabilized Silty Clay. Soil and Foundations, 49(1), 85–98.

Horpibulsk, S., Rachan, R., Suddeepong, A., & Chinkulkijniwat, A. (2011). Strength Development in Cement Admixed Bangkok Clay: Laboratory and Field Investigations. Soils and Foundations, 51(2), 239–251.

Horpibulsuk, S., Shibuya, S., Fuenkajorn, K., & Katkan, W. (2007). Assessment of Engineering Properties of Bangkok Clay. Canadian Geotechnical Journal, 44(2), 173–187.

Iamchaturapatr, J., Piriyakul, K., Ketklin, T., Di Emidio, G., & Petcherdchoo, A. (2021). Sandy Soil Improvement Using MICP-Based Urease Enzymatic Acceleration Method Monitored by Real-Time System. Advances in Materials Science and Engineering, 2021, 1–12.

Iamchaturapatr, J., Piriyakul, K., & Petcherdchoo, A. (2022a). Characteristics of Sandy Soil Treated Using EICP-Based Urease Enzymatic Acceleration Method and Natural Hemp Fibers. Case Studies in Construction Materials, 16, e00871.

Iamchaturapatr, J., Piriyakul, K., & Petcherdchoo, A. (2022b). Use of a Piezoelectric Bender Element for the Determination of Initial and Final Setting Times of Metakaolin Geopolymer Pastes, With Applications to Laterite Soils. Sensors, 22(3), 1267.

Jamsawang, P., Poorahong, H., Yoobanpot, N., Songpiriyakij, S., & Jongpradist, P. (2017). Improvement of Soft Clay with Cement and Bagasse Ash Waste. Construction and Building Materials, 154, 61–71.

Kang, G., Tsuchida, T., & Athapaththu, A. M. R. G. (2015). Strength Mobilization of Cement-Treated Dredged Clay during the Early Stages of Curing. Soils and Foundations, 55(2), 375–392.

Kim, A. R., Chang, I., Cho, G. C., & Shim, S. H. (2018). Strength and Dynamic Properties of Cement-Mixed Korean Marine Clays. KSCE Journal of Civil Engineering, 22, 1150–1161.

Li, X. G., Xu, R. Q., & Rong, X. N. (2012). Assessment of Strength Development in Cement-Admixed Artificial Organic Soil with GX07. Journal of Central South University, 19(10), 2999-3005.

Liu, L., Zhou, A., Deng, Y., Cui, Y., Yu, Z., & Yu, C. (2019). Strength Performance of Cement/Slag-Based Stabilized Soft Clays. Construction and Building Materials, 211, 909–918.

Madhyannapu, R. S., Puppala, A. J., Nazarian, S., & Yuan, D. (2010). Quality Assessment and Quality Control of Deep Soil Mixing Construction for Stabilizing Expansive Subsoils. Journal of Geotechnical and Geoenvironmental Engineering, 136(1), 119–128.

Mairaing, W., & Amonkul, C. (2010, September). Soft Bangkok Clay Zoning. In EIT-Japan Symposium on Engineering for Geo-Hazards: Earthquakes and Landslides-Surface and Subsurface Structures Imperial Queen's Park Hotel, Bangkok, Thailand (pp. 6–7).

Miura, N., Horpibulsuk, S., & Nagaraj, T. S. (2001). Engineering Behavior of Cement Stabilized Clay at High Water Content. Soils and Foundations, 41(5), 33–45.

Nakayenga, J., Cikmit, A. A., Tsuchida, T., & Hata, T. (2021). Influence of Stone Powder Content and Particle Size on the Strength of Cement-Treated Clay. Construction and Building Materials, 305, 124710.

Naveena, P. C., Mamatha, K. H., & Dinesh, S. V. (2013). Prediction of Strength Development in Stabilized Sandy Clay at High Water Contents. Int J Geol, 7(1), 9–23.

Petcherdchoo, A. (2018). Probability-Based Sensitivity of Service Life of Chloride-Attacked Concrete Structures with Multiple Cover Concrete Repairs. Advances in Civil Engineering, 2018, 1–17.

Petcherdchoo, A. (2015, May). Service Life and Environmental Impact Due to Repairs by Metakaolin Concrete After Chloride Attack. In Calcined Clays for Sustainable Concrete: Proceedings of the 1st International Conference on Calcined Clays for Sustainable Concrete (pp. 35–41). Dordrecht: Springer Netherlands.

Petcherdchoo, A. (2018). Sensitivity of Service Life Extension and CO_2 Emission Due to Repairs by Silane Treatment Applied on Concrete Structures under Time-Dependent Chloride Attack. Advances in Materials Science and Engineering, 2018.

Petcherdchoo, A., Hongubon, T., Thanasisathit, N., Punthutaecha, K., & Jang, S. H. (2020). Effect of Curing Time on Bond Strength Between Reinforcement and Fly-Ash Geopolymer Concrete. Applied Science and Engineering Progress, 13(2), 127–135.

Piriyakul, K. (2010). A Development of a Bender Element Apparatus. Journal of King Mongkut's University of Technology North Bangkok, 20, 363–369.

Piriyakul, K., & Pochalard, S. (2012). Using Shear Wave Velocity to Determine the Cementation Effect of Soft Bangkok Clay Mixed with Cement and Fly Ash. In Multiphysical Testing of Soils and Shales (pp. 311–316). Berlin, Heidelberg: Springer Berlin Heidelberg.

Pochalard, S., Wungsumpow, C., & Piriyakul, K. (2024a). Enhancement on Compressive Strength of Bangkok Clay Cement Using Novel High-Strength Polyethylene Fibers. In IOP Conference Series: Earth and Environmental Science (Vol. 1335, No. 1, p. 012008). IOP Publishing.

Pochalard, S., Wungsumpow, C., & Piriyakul, K. (2024b). Enhancement of Compressive Strength in Cement Admixed Bangkok Clay with Glass Fiber and Bottom Ash for Eco-Friendly Functional Road Materials. Mechanics of Advanced Composite Structures.

Por, S., Nishimura, S., & Likitlersuang, S. (2017). Deformation Characteristics and Stress Responses of Cement-Treated

Expansive Clay under Confined One-Dimensional Swelling. Applied Clay Science, 146, 316–324.

Saadeldin, R., & Siddiqua, S. (2013). Geotechnical Characterization of a Clay–Cement Mix. Bulletin of Engineering Geology and the Environment, 72, 601-608.

Suksiripattanapong, C., Sakdinakorn, R., Tiyasangthong, S., Wonglakorn, N., Phetchuay, C., & Tabyang, W. (2022). Properties of Soft Bangkok Clay Stabilized with Cement and Fly Ash Geopolymer for Deep Mixing Application. Case Studies in Construction Materials, 16, e01081.

Tsuchida, T., & Tang, Y. X. (2015). Estimation of Compressive Strength of Cement-Treated Marine Clays with Different Initial Water Contents. Soils and Foundations, 55(2), 359–374.

Tural, H. G., Ozarisoy, B., Derogar, S., & Ince, C. (2024). Investigating the Governing Factors Influencing Pozzolanic Activity Through a Database Approach for The Development of Sustainable Cementitious Materials. Construction and Building Materials, 411, 134253.

Vichan, S., & Rachan, R. (2013). Chemical Stabilization of Soft Bangkok Clay Using the Blend of Calcium Carbide Residue and Biomass Ash. Soils and Foundations, 53(2), 272–281.

Wungsumpow, C., Towprayoon, S, Chiemchaisri, C., Suanburi, D., & Wangyao, K. (2018). Applying Electrical Resistivity Tomography Measurement in Landfill Mining: A Study on Configuration and Spacing Setting. 7th SEE 2018: Technology and innovation for global energy revolution, Bangkok, Thailand.

Yao, K., Li, N., Chen, D. H., & Wang, W. (2019). Generalized Hyperbolic Formula Capturing Curing Period Effect on Strength and Stiffness of Cemented Clay. Construction and Building Materials, 199, 63–71.

Yoobanpot, N., Jamsawang, P., Simarat, P., Jongpradist, P., & Likitlersuang, S. (2020). Sustainable Reuse of Dredged Sediments as Pavement Materials by Cement and Fly Ash Stabilization. Journal of Soils and Sediments, 20, 3807–3823.