Civil Engineering Infrastructures Journal, 49(1): 149 – 164, June 2016
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.7508/ceij.2016.01.011

Permeability Characteristics of Compacted and Stabilized Clay with Cement, Peat Ash and Silica Sand

Mousavi, S.E.[1*] and Wong, L.S.[2]

[1] Ph.D., Civil Engineering Department, College of Engineering, Universiti Tenaga Nasional, IKRAM-UNITEN Road, 43000 Kajang, Selangor, Malaysia.
[2] Associate Professor, College of Graduate Studies, Universiti Tenaga Nasional, IKRAM-UNITEN Road, 43000 Kajang, Selangor, Malaysia.

Received: 29 Jun. 2015; Revised: 08 Dec. 2015; Accepted: 23 Dec. 2015

ABSTRACT: The present paper investigates the influence of stabilization with cement, peat ash, and silica sand on permeability coefficient (k_v) of compacted clay, using a novel approach to stabilize the clay with peat ash as a supplementary material of cement in the compacted and stabilized soil. In order to assess the mentioned influence, test specimens of both untreated and stabilized soil have been tested in the laboratory so that their permeability could be evaluated. Falling head and one dimensional consolidation tests of laboratory permeability were performed on the clay specimens and the chemical compositions of the materials as well as microstructure of the stabilized soil with 18% cement, 2% peat ash, and 5% silica sand were investigated, using X-ray fluorescence and scanning electron microscopy respectively. Results show that for soil stabilization with up to 8% cement content (of the dry weight of the soil), the average value of coefficient of permeability (k_v) is very close to that of untreated soil, whereas the k_v value decreases drastically for 18% cement under identical void ratio conditions. It is further revealed that addition of 18% cement, 2% peat ash, and 5% silica sand had decreased the coefficient of permeability by almost 2.2 folds after 24 h, while about 1.7 folds increase was observed in coefficient of permeability once 13.5% of cement, 1.5% of peat ash, and 20% of silica sand were added. The partial replacement of cement with the 2% peat ash can reduce the consumption of cement for soil stabilization.

Keywords: Falling Head, One Dimensional Consolidation, Peat Ash, Permeability, Silica Sand.

NOMENCLATURES

k_v: coefficient of permeability in vertical direction (m/s)
k_{20}: coefficient of permeability at 20°C (m/s)
$k_{T°C}$: coefficient of permeability at required temperature (m/s)
A: cross sectional area of the specimen in falling head test (mm^2)
a: cross sectional area of standpipe tube (mm^2)
C_v: coefficient of consolidation (m^2/year)
h: head loss in standpipe (mm)

* Corresponding author E-mail: mousavi.utn@gmail.com

L: length of specimen in falling head test (mm)
m_v: coefficient of volume change (m^2/MN)
S_c: compression settlement (mm)
Q: quantity of flow (mm^3/s)
t: time (s)
V: flow velocity (m/s)
γ_w: unit weight of water (kN/m^3)
S: specific surface of the cement or peat ash (cm^2/g)
S_s: specific surface of the standard sample used in calibration of the apparatus (3640 cm^2/g)
T: time taken for the manometer liquid to drop from the second to the third level during the test (second)
T_s: time taken for the manometer liquid to drop from the second to the third level during the calibration (second)
MDD: Maximum Dry Density (Mg/m^3)
OMC: Optimum Moisture Content (%)

INTRODUCTION

Stabilization of fine grained soils has being executed extensively. The Mesopotamians and Romans separately found that it was possible to improve the ability of pathways to carry the traffic by mixing the weak soil with a stabilizing agent which improved their load-bearing ability (Kowalski et al., 2007). Compacted soil, stabilized with cement, has been widely used in geotechnical engineering applications such as highway embankment and slopes. Stabilization techniques can improve the durability and strength of soil as a result of mixing it with appropriate proportions of different stabilizers such as cement, lime, sand, and various ashes. Scientific techniques of soil stabilization have been introduced in recent years with the use of pozzolanic materials like Portland cement as a stabilizer and hydration agent being quite popular. Stabilizers with pozzolanic properties can bind soil particles together and reduce water absorption by clay particles (Hossain and Mol, 2011). In recent years soil stabilization with cement has become common owing to its low cost of cement and availability in most countries. Stabilization can improve the soil in its water content and cementing agent. In other words, chemical interactions between soil particles, cement, and water content reduce pore spaces of the soil (Horpibulusk et al., 2010). Thus, stabilized soil with cement could gain adequate strength and improved properties in a short time. The improved soil with low permeability, high strength, and sufficient thickness can be used in field requests such as highway construction. Furthermore, clay has many useful applications due to its physical properties such as fine particle size and large surface area. The effect of some influential factors, e.g., water content, pozzolanic materials, cement content and compaction energy on the engineering characteristics of stabilized soil with cement and natural pozzolans have been extensively researched by Hossain and Mol (2011) and Wong et al. (2013). Previous researches have proven that cement decreases the coefficient of permeability while sand increases the permeability (Goodary et al., 2012). Meanwhile, the effect of peat ash on coefficient of permeability of clay soil has not been investigated completely. According to Mousavi and Wong (2015), stabilization of soft clay with cement and peat ash could improve the strength and density of soil. This paper presents a novel material in the form of peat ash that can be obtained by burning peat at the temperature of 440 °C for 4 hours in a muffle furnace (ASTM D2974-14). Peat is an organic soil with a high content of organic matter. Depending on the fiber content, ash content, and pH value, peat can be classified as fibric, hemic, and sapric; low ash, medium ash, and high ash; highly-acidic, moderate-acidic, slightlyacidic, and basic peat respectively (Bujang et al., 2011). Although cement is one of the oldest building materials around; it is produced at a very high temperature of about 1500°C in order to make it possible for the clinker to form. The main concern of cement production is its highly energy-intensive process and greenhouse gas production, resulting in environmental damages due to its carbon dioxide (CO_2) output (Mahasenan et al., 2003). Therefore, utilization of peat ash to stabilize clayey soil and partial replacement of cement with peat ash can reduce the latter's use in the stabilized soil, offering some environmental advantages. On the other hand, the successful application of any ground improvement technology begins with the site application and field demand. Thus stabilized soil with sufficient thickness, bearing capacity and strength can be applied in accordance to a site request such as a request for highway embankment. Therefore, it is important to examine the permeability characteristics of stabilized clay in order to evaluate the reduction of the pore spaces in the stabilized soil as a result of cementation effect. Although, the previous researches have investigated permeability of stabilized soils (Abdi and Pajouh 2009; Ghasemzadeh and Abounouri 2013; Bazargan and Shoaei, 2010), there has been a limited number of studies on the permeability of stabilized clay with cement, peat ash, and silica sand. The main objective of this paper is, therefore, to evaluate coefficient of permeability of compacted and stabilized clay with various proportions of cement, peat ash, and silica sand.

MATERIALS AND METHODS

Collecting Soil Samples and Used Material

The main soil sample of this paper was collected from Taman Wetlands, Putrajaya, Malaysia, using a polyethylene tube with a diameter of 100 mm. In order to obtain the soil sample, 10 trial pits were excavated. Water table was observed at the depth of 1.5 meters below the ground. The tube was pushed into the soil under water table and was then immediately kept in an airtight container, later to be transported to the laboratory. The soft clay ranged about 2 meters deep under the ground, underlain by a layer of hard clay. The soil sample was classified as CLAY of high plasticity (CH) according to the Unified Soil Classification System (USCS) and based on the results of sieve analysis, plastic and liquid limit tests. The soil sample was composed of 23% sand, 15% silt, and 62% clay. The particle size distribution curve of soft clay is shown in Figure 2. Other than clay, Ordinary Portland Cement (OPC), Silica Sand (SS), and Peat Ash (PA) were also used to stabilize the soil. Silica sand was used as particle grading modifier, having been collected nearby the CE-laboratory of Universiti Tenaga Nasional (UNITEN). The type of cement is Ordinary Portland Cement (OPC) from the YTL Company. The peat was sampled from Sri Nadi village in Klang, Selangor, Malaysia. Being part of the tropical peat swamp covering the area of Klang, which is located about 35.4 km off Kuala Lumpur. Peat ash was obtained by heating the organic peat in a muffle furnace at the temperature of 440°C for 4 hours.

Fig. 1. Site of sample peat (Wong et al., 2013)

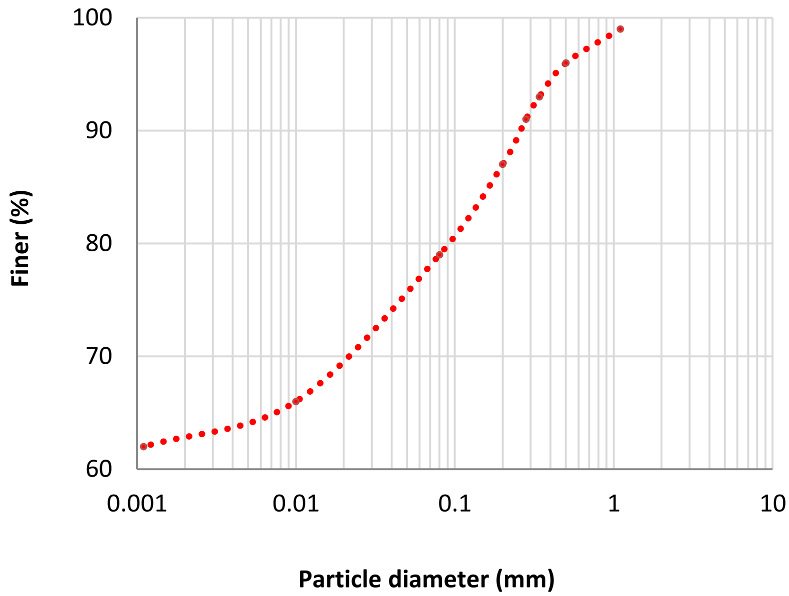

Fig. 2. Particle size distribution curve of the soil (Mousavi and Wong, 2015)

The basic properties of the natural soil sample are tabulated in Table 1, based on which, the soil sample is identified as non-organic clay as its organic content is less than 10%. Therefore the soil is regarded as an inorganic soil. This is justified by Yilmaz and Ozaydin (2013) in that if the organic content is less than 10% it is too little to affect the soil properties. Moreover, the physicochemical properties of peat ash are specified in Table 2.

Table 1. Basic properties of the natural soil sample (Mousavi and Wong, 2015)

Basic Properties	Average Value
Natural Moisture Content (%)	45
Specific Gravity	2.46
pH	7.1
Liquid Limit (%)	56
Organic Content (%)	5.3
Plastic Limit (%)	24
Plasticity Index (%)	32
Dry Density (kg/m^3)	1782

Table 2. Physicochemical properties of peat ash

Property	Value
Color	Dark brown
Specific Gravity	2.23
Surface Area (cm^2/g)	6392
pH	8.2

Mix Design and Specimen Preparation

The trial mix designs of stabilized clay with cement as a binding agent, peat ash as a supplementary material with the capability of partially replacing the cement in stabilized soil, and silica sand as a particle grading modifier are presented in Table 3. In order to stabilize, cement content varied from 0 to 18%. It is noticeable that 0 to 20% cement content for clay improvement is used commonly (Mousavi and Wong, 2015; Bahar et al., 2004; Horpibulsuk et al., 2012). In order to prepare the specimen, the oven-dried clay, cement, peat ash, and silica sand were mechanically mixed with optimum water content in a soil mixer with the mixing time, arbitrarily adjusted at 10 minutes in accordance with Horpibulsuk et al. (2012). For the purpose of standard Proctor compaction test, the uniform stabilized soil admixture was transferred to a cylindrical compaction mould and compacted in three equal layers. The optimum moisture content and maximum dry density for each mix design from trial tests were obtained on the basis of peat ash dosages, ranging from 0 to 6.5% of the soil's dry weight. Due to its high content of organic substances and water, only a small amount of peat ash could be obtained from fresh peat after Loss on Ignition (LOI). The best results, i.e., those which had the highest Maximum Dry Density (MDD), were chosen to apply permeability falling head and 1D consolidation tests. Thus the compacted soil specimen with the highest MDD indicates a high compact ability and actual improvement of the stabilized clay's strength (Mousavi and Wong, 2015). Based on Table 3, it can be seen that the highest MDD was 1.951 Mg/m^3 for the binder composition of 18% OPC, 2% PA, 5% SS; therefore, partial replacement of cement with 2% peat ash was chosen as an ideal mix design. In order to evaluate the effect of silica sand on coefficient of permeability of stabilized soil, the binder composition of 13.5% OPC, 1.5% PA, and 20% SS was also chosen as a trial mix design. The permeability falling head tests were performed on the test specimens at the room temperature of 25°C. Herein, two different stages were considered for the falling head tests. In the first stage, after 24 h the stabilized soil specimens were tested immediately, even though the pozzolanic reaction might occur as a result of the interaction between the cement, peat ash, and water. The second stage corresponds to the soil specimens, cured for 7, 14, 21, and 28 days. In this case, after 24 h the test specimens were removed from the mould, wrapped in vinyl bags, and allowed to cure in the humidity of the room with constant temperature (25 ± 2 °C). Permeability falling head tests were carried out on the test specimens after 7, 14, 21, and 28 days of curing. The chemical composition of the materials by the percentage of the total chemical composition's weight from X-ray Fluorescence (XRF) tests are also indicated in Table 4, according to which, in peat ash the sum of silica (SiO_2) and alumina (AL_2O_3) is 72.6793% of the total chemical composition. This is attributed to the pozzolanic properties of the peat ash as justified by Wong et al. (2013).

Table 3. Trial mix designs of various binder compositions

Description	Binder Composition				MDD	OMC
	Clay (%)	**OPC (%)**	**PA (%)**	**SS (%)**	**(kg/m^3)**	**(%)**
Untreated Clay	**100**	**0**	**0**	**0**	**1.782**	**16.32**
Stabilized clay with cement and peat ash (% of peat ash by dry weight of the soil)	85	10	0	5	1.864	17.81
	85	9.75	0.25	5	1.862	17.66
	85	9.50	0.5	5	1.859	17.57
	85	9.25	0.75	5	1.857	17.40
	85	9	1	5	1.854	17.35
	85	8.75	1.25	5	1.853	17.30
	85	8.50	1.50	5	1.851	17.24
	85	8.25	1.75	5	1.850	16.86
	85	8	2	5	1.848	16.82
Partial replacement of cement with peat ash (Mousavi and Wong, 2015)	90	4.5	0.5	5	1.846	17.11
	85	9	1	5	1.854	17.45
	80	13.5	1.5	5	1.901	19.18
	75	18	2	5	1.951	21.13
Effect of silica sand on the compact ability of the stabilized clay	80	13.5	1.5	5	1.901	19.18
	75	13.5	1.5	10	1.909	18.62
	70	13.5	1.5	15	1.914	18.01
	65	13.5	1.5	20	1.927	17.71
Effect of peat ash on the compact ability of the stabilized clay	80	13.5	1.5	5	1.901	19.18
	77.5	13.5	4	5	1.912	20.31
	75	13.5	6.5	5	1.908	19.30

Table 4. Chemical composition of the additives for soil stabilization under study

Oxide Compound	Weight (%)		
	OPC	Silica Sand	Peat Ash
Al_2O_3	5.6111	5.1661	22.7316
SiO_2	21.5602	89.0011	49.9477
SO_3	2.1688	0.1421	-
Alkali (K_2O, Na_2O)	-	1.4632	2.8794
CaO	64.9375	0.3372	5.5818
Fe_2O_3	3.6576	1.0301	17.7265
Others	2.0648	2.8602	1.133

Experimental Procedures

The test methods are based on the guidelines of ASTM standard. Laboratory investigation focused on the permeability falling head (ASTM D5084-03), one dimensional consolidation (ASTM D2435), and fineness of materials (ASTM C204-11) tests. In addition, standard Proctor compaction test was performed to obtain the mix design in terms of optimum moisture content and maximum dry density (ASTM D698). The diameter and height of the prepared soil specimens were 50 mm and 20 mm for consolidation test respectively, whereas in the falling head test the diameter was 100 mm and the height, 121 mm.

Falling head test

The falling head test was applied in order to determine the coefficient of permeability of both untreated and stabilized soil specimens. To perform the test, the compacted soil specimen at optimum moisture content was placed in a metal mould. Filter papers were positioned at the top and bottom faces of the soil specimen to prevent its separation. The assembled permeameter cell was placed in the immersion tank. Water was allowed to flow through the specimen from a standpipe attached to the top of the mould and saturated the soil specimen. The test was conducted at constant 28°C and at different times, resulting in the head of water change in a standpipe. The flow velocity in the tube is given by Eq. (1) (Das, 1989).

$$V = -\frac{dh}{dt} \tag{1}$$

The coefficient of permeability of the soil specimen is formulated by Eq. (2) (Das, 1989).

$$k=\frac{2.3026aL}{At} log_{10}\frac{h_1}{h_2} \left(\frac{mm}{s}\right) \tag{2}$$

The coefficient of permeability at 20°C is corrected as shown in Eq. (3) (Das, 1989).

$$k_{20°C} = k_{T°C} \times 0.8472 \tag{3}$$

One Dimensional Consolidation Test

The soil sample was placed in a compaction mould and compacted in three equal layers at optimum moisture content and maximum dry density. The compacted soil specimen was then trimmed with a brass cutter ring, 50 mm wide and 20 mm high. Next, the soil specimen was made level with the end faces of the cutting ring and filter papers and porous stones were positioned at the top and bottom faces of the test specimen. The 1D consolidation tests were applied on the soil specimens under identical void ratio conditions. Similar to untreated soil specimen, the mixture of soil and additives was compacted at optimum moisture content and maximum dry density. The effective vertical stresses of 2.5 kPa, 5 kPa, 10 kPa, 20 kPa, 40 kPa, 80 kPa, and 160 kPa were applied on the 1D consolidation test specimens. The load increment was two folds larger than the previous load. The duration of each load was 24 hours. Based on the results of the 1D consolidation test, the coefficient of permeability was determined by Eq. 4 (Das, 1989).

$$k = c_v \times m_v \times \gamma_w \tag{4}$$

Fineness test

The hydration rate depends on the fineness of the cement particles. Hydration of cement starts at the surface of cement particles. Since the total surface area of cement represents the material available for hydration. Similarly, high fineness is necessary to achieve rapid development of strength (ASTM C204-11). To determine the fineness of cement and peat ash the manometer liquid top surface inside the manometer was adjusted at the lowest marked level of the manometer. A sample of ordinary Portland cement of 2.80 g was prepared in a container. The perforated disk was placed inside the cell and pushed to the bottom of the cell. The filter paper was positioned into the cell to sit on top of the perforated disk. The cement sample was poured into the cell, and a filter paper was placed on top of the cement sample, using a plunger. The top surface of the manometer, where the cell should be placed, was lightly lubricated. The manometer’s valve and air pump were opened and the cell was placed on top of the former. The level of the liquid moved up after both the pump and the manometer’s valve were closed at the point in which the liquid level reached the highest marked level of the manometer, itself. The stopwatch was started as soon as the level of liquid started to fall down. The time between the second marked level from the top and the third marked level was recorded. The test also was repeated with 2.80 g peat ash sample and the specific surface of the cement sample is formulated in Eq. (5) (Das, 1989).

$$S = S_S \sqrt{T} \Big/ \sqrt{T_S} \tag{5}$$

Microstructure analysis

The microstructure of the stabilized soil with a binder composition of 18% OPC, 2% PA, and 5% SS was examined under Scanning Electron Microscopy (SEM) tests, for which a 10×5 mm^2 test specimen was cut from the compacted and stabilized soil. The SEM is a microscope that uses electrons instead of light to form an image. Since SEM utilizes vacuum conditions and electrons to form an image, special preparations must be done on the test sample. Therefore, the sample was prepared in dried condition as the presence of water would result in moisture vaporizing in the vacuum.

RESULTS AND DISCUSSION

Permeability Falling Head

Untreated soil

The permeability falling head test was applied on untreated soil specimen, 100 mm in diameter and 121 mm in height. The total duration for untreated clay from the beginning to the end was determined to be 10171 seconds. Figures 3 and 4 present the results of this test on untreated soil specimen. Figure 3 also shows the relationship between flow velocity at 20°C and hydraulic gradient, obtained from falling head test. By analyzing coefficient of determination (R^2), as shown in the Figure 3, it can be seen that the results are satisfactory because R^2 is almost close to 1. Likewise, Figure 4 illustrates the water flow versus time in total duration of 10171 seconds for untreated clay. Similarly, a study, conducted by Bahar et al. (2004) on stabilization of local clay with 20% cement, supports the present results. It has been found by Bahar et al. (2004) that the k_v value at 20°C of local clay is 19×10^{-8} ms^{-1}. Thus, such rate of permeability is very close to that, investigated in this paper. Such a small difference of k_v is due to the fact that the nature of clay of this study is different from the clay examined by Bahar et al. (2004). Besides, the similar behavior of Bangkok clay was found by Horpibulsuk et al. (2011). According to Horpibulsuk et al. (2011), the coefficient of permeability of Bangkok clay was determined about 10^{-7} to 10^{-8} cm/s.

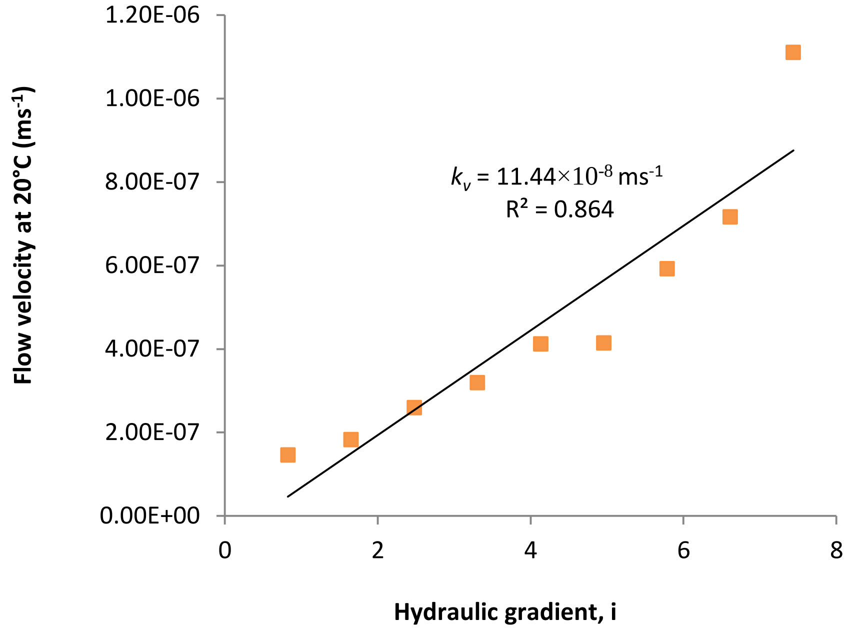

Fig. 3. Rate of permeability of the untreated clay

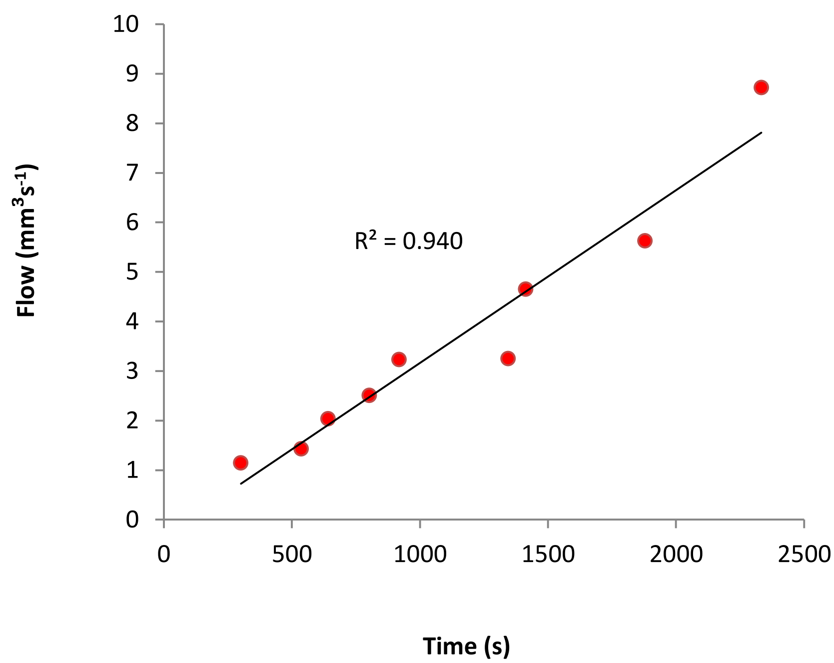

Fig. 4. Flow-time relationship of the untreated clay

Stabilized soil

The influence of cement, peat ash, and silica sand on coefficient of permeability of the compacted clay is shown in Figures 5 and 6. From Figure 5, it can be observed that the permeability of stabilized soil with binder composition of 13.5% OPC, 1.5% PA, and 20% SS was increased by almost 1.7-fold. This implies that adding more silica sand imposes more porous and less binding effect of the cement in the stabilized soil. As shown in Figure 5, the permeability of the soil specimen with binder composition of 18% OPC, 2% PA, and 5% SS decreased by almost 2.2-fold; because, cement as a binding agent and peat ash as a very fine material had filled the pore spaces of the stabilized soil and had reduced the voids by increasing inter-cluster cementation bonding. Therefore, low porosity of the stabilized clay specimen indicates low permeability, showing that the effect of water flow on the stabilized soil was reduced. On the other hand, the stabilized test specimen with 13.5% OPC, 1.5% PA, and 20% SS had increased the quantity of the flow. Figure 6 illustrates the relationships between flow and time. Here, it can be seen that the maximum value of the flow corresponds to the stabilized soil with the binder composition of 13.5% OPC, 1.5% PA, and 20% SS; moreover, in case of the falling head test, total test duration for the untreated clay was 10171 seconds; while, for the stabilized soil specimen with 13.5% OPC, 1.5% PA, and 20% SS, a period of 6026 seconds was determined, implying that adding 20% silica sand to the stabilized soil induced more porous and enhanced the ability of water flow as well as the permeability rate.

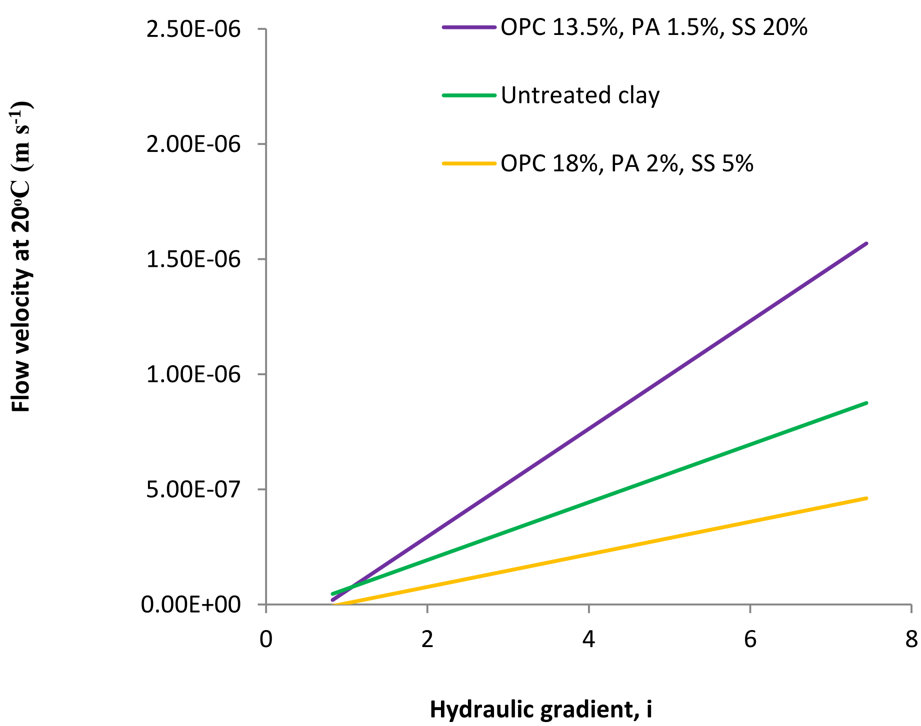

Fig. 5. Rate of permeability of the untreated and stabilized soil specimens

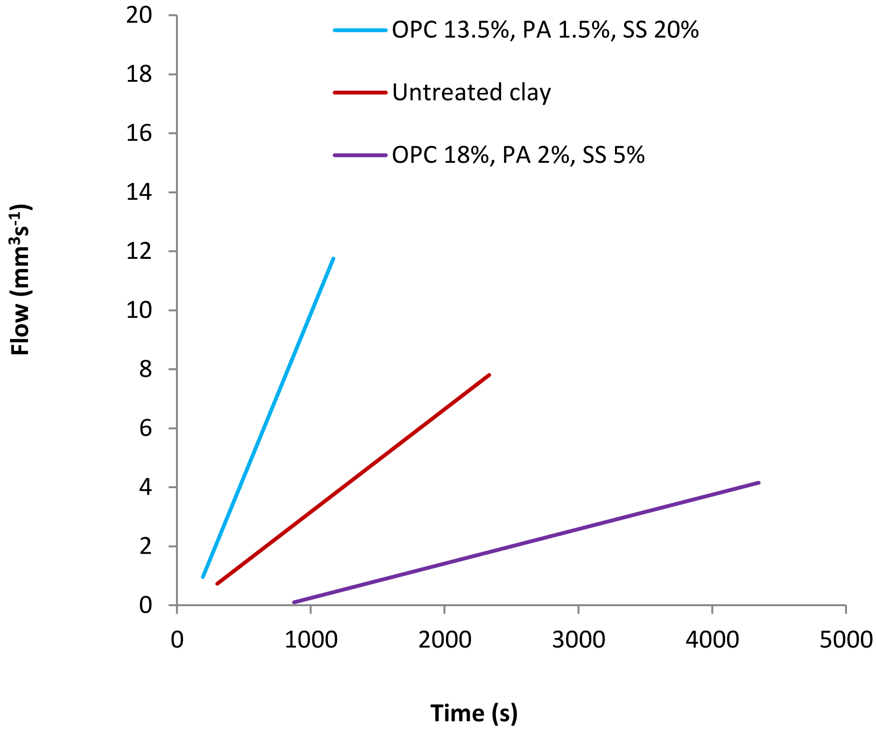

Fig. 6. Flow-time relationships of untreated and stabilized clay

Table 5 presents the average values of k_v of the soil specimens after 7, 14, 21, and 28-day curing. From Table 5, it can be observed that curing leads to an abrupt decrease in k_v for both untreated and stabilized soil specimens. The significant decrease in the quantity of flow during the test, and caused by cement, peat ash, and silica sand occurred when the cement with 2% peat ash was partially replaced after a 28-day curing. For the binder composition of 18% OPC, 2% PA, and 5% SS, the quantity of flow and total duration of the falling head test were determined 1.78 mm^3/s and 20834 seconds respectively. Therefore, the total elapsed time for the stabilized soil specimen with the binder composition of 18% OPC, 2% PA, and 5% SS is the highest. Indeed, the fineness of peat ash contributed to the refinement of pore spaces in the stabilized soil with 18% OPC, 2% PA, and 5% SS that further reduced its rate of water permeation. This can be attributed to the increase of cement content, probable importation of sufficient bonding of the cement due to the increased inter-cluster cementation bonding, decrease of the pore space and pore refinement by peat ash, and consequently less porous and permeability of the stabilized soil. On the other hand, the stabilized soil with a binder composition of 13.5% OPC, 1.5% PA, and 20% SS showed a rather spongy quality under falling head test, which can be attributed to the presence of 20% of silica sand, consisted of coarse particles that enhance the porosity of the soil specimen. However, after curing it also decreased the coefficient of permeability, which is due to the growth of cementation products over time. It has been proven by Bahar et al. (2004) that increasing the cement content in stabilized clay would decrease the coefficient of permeability while adding 20% cement would reduce the permeability from 19×10^{-8} to 10^{-9} m/s. The permeability results of both Bahar et al. (2004) and the present paper are in close agreement.

Table 5. k_v values determined by falling head tests after curing

Target Mix Design	Coefficient of Permeability After Curing (m/s)			
	7-day	**14-day**	**21-day**	**28-day**
Untreated Clay	6.37×10^{-8}	1.16×10^{-8}	10.71×10^{-9}	0.34×10^{-10}
18% OPC, 2% PA, 5% SS	0.12×10^{-8}	7.61×10^{-9}	2.25×10^{-9}	0.58×10^{-10}
13.5% OPC, 1.5% PA, 20% SS	14.21×10^{-8}	11.33×10^{-8}	7.55×10^{-8}	1.08×10^{-8}

One Dimensional (1D) Consolidation

Results of 1D consolidation test on untreated and stabilized soil specimens are given in Table 6. The compacted soil specimen at optimum water content and maximum dry density with a diameter of 50 mm and height of 20 mm were tested under effective vertical stresses that amounted to 2.5 kPa, 5 kPa, 10 kPa, 20 kPa, 40 kPa, 80 kPa, and 160 kPa. After analyzing Table 6, it can be seen that the coefficients of permeability of test specimens, formulated with various mix designs, varied due to various combinations of cement, peat ash, and silica sand. Similar to falling head test, the k_v value of the test specimen, corresponding to the stabilized soil with 18% OPC, 2% PA, and 5% SS under 1D consolidation test, also decreased drastically, which can be interpreted by the fact that adding cement promoted the formation of cementation products which decreased the porosity of the stabilized soil due to its binding actions. The low porosity of the stabilized clay resulted in its low permeability. In comparison to that of untreated soil specimen, it can be stated that the reduction in the rate of permeability of the stabilized soil, corresponding to the binder composition of 18% OPC, 2% PA, and 5% SS, is abrupt. Based on Table 6, an abrupt increase in the coefficient of permeability of the stabilized soil with 13.5% OPC, 1.5% PA, and 20% SS can be seen. This phenomenon occurs because 20% silica sand in stabilized soil takes up the spaces that would have been occupied by the soil particles. Such result and description of permeability of the stabilized soil with cement was reported by Horpibulsuk et al. (2011). Obviously, the results difference is due to different binder types and dosages.

Table 6. k_v values determined by 1D consolidation tests

Soil Composition	Average k_v (ms^{-1})
Untreated Soil	0.84×10^{-10}
Stabilized Soil with 13.5% OPC, 1.5% PA, 20% SS	11.74×10^{-9}
Stabilized Soil with 18% OPC, 2% PA, 5% SS	0.50×10^{-10}

The results of 1D consolidation tests of untreated and stabilized soil specimens are summarized in Table 7. To perform the recompression tests, each vertical load was held constant for 24 hours prior to the next loading increment. At the end of the loading period for 16 kg, the vertical load was removed and the specimen allowed to be swelled for 24 hours. The amount of consolidation settlement was estimated. It can be observed from Table 7 that a 1.14 mm compression settlement of the untreated soil has been reached by the clay under a consolidation stress of 160 kPa. Likewise, a 0.86 mm compression settlement of the stabilized soil happened under a consolidation stress of 160 kPa. The positive results imply that the binder composition of 18% OPC, 2% PA, and 5% SS improved the settlement by almost 33%.

The variation of k_v versus final void ratio (e) of untreated and stabilized soil specimens is shown in Figure 7. Both the coefficient of permeability (k_v) and the void ratio have increased. Besides, adding 20% silica sand is believed to cause the abrupt increase in void ratio and coefficient of permeability.

Table 7. Results of 1D consolidation tests

Test Specimen	Pressure (kPa)	Compression Settlement, S_c (mm)
Untreated Soil	0	0
	2.5	0.035
	5	0.094
	10	0.175
	20	0.234
	40	0.316
	80	0.526
	40	0.414
	20	0.256
	10	0.202
	5	0.136
	2.5	0.068
	5	0.112
	10	0.188
	20	0.254
	40	0.342
	80	0.526
	160	1.136
Stabilized Soil with 18% OPC, 2% PA, 5% SS	0	0
	2.5	0.038
	5	0.074
	10	0.144
	20	0.196
	40	0.294
	80	0.474
	40	0.418
	20	0.232
	10	0.184
	5	0.110
	2.5	0.054
	5	0.088
	10	0.172
	20	0.226
	40	0.324
	80	0.508
	160	0.857

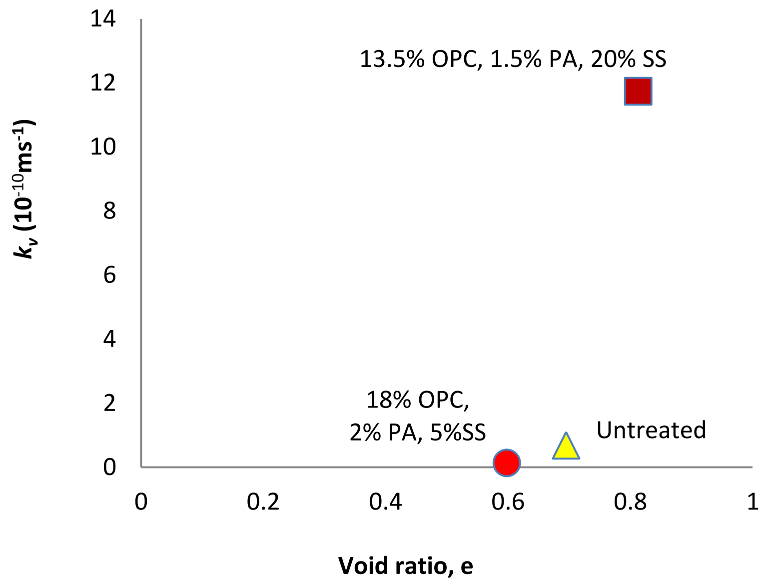

Fig. 7. Permeability-void ratio relationships under 1D consolidation tests

Table 8 offers a brief comparison of the results from the laboratory falling head and 1D consolidation tests. Based on this table, in both falling head and 1D consolidation tests a similar behavior of hydraulic conductivity could be observed. The difference between these results is due to different tests and methods. It is noticeable that the falling head test was conducted after 24 h of stabilization, while during the 1D consolidation tests (each vertical load was held constant for 24 h) more cementation crystals were formed and the soil matrix improved further.

Fineness of Materials

The results of fineness test are given in Table 9, which shows that specific surface of the peat ash particles is greater than that of OPC. Based on ASTM C204-11, the hydration rate depends on the fineness of the cement particles. High fineness is necessary to achieve rapid strength development. Based on Table 9, the fineness of peat ash particles is higher than OPC; therefore, peat ash has filled up the pore spaces of the stabilized soil and due to its filler effect the matrix of the soil has improved.

Scanning Electron Micrographs (SEM) of Stabilized Soil

The SEMs of stabilized soil with a binder composition of 18% OPC, 2% PA, and 5% SS are shown in Figures 8 and 9. It can be identified from the micrographs that the pore spaces of stabilized soil were clogged by cementation products as a consequence of adding cement and peat ash. Figure 9 shows the evidence of a cementation crystal that functioned by binding the soil particles together. It is shown in the both figures that the stabilized soil was characterized by a well-cemented soil matrix with very small pore spaces. This is due to the hydration reaction of cement and fineness of peat ash in stabilized soil. Similar microscopic photos on stabilized soil with cementation crystals can be observed in the study of Horpibulsuk et al. 2011, which analyzed microstructures of Bangkok clay, stabilized with cement, fly ash, and biomass ash, showing that the pores of the stabilized soil were filled up with cementation crystals as a result of the binding mechanism of the materials.

Table 8. Comparison of the coefficient of permeability of the test specimens

Binder Composition	Coefficient of permeability (ms^{-1})	
	Falling Head	**1D Consolidation**
13.5% OPC, 1.5% PA, 20% SS	19.35×10^{-8}	11.74×10^{-9}
Untreated Soil	11.44×10^{-8}	0.84×10^{-10}
18% OPC, 2% PA, 5% SS	5.24×10^{-8}	0.50×10^{-10}

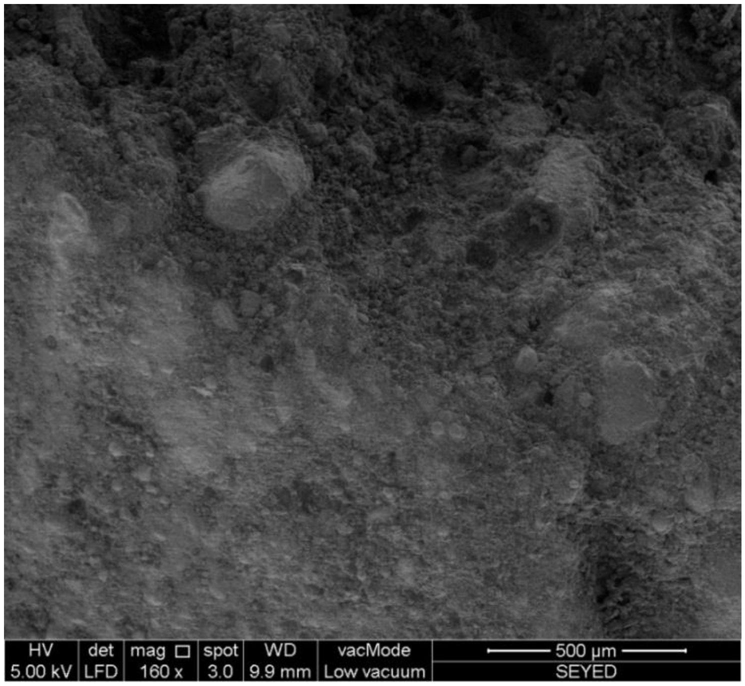

Fig. 8. SEM micrographs taken from the surface of the stabilized soil specimen with a binder composition of 18% OPC, 2% PA, and 5% SS (Mousavi and Wong, 2015)

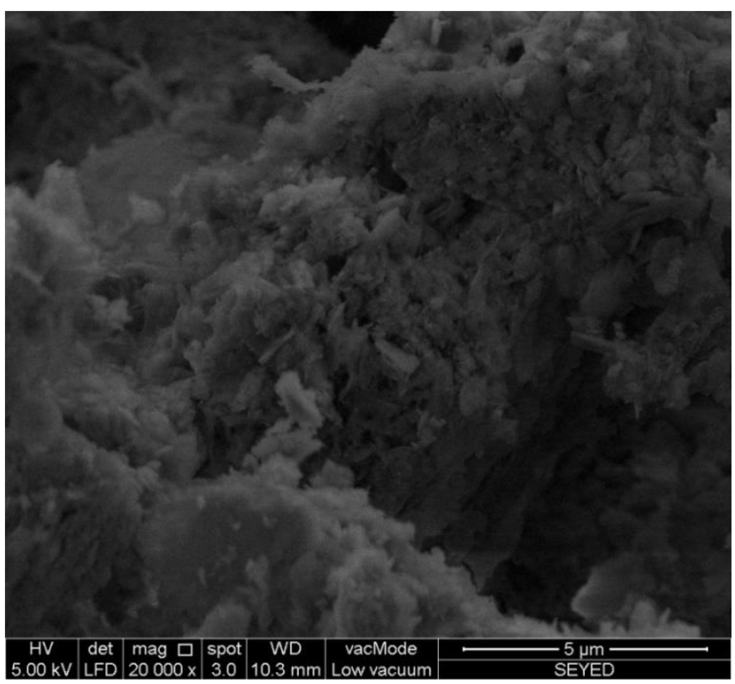

Fig. 9. Cementation crystals of the stabilized soil specimen with 18% OPC, 2% PA, and 5% SS after 24 h

Table 9. Results of fineness of particles test

Material	Specific Surface of the Particles (cm^2/g)
Ordinary Portland Cement	3865
Peat Ash	6392

CONCLUSIONS

Standard Proctor Compaction Test was applied on untreated and stabilized soil specimens. The test specimens which had the highest MDD were chosen to apply permeability falling head and 1D consolidation tests. The following conclusions can be drawn from this research:

i) The stabilized soil specimen with the binder composition of 13.5% OPC, 1.5% PA, and 20% SS drastically increased the coefficient of permeability. However, after curing, the k_v values decreased.

ii) The stabilized soil with partial replacement of cement with 2% peat ash decreased the coefficient of permeability under both falling head and 1D consolidation tests.

iii) Having compared the moisture contents of stabilized soil with binder compositions of 18% OPC, 2% PA, and 5% SS on one hand, and 8% OPC, 2% PA, and 5% SS on the other, it was revealed that at lower water contents, the available free water in the mixtures was not sufficient to promote hydration reaction of cement with water. Furthermore, as the water content increased up to the optimal level, compaction coupled with hydration effect contributed to the hardening of the improved soil.

iv) Peat ash due to its filler and pozzolanic effects, as evident in chemical composition and fineness of peat ash test, filled the pore spaces, reducing the porosity and improving the matrix of the soil.

v) It can be identified from the micrographs that the pore spaces of stabilized soil were clogged by cementation products as a result of cement and peat ash additions. Also the stabilized soil was characterized by a well-cemented soil matrix with very small pore spaces.

vi) Based on the results, soil stabilized with a binder composition of 18% OPC, 2% PA, and 5% SS was chosen as the ideal mix design. The partial replacement of cement with the 2% peat ash can reduce the consumption of cement when stabilizing the soil.

ACKNOWLEDGMENTS

The authors wish to express their sincere thanks to Universiti Tenaga Nasional (UNITEN) for providing facilities and equipment to carry out this research.

REFERENCES

Abdi, M.R. and Parsa Pajouh, A. (2009). "Use of bentonite and lime for decreasing the permeability of liner and cover in landfills", *Civil Engineering Infrastructures Journal*, 43(1), 61-70.

ASTM D5084-03. (2003), *Standard test methods for measurement of hydraulic conductivity of saturated porous materials*, American Society of Testing and Materials, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

ASTM D2435. (2003), *ASTM D2435, Standard test method for one-dimensional consolidation properties of soils using incremental loading*, American Society of Testing and Materials, Annual Book of ASTM Standards, Philadelphia, 04.08, pp. 1-10.

ASTM C204-11. (2014), *Standard test methods for fineness of hydraulic cement by air permeability apparatus*, American Society of Testing and Materials, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

ASTM D698. (2012), *Standard test methods for laboratory compaction characteristics of soil using standard effort*, American Society of Testing and Materials, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

ASTM D2974-14. (2014), *Standard test methods for moisture, ash, and organic matter of peat and other organic soils*, American Society of Testing and Materials, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

Bujang, B.K.H., Kazemian, S., Prasad, A. and Barghchi, M. (2011). "State of an art review of peat: General perspective", *International Journal of the Physical Sciences*, 6(8), 1988-1996.

Bazargan, J. and Shoaei, S.M. (2010). "Analysis of non-darcy flow in rock fill materials using gradually varied flow method", *Civil Engineering Infrastructures Journal*, 44(2), 131-139.

Bahar, R., Benazzoug, M. and Kenai, S. (2004). "Performance of compacted cement-stabilised soil", *Cement and Concrete Composites*, 26(7), 811-820.

Das, B.M. (1989). *Soil mechanic laboratory manual*, 6th Edition, Hardcover, Oxford.

Ghasemzadeh, H. and Abounouri, A.A. (2013). "The effect of dynamic permeability on velocity and intrinsic attenuation of compressional waves in sand", *Civil Engineering Infrastructures Journal*, 46(2), 221-231.

Goodary, R., Lecomte-Nana, G.L., Petit, C. and Smith., D.S. (2012). "Investigation of the strength development in cement-stabilised soils of volcanic origin", *Construction and Building Materials*, 28(1), 592-598.

Hossain, K.M.A. and Mol, L. (2011). "Some engineering properties of stabilized clayey soils incorporating natural pozzolans and industrial wastes", *Construction and Building Materials*, 25(8), 3495-3501.

Horpibulusk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y. and Suddeepong, A. (2010). "Analysis of strength development in cement-stabilized silty clay from micro structural considerations", *Construction and Building Materials*, 24(10), 2011-2021.

Horpibulsuk, S., Phojan, W., Suddeepong, A., Chinkulkijniwat, A. and Liu Martin, D. (2012). "Strength development in blended cement admixed saline clay", *Applied Clay Science*, 55, 44-52.

Horpibulsuk, S., Rachan, R. and Suddeepong, A. (2011). "Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite", *Applied Clay Science*, 52(1-2), 150-159.

Kowalski, T.E., Dale, W. and Starry, Jr. (2007). "Modern soil stabilization techniques", *Annual Conference of the Transportation Association of Canada, Saskatoon, Saskatchewan, October*, pp. 14-17.

Mahasenan, N., Steve, S., Kenneth, H. and Kaya, Y. (2003). "The cement industry and global climate change: Current and potential future cement industry CO_2 emissions", *Greenhouse Gas Control Technologies, 6th International Conference*, Oxford, Pergamon, pp. 995-1000.

Mousavi, S.E. and Wong, L.S. (2015). "Performance of compacted and stabilized clay with cement, peat ash and silica sand", *Jordan Journal of Civil Engineering*, 9(1), 20-32.

Wong, L.S., Hashim, R. and Ali, F. (2013). "Utilization of sodium bentonite to maximize the filler and pozzolanic effects of stabilized peat", *Engineering Geology*, 152(1), 56-66.

Yilmaz, Y. and Ozaydin, V. (2013). "Compaction and shear strength characteristics of colemanite ore waste modified active belite cement stabilized high plasticity soils", *Engineering Geology*,155, 45-53.