Bull Eng Geol Environ (2014) 73:733–746
DOI 10.1007/s10064-013-0549-5

ORIGINAL PAPER

A review of the stabilization of tropical lowland peats

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Received: 30 August 2013 / Accepted: 5 November 2013 / Published online: 24 November 2013

Abstract The Deep Mixing Method, which involves the formation of in situ stabilized peat columns, is suitable for deep peat stabilization, whereas the mass stabilization technique is used to stabilize the soil of shallow peat deposits instead of the costly and problematic removal and replacement method. The concept of soil-cement stabilization involves the addition of water to cement, resulting in a chemical process known as cement hydration. Stabilization of peat by cement, which requires a significant strength increase in the cement-stabilized peat or organic soil, is attributed largely to physicochemical reactions that include cement hydration, hardening of the resulting cement paste and interactions between soil substances and primary and secondary cementation hydration products. The factors that affect these physicochemical reactions and the interactions of peat soil-cementation products that influence peat stabilization are the amount of solid particles, the water: soil ratio, the quantity of binder, the presence of humic and/or fulvic acids, the soil pH and the amount of organic matter in the peat. With the Air Curing Technique, stabilized peat samples for unconfined compressive strength (UCS) tests were kept at a normal air temperature of 30 ± 2 °C and strengthened by gradual moisture content reduction instead of the usual water-curing technique or water submersion methods that have been common practice in past experiments involving the stabilization of peat with cement. The principle of using the Air Curing Technique to strengthen stabilized peat is that peat soil at its natural moisture content contains sufficient water (water content from 198 to 417 %) that, when mixed with cement, a curing process takes place that causes the stabilized peat soil to gradually lose its moisture content and to become drier and harder throughout the curing period. This process does not require the addition of water.

Keywords Peat stabilization · Dry-curing technique · Tropical lowland peats · Sand filler · Clay pozzolan · Tobomerite gel

Résumé Méthode de mixage profond (DMM), ce qui implique la formation de colonnes in-situ stabilisées tourbe, est approprié pour la stabilisation de la tourbe profonde, alors que la technique de stabilisation de masse est utilisé pour stabiliser le sol de dépôts de tourbe peu profonds au lieu de l' enlèvement et le remplacement coûteux et problématique Procédé. La notion de stabilisation sol-ciment implique l'addition d'eau à du ciment, ce qui entraîne un processus chimique connu sous l'hydratation du ciment. La stabilisation de la tourbe par du ciment, ce qui nécessite une augmentation de la résistance significative de la tourbe stabilisée au ciment ou du sol organique, est attribuée en grande partie à des réactions physico-chimiques qui comprennent l'hydratation du ciment, le durcissement de la pâte de ciment obtenue et les interactions entre les substances du sol et de l'hydratation de la cimentation primaire et secondaire produits. Les facteurs qui influent sur ces réactions physico-chimiques et les interactions des produits de tourbe du sol

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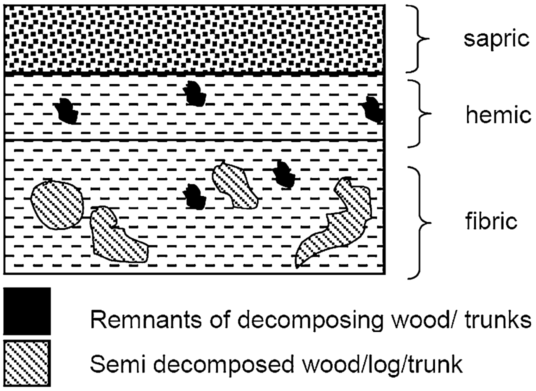


Fig. 1 Profile morphology of drained peat soil (from Muttalib et al. 1991)

cimentation qui influencent la tourbe stabilisation sont la quantité de particules solides, le rapport eau du sol, la quantité de liant, la présence d'acides humiques et / ou des acides fulviques, le sol le pH et la quantité de matière organique dans la tourbe. Avec l' Air Durcissement Technique, stabilisé échantillons de tourbe pour les tests UCS ont été maintenus à une température de l'air normal de 30 ± 2 ° C et renforcé par la réduction progressive de la teneur en humidité au lieu de la technique de watercuring habituel ou méthodes submersion d'eau qui ont été de pratique courante dans les expériences antérieures concernant la stabilisation de la tourbe avec du ciment. Le principe de l'utilisation de la technique de durcissement à l'air à renforcer stabilisé tourbe est que la tourbe sol à sa teneur naturelle en eau contient suffisamment d'eau (teneur en eau de 198 % à 417 %) qui, lorsqu'il est mélangé avec le ciment, un procédé de durcissement a lieu qui provoque l' stabilisée tourbe sol à perdre progressivement son taux d'humidité et de devenir plus sèche et plus dure pendant toute la période de durcissement. Ce procédé ne nécessite pas l'addition d'eau.

Mots clés Peat stabilisation · la technique de séchage à sec · Peats tropicales de basse altitude · remplissage de sable · d'argile pouzzolane · Tobomerite Gel

Introduction

Peats, as we now know, are formed by the limited decomposition and accumulation of organic soil materials. These organic materials can further consist of undecomposed, partially decomposed and highly decomposed plant remains. Tropical lowland peats usually contain undecomposed and partly decomposed branches, logs and twigs (Fig. 1). Due to their domed shape, tropical lowland peats form a fragile ecosystem and are almost purely organic (Paramananthan 1998, 2010). Tropical lowland soils, which typically have mean annual soil temperatures greater than 22 °C with monthly variations of less than 5 °C, have an isohyperthermic or a warm soil temperature regime and a common elevation of less than 750 m (2,500 feet) (Paramananthan 2010). According to Paramananthan (2010), lowland organic soils are soils in which the thickness of the organic soil layers makes up more than half the soil to a depth of 100 cm (or shallower if rocks or parent materials occur at less than 100 cm depth). Lowland organic soils are subdivided based on the thickness of their organic soil layers. Lowland organic soils, including peat and histosol soils, are subdivided into ombrogambists or deep organic soils that are more than 150 cm thick and topogambists or moderately deep and shallow organic soils that are 50 to 150 cm thick.

Soil improvement in peat

Peat is an extreme form of soft soil and is subject to instability and massive primary and long-term settlement when subjected to load increases during construction work (Huat 2004). Access to peat sites can be difficult and sometimes impossible, especially in swampy, waterlogged peat areas, leading to difficulties in sampling peat for laboratory tests. Tests involving peat also often result in large variations in peat index properties.

Although buildings constructed on peat are usually suspended on piles driven into underlying mineral soil and bedrock, the soft ground around such buildings may still settle, resulting in cracks in pavement and driveways and broken drains around the building structure. Settling of roads built on peat ground may result in bulging and tilting of houses situated near or alongside the roads (Huat 2004). Due to problems with settlement, the difficulty of construction on peat ground and the inevitable high building and maintenance costs involved, engineers and developers tend to avoid building on problematic peat ground. However, due to the scarcity and sometimes the unavailability of suitable construction ground, this is not always possible, especially in coastal lowland areas where there is often high pressure for land development. Hence, peat land development is becoming more and more unavoidable. Because of this problem, ground improvement methods are now being developed for tropical lowland peats.

According to Edil (2003), and Kazemian et al. (2011), the following current construction methods are suitable for use on peat ground:

1. Avoidance: consider avoidance of peat lands, if possible.
2. Excavation-displacement/replacement: practical in peats that are up to 5 meters in peat depth.

3. Ground improvement and/or reinforcement for enhancement of soil strength and stiffness:
    (a) Stage construction and preloading: This method is used to overcome problems of instability in fills constructed over weak deposits such as peat ground. Although it is time-consuming, it can be accelerated by the construction and use of vertical wick drains, and geosynthetic reinforcement can be used to enhance stability. Placement of loads on the surface or vacuum consolidation can be used to achieve loading.
    (b) Deep in situ mixing (lime-cement columns): This method involves forced mixing of lime, cement, or both with soft mineral soil deposits to form stabilized soil columns. This method of peat stabilization is still being developed.
    (c) Stone columns: Compacted gravel is used to fill water-jetted holes in soft ground.
    (d) Piles: Piling is an expensive but reliable solution for building foundations with suspended floors and for creating embankment supports.
    (e) Thermal precompression: In this method, the ground is moderately heated (15–25 °C) to accelerate settlement and reduce long-term compression upon cooling. This method has been field-tested but has not yet been applied commercially.
    (f) Preload piers (Geopiers): This method, which is currently being developed, involves packing stones in dense layers in a hole to allow radial pre-compression in the ground.
4. Reduction of driving forces by the use of light-weight fill: Light but sufficiently strong and stiff materials such as woodchips, sawdust, tire chips, geofoam and expanded shale are used as fill.

The deep in situ mixing (lime-cement columns) method is a deep stabilization technique that has been popularly used in Sweden and Finland to strengthen soft soils such as silt and clay using cement or lime mixes or pure cement. The increase in strength obtained using this method was reported to be as high as 30-fold. However, strength gain in peats may not be as high due to the high water content and low strength of peat soils, and it is further inhibited by the high organic content of peats (Huat 2004). With the addition of sufficient stabilizers and the use of appropriate binders, soil stabilization by suitable chemical admixture results in increments in shear strength and bearing capacity, reductions in permeability and compressibility, and improvement in the swelling characteristics of soft soils.

The Deep Mixing Method (DMM) is suitable for deep peat stabilization (Axelsson et al. 2002; Janz and Johansson 2002; Wong 2010). In DMM, columnar soil reinforcement is used in the form of in situ stabilized peat columns constructed by a deep mixing rig. The rig mixes the injected binder with peat soil, dispersing the binder into the soil to provide conditions that permit the binder's chemical reaction to take place (Larsson 2003). The DMM technique involves mechanically mixing binder and soil or peat with a mixing head equipped with a nozzle for binder feeding. The mixing tool is connected to the rotating Kelly of the rig (EuroSoilStab 2002). The formation of stabilized peat columns by the dry method of deep peat stabilization usually begins by driving the rotating shaft and mixing tool to the desired depth and is followed by simultaneous lifting of the mixing tool while feeding the binder into the peat ground.

For shallow peat deposits, the mass stabilization technique is often used to stabilize the soil instead of the removal and replacement method, which is costly and problematic in terms of transportation and disposal of the replaced unsuitable soil (Axelsson et al. 2002). The mass stabilization method is a soil reinforcement technique in which the entire soil layer is blended with stabilizing binders, resulting in a stabilized "block" of the shallow peat layer (Axelsson et al. 2002). The machines used for mass stabilization are essentially excavators that are installed and modified using mass stabilization mixers. The binder is fed into the mixing head while the mixer simultaneously rotates and moves vertically and horizontally (EuroSoilStab 2002).

The concept of soil-cement stabilization involves the addition of water to cement, resulting in a chemical process known as cement hydration. This process occurs when the pore water or ground water in soil interacts with ordinary Portland cement to form a cement paste containing primary cementation products that harden to create a system of interlocking crystals that bind the material together, thus stabilizing the peat soil.

Stabilization of peat by cement results in a significant increase in the strength of the cement-stabilized peat/organic soil. Peat stabilization by cement is attributed largely to physicochemical reactions, which include cement hydration, hardening of the resulting cement paste and interactions between soil substances and primary and secondary cementation hydration products.

Concept of soil-cement stabilization

The addition of water to cement results in the occurrence of a chemical process known as hydration. Hydration of cement occurs when pore water or ground water in soil interacts with ordinary Portland cement to form primary cementation products that include hydrated calcium

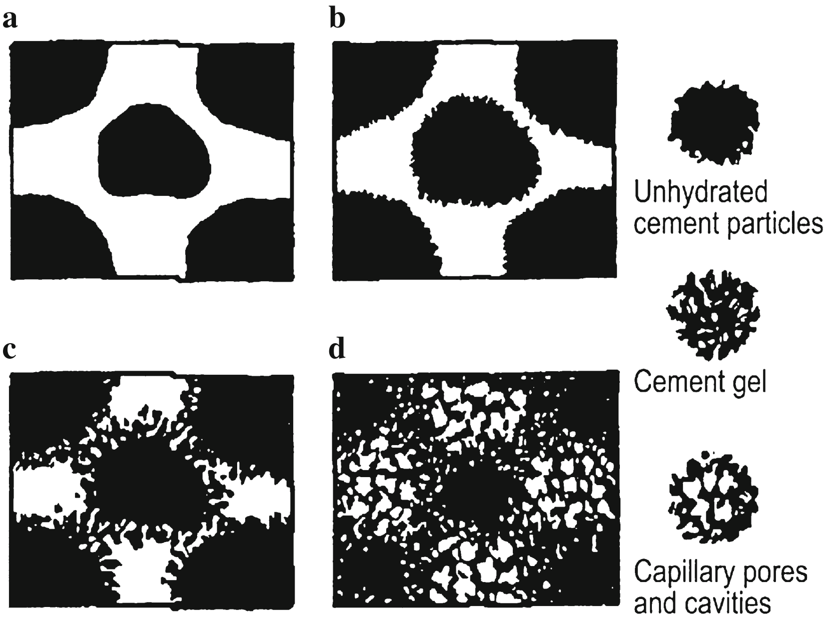


Fig. 2 Structure of cement paste, mix and cement gel (from Fagerlund 1994, in Janz and Johansson 2002). **a** Structure of cement paste or mix immediately after mixing. **b** Structure of cement paste or mix after a few minutes. **c** Structure of cement paste or mix upon setting. **d** Structure of cement paste or mix after some months

silicates (C3S2H4), ettringite (C6AS3H32), monosulfate (C4ASH12), and hydrated lime (CH) (Janz and Johansson 2002; Wong 2010). During hydration, a cement paste is produced that hardens to create a system of interlocking crystals that weave the material together (Elbadri 1998). During hydration of a cement particle, an extremely fine-pored cement gel also known as tobermorite or C–S–H gel is formed around the cement particle (Janz and Johansson 2002). The binding agent that acts as a stabilizer is not the cement itself but instead is the mixture of cement and water that forms the cement gel (Elbadri 1998). The cement gel, which includes C–S–H gel, ettringite and monosulfate (Janz and Johansson 2002; Wong 2010), gradually fills the void spaces between the cement and the soil particles during the hydration reaction of water and cement in the soil (Fig. 2). Because the hardening cement gel is porous and contains chemically combined water (water of crystallization), the volume of the hardened cement paste will be greater than that of the cement particles prior to reaction, and the paste will set, harden and grow denser and stronger with time (Janz and Johansson 2002). The cement gel acts as a binder between adjacent cement grains to form a hardened skeleton or matrix that encloses the unaltered soil particles and stabilizes the soil (Bergado et al. 1996). This hardening soil-cement paste would eventually grow denser and stronger with time. If the binder is insufficient or is not well dispersed into the soil or if there is a high water-cement ratio, the cement particles may be widely separated from each other, resulting in high porosity and low strength of the soil-cement paste.

The presence of a high water-cement ratio means that more water is present for hydration, resulting in a higher porosity and lower strength of the hardened soil-cement paste. According to Janz and Johansson (2002), the strength of the hardened cement paste depends largely on its porosity and on the separation between particles. Wider separation between particles results in higher porosity and lower strength. The water:cement ratio, *wcr*, gives a measure of the cement content and, hence, of the separation between particles (Janz and Johansson 2002). A high *wcr* implies wider separation between cement particles, higher porosity, and lower strength.

$$wcr = W/C,$$

where W is the weight of mixing water [kg] and C is the weight of cement [kg].

In the cement paste, the four clinker minerals that act as major strength-enhancing compounds are tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminate ferrite (Ferrit) (Table 1). The oxide

Table 1 Clinker minerals acting as major strength-enhancing compounds of ordinary Portland cement (Janz and Johansson 2002)

Name	Chemical formula[a]	Abbreviation
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S
Dicalcium silicate	$2CaO \cdot SiO_2$	C_2S
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium aluminate ferrite (Ferrit)	$4CaO \cdot Al_2O_3{\cdot}Fe_2O_3$	C_4AF[b]

[a] Although, e.g., tricalcium silicate is written as $3CaO \cdot SiO_2$, it does not imply that the oxides are present individually

[b] Although the composition of tetracalcium aluminate ferrite ranges between C_6A_2F and C_6AF, the average composition is close to C_4AF

components of cement are conveniently represented by simplified notations such as $CaO = C$, $SiO_2 = S$, $Al_2O_3 = A$, $Fe_2O_3 = F$, $SO_3 = S$, $MgO = M$ and $H_2O = H$ (Janz and Johansson 2002; Wong 2010).

According to Bergado et al. (1996), the chemistry of the transformation of ordinary Portland cement into cement paste with the addition of water is as follows:

$$\underset{\text{(tricalcium silicate)}}{2(3CaO \cdot SiO_2)} + \underset{\text{(water)}}{6H_2O} = \underset{\text{(tobermorite gel=primary cementation product)}}{3CaO \cdot 2SiO_2 \cdot 3H_2O} + \underset{\text{(calcium hydroxide)}}{3Ca(OH)_2}, \tag{2.1}$$

$$\underset{\text{(bicalcium silicate)}}{2(2CaO \cdot SiO_2)} + \underset{\text{(water)}}{6H_2O} = \underset{\text{(tobermorite gel = primary cementation product)}}{3CaO \cdot 2SiO_2 \cdot 3H_2O} + \underset{\text{(calcium hydroxide)}}{3Ca(OH)_2}, \tag{2.2}$$

$$\underset{\text{(tetracalcium alumino ferrite)}}{4CaO \cdot Al_2O_3 \cdot Fe_2O_3} + 10H_2O + 2Ca(OH)_2 = \underset{\text{(calcium alumino ferrite hydrate)}}{6CaO \cdot Al_2O_3 \cdot Fe_2O_3 \cdot 12H_2O}, \tag{2.3}$$

$$\underset{\text{(tricalcium aluminate)}}{3CaO \cdot Al_2O_3} + 12H_2O + Ca(OH)_2 = \underset{\text{(calcium alumino ferrite hydrate)}}{3CaO \cdot Al_2O_3 \cdot Ca\ (OH)_2 \cdot 12H_2O}, \tag{2.4}$$

$$\underset{\text{(tricalcium aluminate)}}{3CaO \cdot Al_2O_3} + 10H_2O + \underset{\text{(gypsum)}}{CaSO_4 \cdot 2H_2O} = \underset{\text{(calcium monosulfoaluminate)}}{3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O}. \tag{2.5}$$

Calcium silicates form 75 % of ordinary Portland cement. Equations 2.1 and 2.2 indicate that the hydration reactions of tricalcium silicate and bicalcium silicate produce two new compounds, lime and tobermorite gel. Tobermorite gel is also known as 'primary cementation product', C–S–H gel or hydrated gel. The bonding strength and variation in the volume of the soil-cement mixture are governed by tobermorite gel (Bergado et al. 1996; Janz and Johansson 2002; Wong 2010).

When the clinker mineral tricalcium silicate, C3S, is mixed with water, hydroxide ions are formed and calcium ions are rapidly released into solution, causing the pH to rise above 12 within a few minutes. When the concentration of calcium and hydroxide ions reaches a certain threshold, calcium hydroxide $Ca(OH)_2$ crystallizes out of solution, while a layer of calcium silicate hydrate gel (CSH) or tobermorite gel forms on the surface of the C3S particles. As the CSH layer grows, it forms a 'barrier' that the water must penetrate to reach the unhydrated C3S and through which ions must diffuse for further hydration reactions to occur. The hydration reaction is now diffusion-controlled, whereas the initial hydration rate was temperature-dependent. Thus, the temperature dependency of the reaction lessens after the reaction becomes diffusion-controlled (Janz and Johansson 2002). The hydration reaction of dicalcium silicate, C2S, is similar but occurs more slowly due to the lower reactivity of C2S.

The reactions of tricalcium silicate, C_3S, and dicalcium silicate, C_2S, are

$$2C_3S\ +\ 7H\ C_3S_2H_4 + 3CH, \tag{2.6}$$

$$2C_2S\ +\ 5H\ C_3S_2H_4 +\ CH, \tag{2.7}$$

where $C_3S_2H_4$ is the CSH gel (Janz and Johansson 2002).

Hydrous silica and alumina are produced from reactions of base with acidic soil silica and alumina to form hydrous silica and alumina. Secondary pozzolanic reactions occur when secondary cementation products or insoluble compounds are produced by reaction of hydrous silica and alumina with calcium ions resulting from cement hydrolysis. The secondary cementation products harden upon curing and stabilize the soil. In addition, further strength is acquired by the solution of soil silicates and aluminates. The bonding strength of the primary cementation product (tobermorite gel) is much greater than that of the secondary cementation products (Bergado et al. 1996).

Stabilization of peat by cement

Organic soils can retard or prevent the hydration of chemical binders such as cement in binder-soil mixtures (Hebib and Farrel 2003). The high organic content and significantly lower amounts of solid particles in peat (e.g., ombrogenic peats have very high organic content and, hence, very low ash values) make cement alone insufficient to provide desirable stabilization strength in peat ground improvement. Mud and peats have fewer solids to stabilize compared to mineral soils such as silt or clay; hence, more stabilizer is needed to bind the solid particles in mud and peats together (Janz and Johansson 2002). Furthermore, compared to clay or silt, peat has a considerably lower content of solid clay particles that can enter into secondary pozzolanic reactions (Janz and Johansson 2002; Wong 2010). Therefore, often no significant strength gain is achieved from the use of cement binder alone in peat stabilization unless cement is added to the soil in large and uneconomical amounts.

Ahnberg et al. (1995) showed that cement-stabilized peat alone and cement-stabilized peat with high water-to-cement ratios achieved lower shear strength compared to cement stabilized mud, silty clay, clayey silt and other types of soil. The high water: soil ratio of peats gives a high water-to-cement ratio, resulting in lower stabilization strength. The increase in the *wcr* ratio means that more stabilizer must be added to achieve an equivalent increase in strength (Janz and Johansson 2002).

Axelsson et al. (2002) stated that there are indications that soils with high organic content, such as peats, show a

Table 2 Stabilized strength enhancement reactions of cement and pozzolan (Janz and Johansson 2002)

Binder	CaO/SiO_2	Reaction	Co reagents	Time scale
Cement	Approximately 3	Hydraulic	Water	Days (relatively rapid)
Pozzolan	Approximately 0	Pozzolanic	Water + $Ca(OH)_2$ from cement	Weeks

threshold effect whereby the quantity of binder used must exceed a certain threshold before any stabilization is obtained. This 'threshold effect' may occur because a sufficient amount of binder must be added to neutralize the humic acids in peats.

It was concluded by Chen and Wang (2006) that the higher amounts of organic matter and the lower amounts of solid particles present in peat tend to impede the hydration of cement used in peat stabilization. This impediment to the cementation and hardening of the peat-cement admixture is due to the presence in peat of black humic acid and fulvic acid. Humic substances, which include humic acid, fulvic acid, and humin, are the major components of the organic matter in peat. Black humic acid reacts strongly with calcium liberated from cement hydrolysis to form insoluble calcium humic acid (Chen and Wang 2006; Wong et al. 2009). The strong affinity of humic acid for calcium retards calcium crystallization, thus impeding the increase in peat soil-cement mixture strength.

Fulvic acid in peat tends to associate with mineral particles containing aluminum, leading to the destruction or decomposition of the layered crystal lattice within the peat soil-cement mixture. The chemical interactions that occur after the initial hydration between fulvic acid and the cement minerals may also result in the production of an absorbed layer that impedes further hydration of the cement. In addition, fulvic acid may decompose calcium aluminate hydrate, calcium sulfate-aluminate hydrate and calcium ferrite-aluminate hydrate crystals, further preventing the formation of the soil-cement structure (Chen and Wang; Wong 2010).

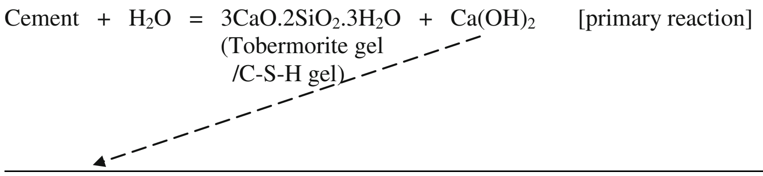
The organic acids present in peat may cause the soil pH to drop, decreasing the reaction rate of hydration of the cement binder and resulting in a slower strength gain in peat (Axelsson et al. 2002; Wong 2010). Unless a large (and most likely uneconomical) quantity of cement is mixed with the soil for stabilization, the mixture of organic acids, soil and cement produces a pH lower than 9 in the pore solution, which is too low to permit secondary mineral or secondary cementation product formation and, thus, retards the stabilization effect (Tremblay et al. 2002; Wong 2010).

Based on the above evidence, it is clear that the significant strength increase that occurs in cement-stabilized peat or organic soil is attributable largely to specific physicochemical reactions, including the hydration and hardening of cement paste and the interaction between soil substances and primary and secondary cementation hydration products.

According to Chen and Wang (2006), the large amount of organic matter present in peat gives the peat a high water retention capacity and a high natural moisture content that cause organic particles to adsorb to the surface of the cement and to the surfaces of solid mineral soil particles, thereby preventing the formation of cement hydration products and inhibiting hydration reactions between solid soil particles and hydration products. This results in a limited increment in peat-cement admixture strength.

Effect of clay particles as pozzolan and secondary additives on peat stabilization

Small amounts of pozzolans such as kaolinite can be added to cement-stabilized peats to enhance the secondary pozzolanic reaction in the stabilized soil. The reactivity of cement and pozzolan with water in the soil during peat stabilization is dependent on the ratio of lime to silica ($CaO:SiO_2$). A higher lime-to-silica ratio means that the material is more hydraulic (Janz and Johansson 2002). From Table 2, it can be seen that cement and pozzolan have calcium-to-silica ratios of approximately 3 and 0, respectively. The relatively high calcium-to-silica ratio of cement is indicative of the fact that cement is a hydraulic material that upon reaction with water initially increases rapidly in strength followed by a secondary pozzolanic reaction. However, the almost zero calcium-to-silica ratio of pozzolans such as kaolinite or kaolinic clay shows that these materials are pozzolanic materials that react



$$\text{Cement} + H_2O = \underset{\substack{\text{(Tobermorite gel}\\ \text{/C-S-H gel)}}}{3CaO.2SiO_2.3H_2O} + Ca(OH)_2 \quad \text{[primary reaction]} \tag{2.8}$$

with water when activated by calcium hydroxide resulting from cement hydration (Janz and Johansson 2002).

$$\begin{aligned} &\mathrm{Ca(OH)_2} + \underset{\mathrm{(Kaolinitic clay)}}{\mathrm{Pozzolan}} + \mathrm{H_2O} \\ &= \underset{\mathrm{(Tobermorite gel/C-S-H gel)}}{3\mathrm{CaO}\cdot 2\mathrm{SiO_2}\cdot 3\mathrm{H_2O}}\,[\text{secondary reaction}] \qquad (2.9) \end{aligned}$$

Equations 2.8 and 2.9 show the general chemical reactions that occur between cement and pozzolan in the presence of water. Tobermorite gel ($3CaO\cdot 2SiO_2\cdot 3H_2O$), which acts as a glue binding the soil particles together, is formed during cement hydration in peat stabilization (Eq. 2.8). However, the humic acid present in peat reacts with calcium ions from $Ca(OH)_2$ to form insoluble calcium humic acid. The secondary pozzolanic reaction described by Eq. 2.9 and the production of additional tobermorite gel are thereby inhibited, slowing the rate of strength gain in the soil-cement mixture. Organic soils and peats often do not contain sufficient pozzolanic mineral soil particles to consume and react with all of the $Ca(OH)_2$ that is formed when latent hydraulic cement is hydrated. In addition, peat, especially ombrogenic peats or peats with high organic content, contains very low levels of mineral clay or silt particles (low ash content), indicating that peat has a low content of silica and alumina that can enter into secondary pozzolanic reactions (Janz and Johansson 2002). Fortunately, cement is less sensitive than humic acid, allowing secondary tobermorite or C–S–H gels to form when pozzolans react with calcium hydroxide [$Ca(OH_2)$] (Eq. 2.9). However, as stated earlier, the pozzolan in peat is non-reactive; thus, if it is to be used as an effective binder, it must be activated by an activator, which in this case is cement. When pozzolans such as kaolin are included in peat-cement stabilization mixtures, the hydration of cement is accelerated when the pozzolan reacts with calcium hydroxide [$Ca(OH_2)$] and water to form secondary tobermorite gels (Eq. 2.9), further contributing to increases in stabilization strength.

Clays can act as pozzolans that provide silica as a result of mineralogical breakdown in a high pH environment. With the addition of lime, aluminous and siliceous minerals in clay react with the lime to produce calcium silicates and aluminates that bond the particles together. Cement, however, provides its own pozzolans and, therefore, only requires a supply of water. Pozzolanic reactions are time-dependent and temperature-dependent (Jacobson and Filz 2002).

An additional advantage of the use of pozzolans in the stabilization of peat soils is that, after activation by cement, pozzolans containing excess silica and alumina will neutralize the peat acids and create an alkaline environment that enhances the secondary pozzolanic reaction within the cemented soil, thereby generating more and more secondary tobermorite gel that eventually hardens, blocking the pore space between soil particles and reducing the soil permeability while increasing the stabilized strength of the cemented soil (Wong 2010).

Effect of siliceous sand particles (fine aggregates) as filler in peat stabilization

Maximum densification of the stabilized soil mix can be provided by introducing a suitable amount of well-sorted or well-graded fine siliceous material in the form of siliceous sand (Wong 2010). Well-sorted sand is necessary to minimize the occurrence of void spaces within the stabilized soil mix structure. The interstices of the interconnected void space are filled and packed with well-graded fine-grained to coarse-grained particles of fine aggregates, such as sand, applied as filler material. The use of fillers, such as siliceous sand, enhances the strength of stabilized peat-cement mixtures by supplying more solid particles for the binder to unite, minimizing unbridged ‘gaps’ in the pore interstices and, thus, forming a stabilized, load-sustainable structure. According to Alwi (2008), peat contains fewer solid particles to aid in stabilization than clay; thus, peat requires greater quantities of stabilizer. Peat also has a considerably higher water: soil ratio than other soils such as clay. The higher amount of water in peat implies larger voids and, thus, requires more stabilizers (Alwi 2008). Thus, the use of filler materials such as siliceous sands to fill these voids is necessary to minimize or offset the amount of cement or chemical stabilizer that must be used in the peat stabilization process.

Different binding agents stabilize the soil by different mechanisms. When cement binder is used, the reaction products (tobermorite gel) that bind the soil particles together ‘grow’ on the surfaces of the cement particles (Janz and Johansson 2002). It is therefore important that the cement be uniformly distributed through the soil. The cementation effect of siliceous sand as a filler occurs when cementation products or C–S–H gels (tobermorite gels) from the primary cement hydration reaction and secondary pozzolan reactions ‘glue’, weld or bind the solid particles of the sand filler material together at their contact points (spot welding). This results in the further ‘restriction/constriction/confinement’ of the peat particles that fill up the spaces between the interstices of the interconnected cement paste/gel, which are now reinforced further by siliceous sand particles acting as filler material in the binder mix. Hence, the organic particles of the peat are ‘stabilized’, ‘confined’ and interlocked (locked-up) by the cementation of siliceous solid particles due to hardening of the cement paste or gel. Thus, although no continuous peat matrix is formed, the peat soil is ‘stabilized’ and strength gain is achieved due to the hardening and cementation effect (spot welding) of the filler material in the cement paste of the peat-cement-filler mixture. The likelihood of failure of such a matrix due to fracturing depends on the strength of the interparticle bonds between solid particles and on the natural strength of the solid particles (Kezdi 1979).

The excellent cementation effect of sand particles is due to the spherical particle shape of rounded sand quartz grains, which are almost spherical and uniform with no internal voids (Ismail et al. 2002). This is especially true where well-weathered and rounded sedimentary quartz grains occur or are deposited and extracted for use as construction materials. The spherical shape of the quartz grains allows them to come into contact with more surrounding quartz grains via contact points that are welded or bound in the cementation-stabilizing process, thus contributing to the structure of the cemented particle matrix consisting of many welded point-to-point contacts among the sand-filler particles in the hardened, stabilized cement paste-peat-filler soil mixture.

It is possible for siliceous sand fillers to be activated or enter into secondary pozzolanic reactions; however, due to their relatively large particle size and corresponding low surface area, only a small portion of the surface area of siliceous sand filler particles is actually exposed to calcium hydroxide. This likely results in the negligible occurrence of secondary pozzolanic reactions, low reactivity or inertness (Janz and Johansson 2002). According to Wong (2010), the inclusion of siliceous sand as filler may allow it to act as a pozzolan and enter into the secondary pozzolanic reaction with calcium hydroxide [$Ca(OH)_2$] to produce more tobermorite gel and contribute to strength gain (Eq. 2.9) in peat-cement stabilization, but this reaction is inhibited due to the low specific reaction-surface area of the particles of sand filler. Wong (2010) further stated that theoretically it may be possible to replace a certain portion of the cement binder with fillers that may also act as pozzolans to reduce the cost of stabilization. However, if the filler itself were siliceous and of smaller particle size, as in the case of fine sand, silt or clay-sized particles, then the pozzolan effect would be possible and the ‘fillers’ can and would doubly act as a pozzolan for cement-peat mix stabilization strength gain.

Alwi (2008) studied the properties of stabilized peat (Banting peats) with and without the addition of sand. He concluded that the liquid limit of stabilized peat without sand decreased when binder cement (ordinary Portland cement + sodium bentonite) was added and when the curing time was prolonged. The plasticity index was only significantly reduced by addition of cement + sodium bentonite after longer or prolonged curing times (wet curing method) of 28 and 56 days. The addition of cement + sodium bentonite to the stabilized peat with sand caused a significant reduction in the liquid limit, the plastic limit and the plasticity index of the stabilized mixture. The curing time had a slight effect in reducing the liquid limit, plastic limit and plasticity index of the stabilized mixture. Alwi concluded that the shrinkage of stabilized peat without sand was reduced with increased admixture content and curing time. Linear shrinkage was significantly reduced by the addition of admixture and by extension of the curing period of stabilized peat with sand.

The unconfined compressive strength (UCS) of peat stabilized by addition of chemical admixtures was greater than that of untreated, unstabilized peat. Peat stabilized using admixtures with dosages of less than 200 kg/m^3 of blast-furnace slag + gypsum or blast-furnace slag alone without sand did not show significant improvement in UCS due to the high organic content of peat soil, which causes retardation of the hydration process of the chemical admixture (Alwi 2008). The UCS of stabilized peat without sand reached a maximum of 58 kPa after 56 days curing with an admixture dosage of 250 kg/m^3 of sample CB3C. The UCS of stabilized materials (peat + cement + sodium bentonite + sand) formed with sand as filler was significantly greater than that of stabilized peat without sand. The highest compressive strength of 850 kPa was achieved after 28 days of curing with an admixture dosage of 300 kg/m^3 and 41 % sand filler content of sample CBS-4C. It was concluded that the UCS of stabilized peat with sand filler increases significantly with increased admixture dosage and sand filler content (Alwi 2008). Wong et al. (2009, 2011), and Wong (2010) concluded that high organic content stabilized peats sampled from Klang showed a marked improvement relative to untreated peats in terms of UCS with the addition of calcium chloride as cement accelerator, rapid settling cements (Type I Portland Composite Cement and Portland Pulverised Fuel Ash Cement) as binding agents, kaolinite and sodium bentonite as pozzolans and siliceous sand as filler to the peat-cement mix. The best experimental mix design reported by Wong (2010) and Wong et al. (2009) was stabilized peat at 300 kg m^{-3} binder dosage, 100 % Portland pulverized fuel ash cement (PPFAC) with superplasticizer as a cement-dispersing agent, 4 % calcium chloride (as an accelerator) binder composition and 25 % siliceous sand filler by volume of peat at a natural moisture content of 668 % (Wong 2010). Wong et al. (2009) concluded that high strength cemented peat can be produced when MASCRETE, a rapid-setting pulverized fuel ash cement formed with high fineness with added superplasticizer as a cement-dispersing agent, and kaolinite-stabilized peat admixture with siliceous sand acting as a filler was activated by calcium chloride. This mixture accelerated the rate of cement hydration in the soil, giving the highest UCS of 413.0 kPa after seven curing days in water. Deboucha et al. (2008)

also concluded that cement binder-sand-stabilized peat soils showed increased UCS.

The addition of cement admixtures to stabilized peat without sand reduced its coefficient of compression, C_c, relative to untreated peat. However, the coefficient of permeability (k) was not reduced, due to flocculation that occurs during the hydration process between peat soil particles with admixture (without sand), forming porous crystalline material with larger voids (Alwi 2008). Increasing the admixture content of stabilized peat with sand also reduced the coefficient of compression. Consolidation test results obtained by Alwi (2008) indicated that sand increments to stabilized peat with sand significantly reduced the coefficients of consolidation (Cv) and permeability (k) compared to stabilized peat without sand filler. The addition of sand to the stabilized peat significantly reduced the permeability (8-fold) for stabilized peat with 250 kg/m^3 admixture dosage and 41 % sand content (for CBS-4B) compared to that of stabilized peat without sand at the same admixture dosage (CB-3C).

Addition of and increments in admixture content to stabilized peat without sand resulted in an increase in pH values. Similarly, an increment in pH value was observed with increases of admixture content of stabilized peat with sand filler.

From laboratory vane shear tests, the highest undrained shear strength of 265 kPa was achieved after a 7-day wet curing period for stabilized peat with an admixture binder dosage of 300 kg/m^3 and 41 % sand filler content (sample CBS-4C). Similarly, the undrained shear strength from laboratory vane shear tests of stabilized peat with 250 kg/m^3 admixture dosage with 41 % sand filler content was 1.70 times higher than that of stabilized peat with the same dosage and admixture type but without sand as filler (Alwi 2008).

According to Alwi (2008), the minimum DMM requirement for soil-cement pile/columns was 250 kg/m^3 admixture dosage of cement + sodium bentonite to stabilized peat with sand filler, and the minimum sand content was 34 % by weight of in situ peat for the same admixture dosage of 250 kg/m^3. The minimum 18 % sand content for an admixture dosage of 300 kg/m^3 still fulfilled the DMM strength requirement of 300–4,000 kPa.

Effect of curing time in water on peat stabilization

The effect of curing time in water on the UCS of stabilized Ballydermot peat was studied by Hebib and Farrel (2003), who used curing times of 7, 28, 90 and 360 days to show that temperate peats can be stabilized using different laboratory mix designs and that strength increased with curing time in water. The UCS of Soderhamn, Sweden stabilized peats also showed an increase after 360 days curing time in water with the use of different binder mixes such as cement-blast furnace and cement-fly ash mixes (EuroSoilStab 2002). Generally, these studies show that the strength of stabilized peats increases with longer or increased curing periods in water (Wong 2010; Alwi 2008; Janz and Johansson 2002).

The effect of curing time in water on the peat stabilization process differs according to the type of binder mix used (Wong 2010; Alwi 2008; Janz and Johansson 2002; EuroSoilStab 2002; Deboucha et al. 2008; Hashim and Islam 2008). The reaction of cement as a binder for peat stabilization is nearly complete after 28 days or the first month of curing (Wong 2010; Alwi 2008; Janz and Johansson 2002; Axelsson et al. 2002; EuroSoilStab 2002), while the stabilization reaction process of binders such as furnace slag or fly ash continues for months (Wong 2010; Janz and Johansson 2002). Hashim and Islam (2008) conducted tropical peat soil stabilization tests after 1, 3, 7 and 28 days curing time to examine the effect of curing time on UCS and found that strength increased with increased curing time. The UCS of cement-stabilized peat with sand filler also showed an increment when the curing time was increased from 7 to 14 days (Deboucha et al. 2008).

Most of the peat stabilization studies so far reviewed have employed the water curing technique. However, in the field, the peat stabilization process involves the mobilization of vehicles mounted with heavy machinery, and transportation of such equipment would most likely be impeded by the soft ground and waterlogged swampy terrain of the tropical lowland peats found in most peatlands in Malaysia and in the tropics in general. Thus, practical stabilization procedures often include the initial draining of the peat area targeted for stabilization, resulting in improved, relatively drier ground conditions. Because of this, the authors believe that the air-curing peat stabilization technique should be studied to imitate the actual drained peat ground conditions described earlier. The air-curing technique involves the use of in situ or naturally occurring peat water (natural moisture content) for the cement hydration reaction in the peat stabilization process.

The Air-Curing (dry-curing) Technique for peat stabilization

Tropical lowland peat swamps are usually waterlogged for most of the year. Drainage is needed to make these waterlogged lands suitable for agriculture or other land use, such as infrastructure and housing development. The leading principle of most water management practices is solely based on fulfilling the drainage requirements: avoiding flooding by evacuating excess rainfall within a certain period of time. The rapid removal of excess rainfall in combination with the high permeability of peat results in the lowering of overall water levels. This has various negative consequences such as land subsidence (D.I.D 2001).

Water management for agricultural development and for development of the associated infrastructure involves the draining of tropical lowland peat lands that occur largely as coastal peat swamps and results in the lowering of ground water tables, drying and reduction in the 'Natural Moisture Content' of paludal deposits, especially in the upper layers of peat deposits. Furthermore, wet, soft peaty ground must be conventionally drained to enable movement, transport, mobility and access of vehicles and machinery for the development and building of access roads. Therefore, for the reasons mentioned earlier, there is a need to investigate ways to improve or stabilize drained peat ground conditions. In situ drained peat is usually relatively drier than undrained, wet tropical lowland peat.

Stabilization of peat by cement and the Air Curing Technique

Kalantari and Huat (2008) conducted a laboratory study of stabilized peat sampled from Kampung Jawa, West Malaysia at a depth of 0–60 cm using ordinary Portland cement (OPC) as a binding agent with polypropylene fibers as an additive using the Air Curing Technique. This technique involves the curing of stabilized peat specimens without immersion in water during the curing period. Due to the high natural moisture content of peat, the stabilized peat samples have a high initial field water content. No additional water was added to or removed from the peat during the process of mixing the peat, cement and fibers. To reduce gradually their moisture content, the stabilized peat samples were kept at normal air temperature and out of water immersion and were allowed to dry during the curing period. The air curing periods used by Kalantari and Huat (2008) were 28, 90, and 180 days for the material subjected to unconfined compression tests and 90 days for the material subjected to CBR (soaked and unsoaked) tests. As the air curing time for the stabilized peat samples was increased, the moisture content of the material decreased and the water/weight ratio of the cement (W/C) was reduced; as a result, the stabilized peat samples hardened and gained significant strength. The addition of polypropylene fibers to the stabilized peat samples with cement yielded higher strength values and added uniformity and intactness to the stabilized peat as well.

Unconfined compressive strength (UCS) of peat stabilized using the Air Curing Technique

Unconfined compression strength tests were conducted by Kalantari and Huat (2008) on undisturbed peat soil as well as on peat soil that had been stabilized with OPC and fibers. Samples 38 mm in diameter and 76 mm in length were used in the experiments. The samples used for unconfined compression strength tests of the stabilized peat soil were the peat soil samples at their natural (field or in situ) moisture content. The peat soil was first screened using a sieve size of 6.3 mm (0.3″) to remove larger vegetal wood fibers. Specified amounts of OPC and polypropylene fibers were then added to the screened peat soil and mixed well to achieve homogeneity. The mixtures were placed in three successive layers in an unconfined compression strength test mold with an inside diameter of 38 mm and a minimum length/diameter ratio of 2. Each of the three layers of the sample were given ten constant full thumb pressures of approximately 10 s, as used in Sweden for compacting stabilized peat soil samples in molds as described by Axelsson et al. (2002). The samples were then trimmed at both ends, extracted using an extractor jack, and wrapped in plastic sleeves for the air-curing procedure. Unconfined compression strength tests like those done by Kalantari and Huat (2008) on stabilized peat samples were conducted immediately after mixing (day 0) and after the samples had been air-cured for 28, 90 and 180 days.

Curing procedure (Air Curing Technique) for UCS tests

With the Air Curing Technique (Kalantari and Huat 2008), the stabilized peat samples to be used for UCS tests were kept at a normal air temperature of 30 ± 2 °C and out of reach of water intrusion during the curing period. This technique was used to strengthen the stabilized peat soil samples by gradual moisture content reduction instead of by the usual water-curing technique or water submergence method that has been a common practice in past experiments involving peat stabilized with cement, as described by Axelsson et al. (2002), Janz and Johansson (2002), Duraisamy et al. (2007), Alwi (2008), Kalantari and Huat (2008) and Wong (2010). The principle of using the Air Curing Technique for strengthening stabilized peat is that peat soil at its natural moisture content contains sufficient water (water content from 198 to 417 %) for the curing process to take place when the peat is mixed with cement; hence, additional water or submergence of the samples in water is not required. This technique will cause the stabilized peat soils to gradually lose their moisture content during the curing period and to become drier and harder (Kalantari and Huat 2008). Peat stabilization studies by previous researchers (Axelsson et al. 2002 and Janz and Johansson 2002) were conducted using the water-curing technique set to cold or temperate room temperatures and were supposed to imitate actual ground conditions in Sweden. However, the cold and periodically near frozen or below zero Celsius physical soil and peat ground conditions in cold-climate countries such as Sweden are very different from the conditions that exist in very soft and wet tropical lowland peat ground.

Mixture dosages

For UCS tests (Kalantari and Huat 2008), each set of samples consisted of peat soil with natural (field or in situ) moisture content plus 15, 30, or 50 % by weight of ordinary Portland cement (e.g., 15 % cement means that for each 100 g of peat soil with natural moisture content, 15 g ordinary Portland cement powder was added) with or without polypropylene fibers. The polypropylene fiber amounts used for the stabilized UCS soil samples were 0.1, 0.15, and 0.25 % (e.g., 0.15 % fibers means for each 100 g of peat soil with its in situ (field) moisture content, 0.15 g of polypropylene fibers was added).

Concluding remarks

- The DMM, which uses columnar soil reinforcement in the form of in situ stabilized peat columns, is suitable for deep peat stabilization. For shallow peat deposits, the mass stabilization technique is used to stabilize the soil instead of the removal and replacement method, which is costly and problematic in terms of transportation and disposal of the replaced unsuitable soil.
- The concept of soil-cement stabilization involves the addition of water to cement, resulting in a chemical process known as cement hydration. Hydration of cement occurs when the pore water or ground water in soil interacts with ordinary Portland cement to form primary cementation products in the form of hydrated calcium silicates (C3S2H4), ettringite (C6AS3H32), monosulfate (C4ASH12), and hydrated lime (CH). During hydration, a cement paste is produced that hardens to create a system of interlocking crystals that weaves the material together. This extremely fine-pored cement gel, also known as tobermorite or C–S–H gel, is formed around the cement particles during hydration. The binding agent or stabilizer is not the cement itself but rather the mixture of cement and water that forms the cement gel. The cement gel, which includes C–S–H gel, ettringite and monosulfate, gradually fills the void spaces between cement and soil particles during the hydration reaction of water and cement in the soil. Use of a high water-cement ratio means that more water is present for hydration, resulting in higher porosity and lower strength of the hardened soil-cement paste.
- In the cement paste, the four clinker minerals present as major strength-enhancing compounds are tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminate ferrite (Ferrit).
- Stabilization of peat by cement to produce significant strength increases in peat/organic soil is attributed largely to the physicochemical reactions that occur during the stabilization process. These reactions include cement hydration, hardening of the resulting cement paste and interactions between soil substances and primary and secondary cementation hydration products. The factors that determine these physicochemical reactions and the interactions of peat soil-cementation products influence peat stabilization, as discussed in the previous sections. They include:

1. Amount of solid particles—Organic soils can retard or prevent the hydration of chemical binders such as cement in binder-soil mixtures. The high organic content and significantly lower amounts of solid particles in peat (e.g., ombrogenic peats with low mineral ash content) are the reasons that cement alone is insufficient to provide desirable stabilization strength in peat ground improvement.
2. Water: soil ratio—The high water: soil ratio in peats gives a high water-to-cement ratio, which results in lower stabilization strength. A higher *wcr* ratio means that more stabilizer must be added for the desired strength increase.
3. Quantity of binder—There are indications that organic soils or peats exhibit a threshold effect whereby the quantity of binder used must exceed a certain threshold before significant stabilization is obtained.
4. Humic acid—Black humic acid reacts strongly with calcium liberated during cement hydrolysis to form insoluble calcium humic acid, thus retarding calcium crystallization and impeding the increase in peat soil-cement mixture strength.
5. Fulvic acid—Fulvic acid in peat tends to associate with mineral particles containing aluminum, leading to the destruction or decomposition of the layered crystal lattice within the peat soil-cement mixture and resulting in the production of an adsorbed layer that impedes the further hydration of cement. In addition, fulvic acid may further prevent the formation of the soil-cement structure by decomposing calcium aluminate hydrate, calcium sulfate-aluminate hydrate and calcium ferrite-aluminate hydrate crystals.
6. Soil pH—The organic acids present in peat may cause the soil pH to drop, decreasing the reaction rate of the hydrated cement binder and resulting in a slower strength gain in peat. Unless a larger (most likely uneconomical) quantity of cement is mixed with the soil for stabilization, the mixture of organic acids, soil and cement produces a pH lower than 9 in the pore solution, too low to allow secondary mineral or

secondary cementation product formation and, hence, further limiting or retarding the stabilization effect.

7. Amount of organic matter—The presence of excessive organic matter in peat implies that the peat has a high water retention capacity and a high natural moisture content that causes the adsorption of organic particles on the surface of the cement and on the surfaces of solid mineral soil particles, thus preventing the formation of cement hydration products and inhibiting hydration reactions between solid soil particles and hydration products. This also limits the increment in strength of the peat-cement admixture.

- The major aspects of the effect of clay particles such as pozzolan and secondary additives in peat stabilization include:

1. Hydrous silica and alumina are produced from base reactions with acidic soil silica and alumina. Secondary pozzolanic reactions occur when secondary cementation products or insoluble compounds are produced by the reaction of hydrous silica and alumina with calcium ions from cement hydrolysis. The secondary cementation products harden upon curing, thus stabilizing the soil. Further strength is acquired by the solution of soil silicates and aluminates. The bonding strength of the primary cementation product (tobermorite gel) is much greater than that of the secondary cementation products.
2. Small amounts of pozzolans such as kaolinite can be added to cement-stabilized peats to enhance secondary pozzolanic reactions in the stabilized soil. The reactivity of cement and pozzolan with water in the soil during peat stabilization is dependent on the ratio of lime to silica (CaO:SiO_2). A higher lime-to-silica ratio means that the material is more hydraulic.
3. Clays act as pozzolans, providing silica as a result of mineralogical breakdown in a high pH environment. With the addition of lime, aluminous and siliceous minerals in clay react with the lime to produce calcium silicates and aluminates that bond the particles together. Cement provides its own pozzolans and only requires a supply of water. Pozzolanic reactions are time-dependent and temperature-dependent.
4. After activation by cement, pozzolans containing excess silica and alumina neutralize the acids in peat to create an alkaline environment that further enhances secondary pozzolanic reactions within the cemented stabilized soil, thereby generating more secondary tobermorite gel that eventually hardens and blocks the pore spaces between soil particles. This reduces the soil's permeability while increasing the stabilized strength of the cemented soil.

- The major aspects of the effects of siliceous sand particles (fine aggregates) as filler in peat stabilization discussed above can be summarized as follows:

1. Maximum densification of the stabilized soil mix can be provided by introducing a suitable amount of well-sorted or well-graded fine siliceous material in the form of well-sorted siliceous sand. This minimizes the void spaces within the stabilized soil mix structure by filling and packing the interstices of interconnected void spaces with well-graded, fine-to-coarse-grained particles of fine aggregates.
2. The use of fillers such as siliceous sand also enhances the strength of the stabilized peat-cement mix by supplying additional solid particles for the binder to unite, minimizing unbridged 'gaps' in the pore interstices and, thus, forming a stabilized, load-sustainable structure.
3. The cementation effect of uniformly distributed siliceous sand used as a filler occurs when cementation products or C–S–H gels (tobermorite gel) from the primary cement hydration reaction and secondary pozzolan reactions 'glue', weld or bind the solid particles of the sand filler particles together at their contact points (spot welding), resulting in further restriction/constriction/confinement of the peat particles that fill the spaces between the interstices of the interconnected cement paste/gel, which is now reinforced further by siliceous sand particles acting as filler material to the binder mix and interrupting the continuous peat matrix. The peat soil becomes more 'stabilized', and strength is gained with the hardening and cementation effect (spot welding) of the filler material in the cement paste of the peat-cement-filler mixture.
4. The strength of cemented stabilized peat structures depends on the strength of interparticle bonds and on the natural strength of the solid particles of cement and filler material.
5. Filler materials such as siliceous sands are necessary to minimize or reduce the amount of cement or chemical stabilizer required in the peat stabilization process.
6. The excellent cementation effect of sand particles is due to the spherical particle shape of rounded sand–quartz grains. These grains are almost spherical and uniform with no internal voids, allowing them to come into contact with more surrounding quartz grains.
7. There is a possibility that siliceous sand fillers can be activated or enter into secondary pozzolanic reactions, but due to their relatively large particle size and

low specific particle surface area, these fillers are relatively inert.

8. The addition of cement + sodium bentonite to stabilized peat with sand added as a filler was shown to cause a significant reduction in the liquid limit, the plastic limit and the plasticity index of the stabilized mixture.
9. The UCS of stabilized materials (peat + cement + sodium bentonite + sand) with sand added as a filler and using the wet curing method was significantly greater than that of stabilized peat without sand. The highest compressive strength of 850 kPa after 28 days of curing was achieved with an admixture dosage of 300 kg/m^3 and 41 % sand filler content of sample CBS-4C in stabilized peat. It was concluded that the UCS of stabilized peat with sand added as a filler increases significantly with increased admixture dosage and sand filler content.
10. High organic stabilized peats showed marked improvement relative to untreated peats in terms of UCS with addition to the peat-cement mix of calcium chloride as cement accelerator, rapid settling cements (Type I-Portland Composite Cement and Portland Pulverised Fuel Ash Cement) as binding agents, kaolinite and sodium bentonite as pozzolans and siliceous sand as filler. It was concluded that high strength cemented peat can be produced when MASCRETE, a rapid-setting pulverized fuel ash cement formed with high fineness with added superplasticizer as a cement-dispersing agent, and kaolinite-stabilized peat admixture with siliceous sand acting as a filler were activated by calcium chloride. This accelerated the rate of cement hydration in the soil and gave the highest UCS of 413.0 kPa after seven curing days in water.
11. The increase of admixture content to stabilized peat with sand added as filler material also reduced the coefficient of compression (C_c). Consolidation tests indicated that sand increments to stabilized peat with sand significantly reduced the coefficients of consolidation (C_v) and permeability (k) compared to stabilized peat without sand filler. The addition of sand to the stabilized peat significantly reduced the permeability by eight times for stabilized peat with 250 kg/m^3 admixture dosage and 41 % sand content (for CBS-4B) compared to the permeability of stabilized peat without sand with the same admixture dosage (CB-3C).
12. The pH values were observed to increase with increments in the admixture content added to stabilized peat with and without sand filler.
13. Laboratory vane shear tests have shown that the undrained shear strength of stabilized peat with 250 kg/m^3 admixture dosage with 41 % sand added filler content was 1.70 times higher than that of stabilized peat with the same dosage and admixture type prepared without using sand as filler.

- The effect of curing time in water on the peat stabilization process differs according to the type of binder mix used. The reaction of cement as a binder for peat stabilization usually ends after 28 days or during the first month of curing, while the stabilization reaction process for binders such as furnace slag or fly ash continues for months. Tropical peat soil stabilization tests showed that strength increased with an increase in curing time in water. The UCS of cement-stabilized peat with sand filler also showed an increment with increase in curing time from 7 to 14 days.
- With the Air Curing Technique, stabilized peat samples for UCS tests were kept at a normal air temperature of 30 ± 2 °C, and this method was used to strengthen the stabilized peat soil samples by gradual moisture content reduction instead of the usual water curing. The principle of using the Air Curing Technique for strengthening stabilized peat is that peat soil at its natural moisture content, when mixed with cement, has enough water (water content from 198 to 417 %) for the curing process to take place, and, hence,does not require more or additional water. During the curing period, the stabilized peat soils gradually lose their moisture content and become drier and harder.

Hebib and Farrel (2003) argued that the UCS of different peat-binder mixes can differ for different peats with similar water and organic content. Huttunen and Kujala (1996) reported that the stabilization strength of peats decreased with advanced decomposition. Studies by Alwi (2008) and Wong (2010) have shown that tropical peats can be stabilized using various chemical additives with and without siliceous sand fillers, but most of the studies reviewed did not indicate what type of tropical peats were used or which part of the peat 'dome' was sampled for stabilization tests. Classification and characterization of these peats, especially tropical lowland peats, is therefore necessary to gain proper insight into and further knowledge of tropical peat stabilization. As previously mentioned, tropical lowland peats occur as domed-shaped deposits, and the peat displays different characteristics and engineering properties depending on which part of the peat 'dome' is targeted in the peat-stabilization procedure.

Acknowledgments The authors are grateful to the anonymous reviewers who contributed constructive comments that enabled us to improve this manuscript considerably. The authors also acknowledge the IPPP grant RG257-13AFR for financial support from the University of Malaya.

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