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A Review on Experimental Investigations of Peat Stabilization

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Abstract: Thorough experimental investigation of stabilized peat is of great importance in order to formulate an effective mix design that can be applied for deep peat stabilization, which forms economical deep foundation for supporting highway embankments and light structures constructed on deep peat ground. Unsuitable and inadequate binders mixed with peat was often found to be the main reason for the failure in the formation of high strength stabilized peat columns. Since the properties of peat differ from location to location, reactivity of peat to a binder to form high strength stabilized peat is very site specific and requires detail laboratory mix design investigation. Despite of that, not much research is done on stabilized peat mainly because peat is problematic due to its high organic content. Consequently, it is not easy to stabilize the soil as the soil is highly acidic and stabilization of peat with cement only is often unsucessful due to insufficient binder dosage resulting in the retardation of hydration and secondary pozzolanic reactions in the stabilized soil. In order to develop a proper understanding on the reactivity of peat with various types of binder, this paper reviews the results of experimental investigation of stabilized peats developed by some researchers.

Key words: stabilized peat, mix design, binder, cement, binder dosage

INTRODUCTION

Peat originates from plant and denotes the various stages in the humification process where the plant structure can be discerned (Hartlen and Wolski, 1996). The decaying process of plant results in the formation of organic matter in peat. This renders peat extremely soft and problematic type of soil. The rapid global development has seen more and more peat ground is being developed. Found in low lying areas prone to flooding, peat is considered as unsuitable material for supporting highway embankments. With scarcity of land of good soil conditions and the necessity to construct highways on peat ground, use of peat ground for road construction development cannot be avoided. The stability of highway embankments relies on the support of the ground of which they are constructed. If such highways are constructed on untreated peat ground, they would be subjected to excessive bearing failure and the post construction total and differential settlements would be excessive resulting in their serious damage.

Advances in geotechnical engineering over the past decades have seen the development of various soil improvement techniques that can be applied on deep peat ground in order to improve the soil. For deep peat ground, deep peat stabilization is known to be an economical ground improvement method. The method is implemented in such a way that chemical binders and silica sand are dry-mixed with in situ peat to form columnar reinforcements in deep peat ground. However, failure in the formation of the stabilized peat columns with adequate strength was often attributed to unsuitable type and insufficient dosage of binder added to the soil (Wong *et al.*, 2008). Organic matter in peat is known to impede the cementing process in the soil, thus retarding the early strength gain of stabilized peat. To develop a proper understanding on effective deep peat stabilization, laboratory mix design and testing often provide an indispensable guide regarding the choice, dosage and economical amount of chemical binders and silica sand that can be used for the soil stabilization.

With regard to that, the paper is concentrated at reviewing the results of previous laboratory investigations on the engineering properties of stabilized peat at formulating effective laboratory mix designs that can be used for deep peat stabilization. Data from several experimental investigations of stabilized peats (i.e. EuroSoilStab, 2002; Hebib and Farrell, 2003; Chen and Wang, 2006; Alwi, 2008) were reviewed and compared in order to develop a proper understanding on the mechanism of peat stabilization. In particular, the paper reviews the

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effect of binders and silica sand on the engineering characteristics of stabilized peat at various curing time periods in water.

Stabilization of Peat by Cement:

It is well recognized that organic soils can retard or prevent the proper hydration of binders such as cement in binder-soil mixtures (Hebib and Farrell, 2003). With high organic content and less solid particles in peat, cement alone as a chemical admixture is insufficient to provide the desirable function for peat stabilization. Compared with clay and silt, peat has a considerably lower content of clay particles that can enter into secondary pozzolanic reactions (Janz and Johansson, 2002). As such, the interaction between hydrated lime [$Ca(OH)_2$] and the soil yields less effect in secondary pozzolanic reactions. Therefore, no significant strength gain can be achieved from peat stabilization by cement unless cement is added to the soil in a large dosage. Figures 1 and 2 show the relationships between shear strength and a number of soils stabilized by different binding agents, and water to cement ratio (*wcr*) respectively. It can be observed from Fig. 1 that peat achieved the lowest shear strength with cement stabilization if compared to that of other types of soil. Similarly, with the highest water to cement ratio (*wcr*), cement stabilized peat demonstrated the lowest shear strength if compared to other types of soil as shown in Fig. 2. Evidence from both figures shows that it is apparent that with less solid particles and high organic matter in peat which makes the soil porous and spongy in nature, the organic matter tends to impede the hydration of cement when used to stabilize the soil (Chen and Wang, 2006). The impediment to cementation and hardening of peat-cement admixture is attributed to the presence of black humic acid and fulvic acid in peat soil. Humic acid, fulvic acid, and humin are the humic substances, which form the major component of peat organic matter. Humin is the main composition of tightly combined humus, while humic and fulvic acids exist not only in loosely combined humus but also in stably combined humus (Chen and Wang, 2006).

Black humic acid has a strong chemical affinity to calcium liberated from cement hydrolysis; hence where calcium is present in solution, humic acid may react with the calcium and form insoluble calcium humic acid (Chen and Wang, 2006). The combination of humic acid with calcium ions produced in cement hydration makes it difficult for the calcium crystallization, which is responsible for the increase of peat soil-cement mixture strength to take place (Chen and Wang, 2006). On the other hand, fulvic acid within the organic matter tends to associate with the mineral particles containing aluminum, and this may lead to the decomposition of layered crystal lattice within the peat soil-cement mixture (Chen and Wang, 2006). In its natural condition, fulvic acid can be found in a water-soluble form within peat. Exposure of cement to the fulvic acid solution would generate the hydration of cement. In spite of this, the chemical interaction between the fulvic acid and the cement minerals would produce absorbed layer, which impedes the process of cement hydration. In addition, fulvic acid may decompose existing crystals such as calcium aluminate hydrate, calcium sulfate-aluminate hydrate, and calcium ferrite-aluminate hydrate, thus preventing the formation of a soil-cement structure (Chen and Wang, 2006). The acids may also cause the soil pH to drop and this negatively affects the reaction rate of the binder, resulting in a slower strength gain in peat (Axelsson *et al.,* 2002). It appears that organic acids, mixed with soil and cement that produce a pH lower than 9 in the pore solution, prevent the development of the cementing products because the pH is too low to allow secondary mineral formation (Tremblay *et al*., 2002). That means unless a large quantity of cement is mixed with the soil to neutralize the acids, the process of the soil stabilization remains retarded. However, adding a large quantity of cement into the soil is definitely an uneconomical solution to deep peat ground improvement considering the fact that the peat ground is deep and covers a wide area, and the rising cost of cement and its transportation to the site.

As such, it is clear that the strength increase of cement-stabilized soil is attributed to the physico-chemical reactions that take place, including hydration and hardening of the cement and the interaction between substances in the soil and the products of cement hydration (Chen and Wang, 2006). Excessive organic matter in peat implies that the soil has a high water retention capacity and during the process of cement hydrolysis in the soil, absorption of organic particles on the surface of cement and solid soil particles occurs. This would hinder both the formation of cement hydration products, and the hydration between solid soil particles and hydration products (Chen and Wang, 2006). As a result, only limited increment can be achieved in peat-cement admixture strength. This is particularly evident when Chen and Wang (2006) mentioned that the strength of peat did not even reach 300 kPa even with deep mixing with a cement ratio up to 30 % in a foundation reinforcing project on peat undertaken in 1985. Therefore, a clear understanding on the behavior of organic matter in the process of stabilization of peat by suitable chemical admixture is vital in order to outline an effective peat stabilization method.

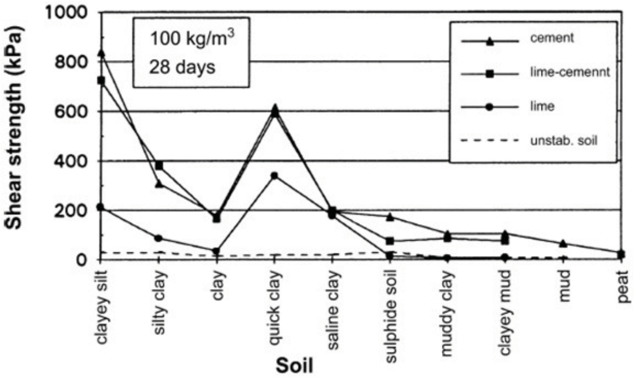


Fig. 1: Measured shear strengths of the stabilized soils in 28 days after mixing, and the shear strengths of the same soils in unstabilized, "undisturbed" condition. Stabilization and strength determination performed in laboratory (Ahnberg *et al.*, 1995)

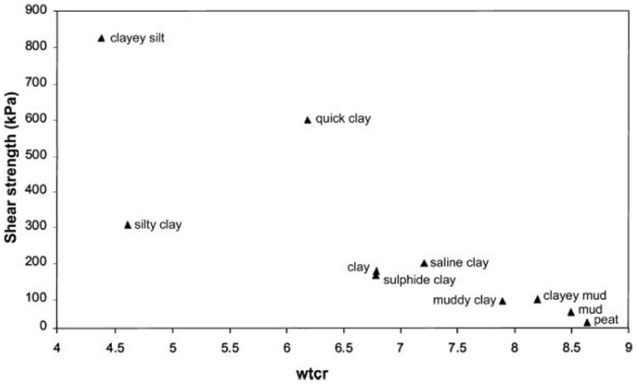


Fig. 2: Measured shear strengths of cement stabilized soils as a function of water to cement ratio 28 days after mixing. Stabilization and strength determination performed in laboratory (Ahnberg *et al.*, 1995)

Effect of Pozzolan as Secondary Addictive in Peat Stabilization:

Small amount of pozzolans such as kaolinite, sodium bentonite and fly ash can be added to cement stabilized peat to enhance the secondary pozzolanic reaction in the stabilized soil. In general, both of the cement and pozzolan used for peat stabilization react with water in the soil under certain condition to form high strength product that bind the soil particles together. However, their reactivity is dependent on the ratio of lime to silica (CaO: SiO_2). The higher is the ratio, the more hydraulic is the material (Janz and Johansson, 2002). Strength enhancing reactions and physical properties of Ordinary Portland cement and pozzolan are summarized in Table 1.

Table 1: Strength enhancing reactions of cement and pozzolan (Janz and Johansson, 2002)

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

It can be observed from Table 1 that both cement and pozzolan have calcium to silica ratio of approximately 3 and 0 respectively. The high calcium to silica ratio in cement indicates that cement is a hydraulic material and that means upon its reaction with water, it gives a rapid initial strength gain followed by a secondary pozzolanic reaction. On the other hand, the almost zero calcium to silica ratio in pozzolan such as kaolinite and sodium bentonite shows that it is a pozzolanic material which needs to be activated by calcium hydroxide from the cement hydration in order to react with water. The general chemical reactions between cement and pozzolan with water are represented by Equations 1 and 2.

$$\text{Cement} + H_2O + = 3CaO.2SiO_2.3H_2O\ \text{gel} + Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + \text{Pozzolan} + H_2O + 3CaO.2SiO_2.3H_2O\ \text{gel} \quad (2)$$

When cement reacts with water in peat, it forms calcium silicate hydrate or tobermorite gels ($3CaO.2SiO_2.3H_2O$), which act as glue that bind and hold the soil particles together. However, with the presence of humic acid which reacts with calcium ion to form insoluble calcium humid acid, the secondary pozzolanic reaction between calcium hydroxide ($Ca(OH)_2$) and the soil is inhibited and this renders a low strength gain in the soil-cement mixture. In addition, low amount of clay particles in peat indicates that the soil has a considerably low content of silica and alumina that can enter into the secondary pozzolanic reaction (Janz and Johansson, 2002). Anyhow, the tobermorite gels can still form even if the acid reacts with calcium hydroxide ($Ca(OH)_2$) since cement is less sensitive to humic acid. Pozzolanic properties enable pozzolan to form strength enhancing products when it reacts with calcium hydroxide [$Ca(OH)_2$]. The pozzolan is non reactive to water and therefore, it needs to be activated by an activator, which is normally cement, if it is to be used as a binder. With the inclusion of pozzolan in the soil-cement mixture, hydration of cement is accelerated when the pozzolan reacts with calcium hydroxide [$Ca(OH)_2$] and water to form more secondary tobermorite gels as shown in Equation 2. This is possible because when activated by cement, the pozzolan, which contains excess silica and alumina, is able to neutralize the acid and create an alkaline environment that enhances the secondary pozzolanic reaction within the cemented soil. This generates more secondary tobermorite gels that in effect, block the pores, reduce the permeability, and increase the strength of the cemented soil. Additional secondary tobermorite gels densify the stabilized peat, thereby further enhancing its strength. With additional secondary tobermorite gels in the stabilized soil, the proportion of calcium silicate hydrate ($CaO.SiO_2.H_2O$) to calcium hydroxide [$Ca(OH)_2$] becomes higher which effectively reduces the permeability of the stabilized soil.

Effect of Silica Sand as Filler in Peat Stabilization:

In order to build a strong stabilized peat, it is important to provide maximum densification to the stabilized soil by introducing a suitable amount of well graded silica sand into it. Well grading of silica sand is necessary considering the fact that void spaces within the stabilized soil is reduced to a minimum when it is well packed with coarse grained sand having the interstices in between filled with fine grained sand. With respect to that, the inclusion of the silica sand as filler produces no chemical reaction but it enhances the strength of stabilized peat by the binder by increasing the number of soil particles available for the binder to unite and form a load sustainable stabilized soil structure.

Furthermore, the filler helps to reduce the void ratio of the soil by filling the void spaces within the soil during stabilization. Since no filler is absolutely inert, it is possible that fillers may enter into pozzolanic reactions (Janz and Johansson, 2002). For example, the inclusion of silica sand may result in the secondary pozzolanic reaction with calcium hydroxide [$Ca(OH)_2$] and contribute to the strength gain. However, as a result of large sizes of sand particles and therefore they have low specific surface, only a relatively small surface area is exposed to the calcium hydroxide and available for the pozzolanic reaction. The effect of filler on the pozzolanic reaction is therefore neglected. Theoretically, it may be economical to reduce the cost of soil stabilization by replacing a certain portion of the binder with filler.

Cementation effect in silica sand as a granular soil takes place in the form of cementation products that bind the solid particles together at its contact points (spot welding) as shown in Fig. 3. In this way, the organic particles in peat not only fill up the void spaces in between the solid particles but also tie up as a result of cementation of the silica sand. Thus, according to Kezdi (1979), no continuous matrix is formed, and the fracture type depends on whether the interparticle bond or natural strength of the particles themselves is stronger.

Similar finding can be observed from the study of Ismail *et al.* (2002), which researched on the effect of sand inclusion on the cementation of porous material using calcite. According to Ismail *et al.* (2002), the excellent strength performance of the rounded sand particles is attributable partly to their rounded shape. The particle shape of the sand (mainly quartz) is almost spherical and uniform, and the structure of each grain is strong and sound with almost no internal voids (Ismail *et al.* 2002). Ismail *et al.* (2002) further stated that the spherical particle of sand allows the sand to be exposed to more contact points within the surrounding grains, and this contributed to cemented matrix of many welded point to point contacts among the sand particles (Fig. 4).

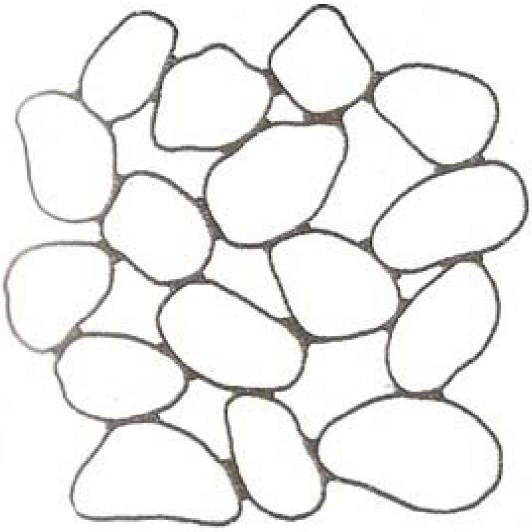


Fig. 3: Cementation effect around the contact points of the coarse grains (Kezdi, 1979)

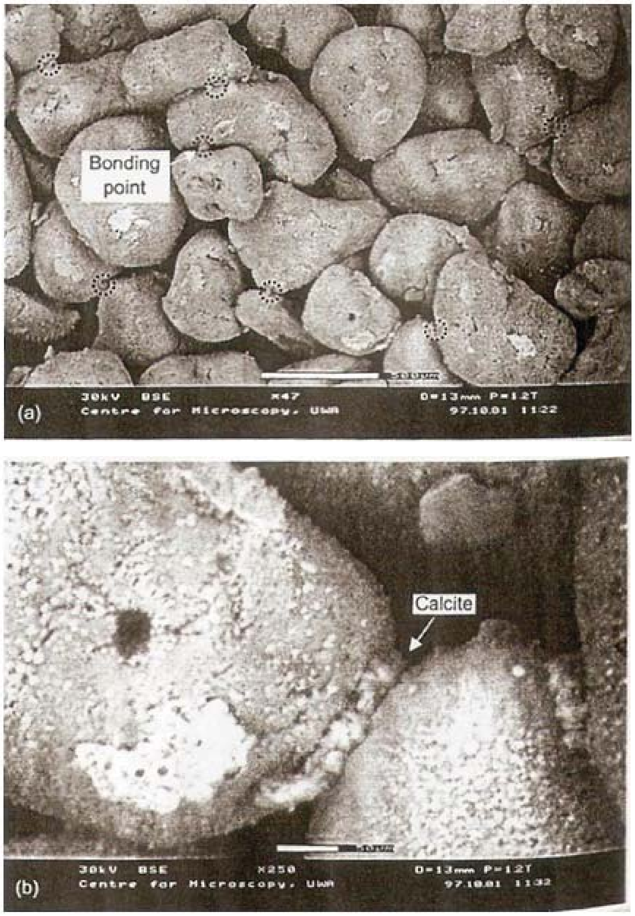


Fig. 4: ESEM micrograph of Si sample cemented with calcite (one flush) showing points of contact, uniformity and soundness of quartz grains (Ismail *et al.*, 2000a)

Strength of Stabilized Peat:

According to Axelsson (2002), in soils with high organic contents, such as mud and peat, the quantity of binder needs to exceed a "threshold" as shown in Fig. 5. At a minimum, the quantity of binder added must be sufficient to build up a load-bearing skeleton (Janz and Johansson, 2002). That means with the amount of binder below the threshold, the soil would remain unstabilized. Thus, more binder of a given type needs to be added to a porous, watery soil such as peat or mud than to a more densely compacted soil (Janz and Johansson, 2002). This is because when sufficient binder is added; neutralization of humid acids within the soil is achieved, thereby increasing the soil pH. Based on laboratory tests of relative strength increase after 28 days of curing on different types of Nordic soils with different binder mixes, the cement-slag admixture was found to be a very good binder for peat with high organic content while it is considered as a good binder for other types of soil as well in many cases (Table 2) (EuroSoilStab, 2002). Although when blended with cement in peat, ground granulated blast furnace slag generally produced stabilized soil with lower early age strength if compared to that of peat stabilized with cement only, its strength was expected to increase significantly at later ages. While cracking potential can be minimized with slower rate of strength development of the stabilized soil, high later strength gain in it ensures its durability and fatigue resistance in long term period.

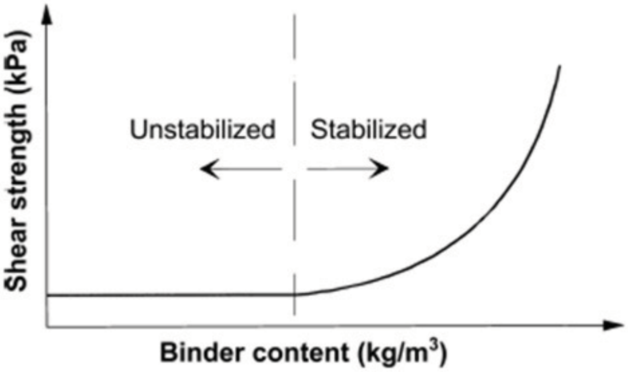


Fig. 5: General relation between binder dosage and shear strength (Janz and Johansson, 2002)

Table 2: Relative strength increase based on laboratory tests (unconfined compressive strength after 28 days of curing) on Nordic soils (EuroSoilStab, 2002)

Binder	Silt	Clay	Organic Soils, e.g. Gyttja, Organic Clay	Peat
	Organic content (0 - 2%)	Organic content (0 - 2%)	Organic content (2 - 30%)	Organic content (50–100%)
Cement	xx	x	x	xx
Cement + gypsum	x	x	xx	xx
Cement + furnace slag	xx	xx	xx	xxx
Lime + cement	xx	xx	x	-
Lime + gypsum	xx	xx	xx	-
Lime + slag	x	x	x	-
Lime + gypsum + slag	xx	xx	xx	-
Lime + gypsum + cement	xx	xx	xx	-
Lime	-	xx	-	-

Note:

xxx	very good binder in many cases
xx	good in many cases
x	good in some cases
-	not suitable

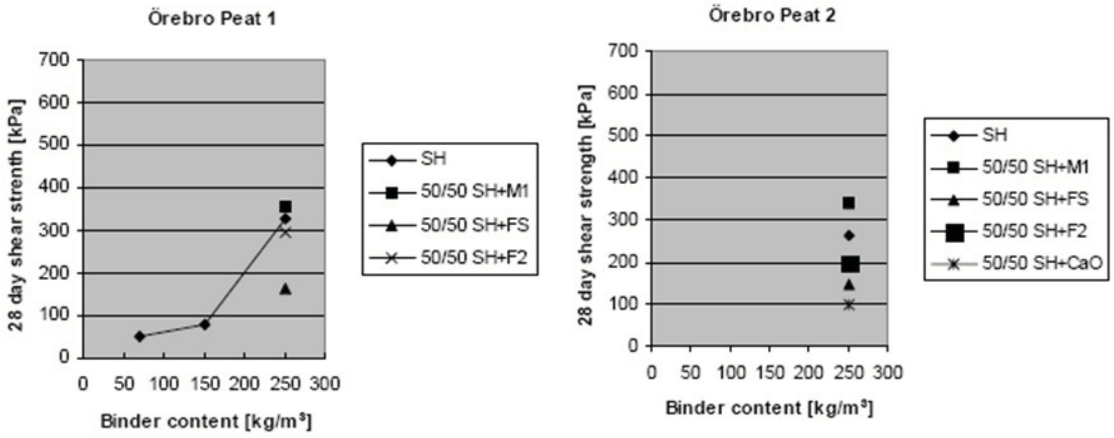
Effect of Binder Type and Dosage on the Strength of Stabilized Peat:

Several laboratory tests were conducted in order to evaluate the effect of binder type and dosage on the strength of stabilized peat (EuroSoilStab, 2002; Axelsson, 2002; Hebib and Farrell, 2003). While Figures 6(a) and 6(b) show that cement-slag admixture with a ratio of 1 to 1 yielded the highest 28 days curing shear strength of above 300 kPa for both Orebro Peat 1 and 2 samples at a binder dosage of 250 kg m^{-3}, Fig. 7 illustrates that with a ratio of 1 to 2, cement-slag admixture gave the stabilized peat from Soderhamn, Sweden, unconfined compression strength as high as above 800 kPa at a binder quantity of 300 kg m^{-3}.

Hebib and Farrell (2003) studied the effect of binder type and dosage on the strength of stabilized Raheenmore peat specimens in unconfined compression tests. The test specimens were cured for 28 days in water prior to testing. With different binder compositions, the test specimens were subjected to binder dosages of 150, 200 and 250 kg m^{-3}. While Table 3 shows the binder compositions of the test specimens, Fig. 8 shows the results of the tests. It can be observed from Table 3 that at 250 kg m^{-3} binder dosage, the SG stabilizer yielded the highest unconfined compressive strength when it was used to stabilize the peat. In all cases, it can be seen that the unconfined compressive strength of the test specimens increased with the increase of binder dosage.

In term of binder dosage, similar trend of increase in strength with the increase of binder dosage of stabilized peat can be observed from the study of Alwi (2008). Alwi (2008) tested stabilized Banting peat specimens without sand using unconfined compression apparatus. All the test specimens were cured in water for 56 days before testing. While Table 4 shows the description of binder compositions of the stabilized peat specimens without silica sand, Fig. 9 illustrates the results of the tests on the test specimens with the binder compositions. The highest unconfined compressive strength of 58 kPa was reached in the stabilized peat with CB-3C admixture at a binder dosage of 250 kg m^{-3}. As Table 5 shows the mix designs of the stabilized peat with sand, Fig. 10 illustrates the results of the tests on test specimens with the mix designs. It is evident from the results that the strength of the stabilized peats with sand increased significantly when compared to those without silica sand. The highest strength of the test specimen was achieved with a mix design of CBS-4C at a binder dosage of 300 kg m^{-3} and sand content of 41 % by weight of natural peat. The unconfined compressive strength of the test specimen reached 850 kPa after 28 days of curing in water.

Basically, the results proved that in all cases, the strength of stabilized peat increased progressively with the increasing amount of cement and silica sand in the stabilized soil admixture and in most of the cases, the strength of the stabilized peats were higher at high binder dosage if compared to the strength of those with low binder dosage. This leads to the fact that in term of choice of binder and its dosage, the strength gain of stabilized peat is rather binder specific and sand dependant and therefore, the positive reactivity of binders on the strength gain of its stabilized peats requires intensive laboratory testing of the stabilized soils.



Note: Peats from feasibility study
Peat 1 = Water content: 1308%Organic content: 99%
Peat 2 = Water content: 1413%Organic content: 97%
Binder symbols: SH = cement SH P; M1 = Ground granulated blast furnace slag 1; FS = Fine sand; F2 = Fly ash 2; CaO = Quicklime

Fig. 6: Results of shear strength of Orebro peat samples determined by unconfined compression test after storage for 28 days (Axelsson *et al.*, 2002)

Binder symbols: Numbers indicate the proportion of different binders that include: C = cement; M = blast furnace slag from Sweden; V = a Swedish fly ash

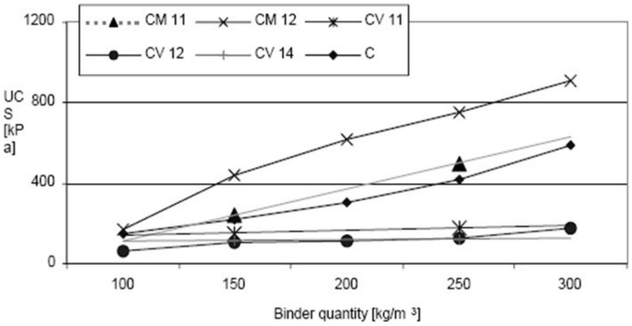


Fig. 7: Effect of binder dosage on unconfined compressive strength of peat from Soderhamn, Sweden 90 days after mixing (EuroSoilStab, 2002)

Table 3: The compositions of the different binders used to stabilize peat in unconfined compression tests (Hebib and Farrell, 2003)

C	Cement
CPL (80, 20)	Cement 80 %; PFA 20 %; Lime 3 %
CPL (60, 40)	Cement 60 %; PFA 40 %; Lime 3 %
CPL (40, 60)	Cement 40 %; PFA 60 %; Lime 3 %
CPL (20, 80)	Cement 20 %; PFA 80 %; Lime 3 %
S	Blast Furnace Slag
SC (60, 40)	Blast Furnace Slag 60 %; Cement 40 %
SG (85, 15)	Blast Furnace Slag 85 %; Gypsum 15 %

Note: PFA = Pulverized Fuel Ash

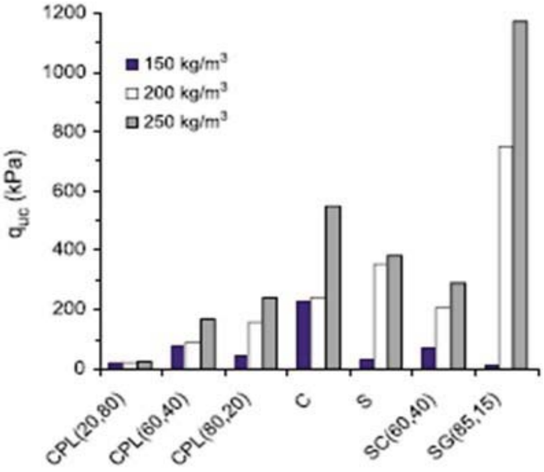


Fig. 8: Unconfined compressive strength for various mixes of stabilized Raheenmore peat specimens (Hebib and Farrell, 2003)

Table 4: Mix design using cement, bentonite, blast furnace slag and gypsum of stabilized Banting peat without sand (Alwi, 2008)

Binder type	Symbols	Description
Cement + Bentonite	CB-1A, CB-1B, CB-1C	1 = 50:50
Cement + Bentonite	CB-2A, CB-2B, CB-2C	2 = 75:25
Cement + Bentonite	CB-3A, CB-3B, CB-3C	3 = 85:15
Blast Furnace Slag + Gypsum	BG-1A, BG-1B, BG-1C	A = 150 kg m^{-3}
Blast Furnace Slag + Gypsum	BG-2A, BG-2B, BG-2C	B = 200 kg m^{-3}
Blast Furnace Slag + Gypsum	BG-3A, BG-3B, BG-3C	C = 250 kg m^{-3}
Cement	OPC-A, OPC-B, OPC-C	OPC = Cement 100 %
Blast Furnace Slag	BFS-A, BFS-B, BFS-C	BFS = Slag 100 %

Note: CB = Cement + Bentonite; BG = Slag + Gypsum; OPC = Ordinary Portland Cement; BFS = Blast Furnace Slag

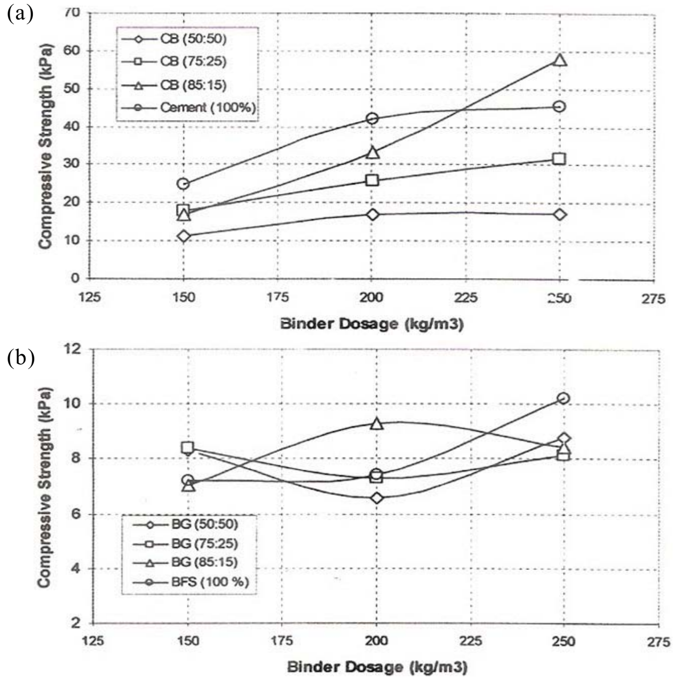


Fig. 9: Unconfined compressive strength of stabilized Banting peat without sand using Cement + Bentonite (CB), Slag + Gypsum (BG), Cement alone (OPC) and Slag alone (BFS) admixtures after 56 days of curing time in water (Alwi, 2008)

Table 5: Mix design using Cement + Bentonite (85 %) of the stabilized peat with sand (Alwi, 2008)

Binder type	Symbols	Description	
		Sand content	Binder content
Cement + Bentonite	CBS-1A, CBS-1B, CBS-1C	1 = 18 %	A = 200 kg m^{-3}
Cement + Bentonite	CBS-2A, CBS-2B, CBS-2C	2 = 26 %	B = 250 kg m^{-3}
Cement + Bentonite	CBS-3A, CBS-3B, CBS-3C	3 = 24 %	C = 300 kg m^{-3}
Cement + Bentonite	CBS-4A, CBS-4B, CBS-4C	4 = 41 %	

Notes: CBS = Cement + Bentonite + Sand

Effect of Curing Time in Water on the Strength of Stabilized Peat:

Investigation on the effect of curing time in water on the strength of stabilized peat showed that the effect of time differed between different mixes of binder as shown in Fig. 11. Utilization of cement as a binder of peat produces stabilization reactions that would almost totally be finished during the first month while the peat stabilization process of materials containing furnace slag or fly ash remarkably continued during several months thereafter (EuroSoilStab, 2002). This leads to the fact that cement needs to be blended with hydraulic latent or pozzolanic materials in order to produce stabilized peat of high long term strength gain. Fig. 11 also proved that stabilization of peat by cement-slag admixture with a ratio of 1 to 1, gave the highest later age unconfined compressive strength gain if compared to that of other types of binder.

However, Hebib and Farrell (2003) argued that the unconfined compressive strength obtained for a particular mixture of binders can be very different for peats having similar water and organic content. Huttunen and Kujala (1996) reported the strength achieved by stabilization decreased with advanced decomposition in all types of peat tested, and this is in agreement with the findings of Hebib and Farrell (2003). In the study of unconfined compressive strength of stabilized Ballydermot peat specimens, Hebib and Farrell (2003) revealed that the strength of the test specimens increased with increasing duration of curing in water. Test specimen with binder of cement at a dosage of 250 kg m^{-3} yielded the highest unconfined compressive strength among all the strength of the test specimens tested in the study (Fig. 12). There was a considerable increase in strength with time over a period of 1 year for cement stabilized Ballydermot peat (Hebib and Farrell, 2003). According to Hebib and Farrell (2003) further, the 90 days unconfined compressive strength of the stabilized peat was about 70 % of its 1 year strength.

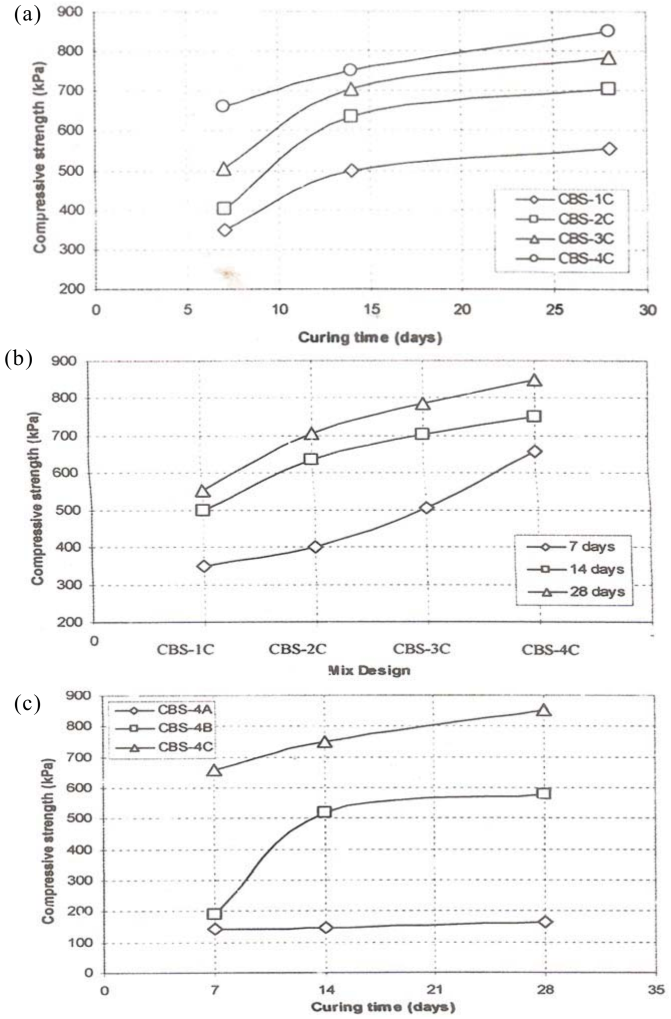
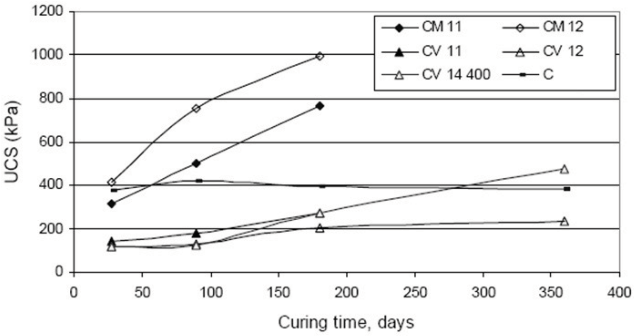


Fig. 10: Unconfined compressive strength of stabilized Banting peat with sand using Cement + Bentonite (CBS) as admixtures after 28 days of curing time in water (Alwi, 2008)



Binder symbols: Numbers indicate the proportion of different binders that include: C = cement; M = blast furnace slag from Sweden; V = a Swedish fly ash

Fig. 11: Effect of curing time in water on unconfined compressive strength of stabilized peat from Soderhamn, Sweden (EuroSoilStab, 2002)

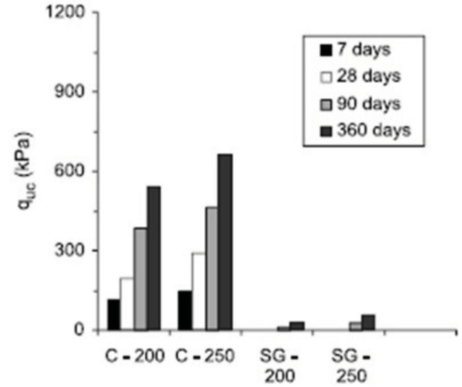


Fig. 12: Effect of curing time in water on the unconfined compressive strength of Ballydermot peat of different laboratory mix designs (Hebib and Farrell, 2003)

Effect on the Permeability and Compressibility of Stabilized Peat:

Stabilization of peat would significantly reduce its permeability. However, the duration of stabilization does not seem to affect its permeability to a large extent. For example, EuroSoilStab (2002) reported that permeability tests on peat with different binders indicated that the permeability of stabilized peat was between 10^{-9} to 10^{-8} m s^{-1} after 28 and 180 days respectively.

The permeability of stabilized peat was also found to be affected by the preloading. Stabilized peat subjected to preloading tend to yield lower permeability as compared to that without preloading. It should be noted that the permeability of preloaded cement-stabilized peat was found to be lower than that of the original peat, whereas for non-preloaded specimens, the permeability was of the same order as that of the original peat (Hebib and Farrell, 2003).

Using standard oedometer consolidation apparatus, Hebib and Farrell (2003) investigated the compressibility behavior of cement-stabilized Ballydermot peat cured in water for 28, 90 and 240 days. For comparison purpose, the void-ratio-effective vertical stress curves of both of the untreated and stabilized peats are shown in Fig. 13. It can be observed from Fig. 13 that there was a significant reduction of compression in the stabilized peats as compared to that of the untreated one. For the cemented peats, the yield stress increased from 18 kPa (i.e. surcharge applied immediately after mixing) to about 210 kPa at 28 days and 520 kPa at 240 days curing time (Hebib and Farrell, 2003). This proves that the yield stress increased with increasing duration of curing in water and the trend of strength gain is in agreement with the progressive increase in strength with the vertical strain of the stabilized soils in unconfined compression tests.

Hebib and Farrell (2003) reported that the ratio of coefficient of secondary compression to compressibility index (c_α / C_c) of the stabilized peat was found to be higher at 28 days than at 90 and 240 days (Figure 13). This shows that the chemical reactions still occurred between 28 and 90 days of curing in water, thus the more was the duration of curing of the stabilized peat in water, the lesser was its ratio of c_α / C_c, implying that it was less compressible after curing for longer time in water.

For a better understanding of the mechanism of compression of the cement stabilized peat, the behavior of the soil in its intact and remolded state are compared in Fig. 14 (Hebib and Farrell, 2003). According to Hebib and Farrell (2003), remolding the specimen at nearly the same water content had no significant effect on the e-log σ'_v curve, suggesting that the intact structure has virtually no influence on the compressibility characteristics of the cement stabilized peat post yield. Furthermore, Hebib and Farrell (2003) stated that when comparing between the intact and remolded (at the liquid limit) behavior, it was suggested that after yielding, some of the cementation components are still contributing to the overall resistance to deformation of the soil.

Alwi (2008) examined the compressibility characteristics of stabilized peats without sand and compared them to the compressibility characteristics of undisturbed and screened peats [Figures 15(a) and 15(b)]. Without stabilization, the compressibility index for undisturbed peat (referred to as in situ peat) was found to be 8.56 whereas, for screened peat, the soil parameter was found to be 2.98. However, after stabilization of the peat with laboratory mix designs of CB-3C, OPC-B and OPC-C, the compressibility indexes were found to be lower at 1.60, 2.00 and 1.24 respectively. This is in agreement with the finding of Hebib and Farrell (2003) that compressibility of peat was reduced after stabilization as compared to that before stabilization. This was largely attributed to the increase in strength of the stabilized soil.

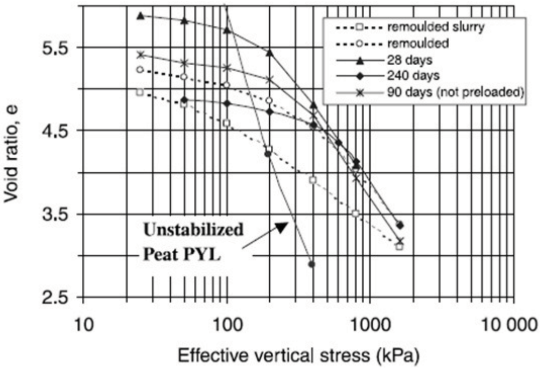


Fig. 13: Void ratio-effective vertical stress curves of untreated and cement stabilized Ballydermot peats (Hebib and Farrell, 2003)

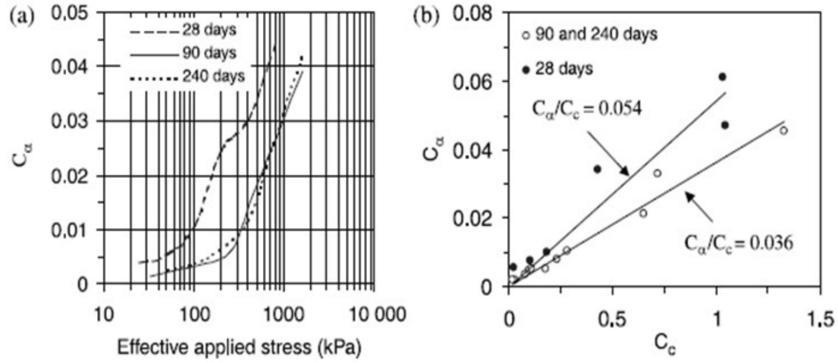


Fig. 14: (a) c_α versus effective applied stress (b) c_α versus C_c (cement-stabilized Ballydermot peat, 200 kg m^{-3}, 90 days) (Hebib and Farrell, 2003)

Effect of Preloading on the Strength of Stabilized Peat:

The strength of stabilized peat is pronouncedly affected by the application of initial load shortly after mixing with binder. Especially when stabilizing peat, an initial surcharge or preloading, in the field has been regarded necessary in order to create a more homogeneous stabilized mass of peat (Ahnberg, 2006). Besides, preloading provides a trafficable bed for the continuous stabilization of adjacent areas, thereby considerably improve the strength of stabilized peat. The effect of preloading on the strength gain contribution to peat stabilized with different binders can be observed in Fig. 16. It can be seen from Fig. 16 that cement-slag admixture provided slightly higher strength gain in stabilized peat if compared to that of cement-gypsum admixture. Basically, the higher the preloading applied on the mass of stabilized peat, the higher the unconfined compressive strength of the stabilized soil is.

In term of long term strength gain, a preload of 18 kPa may increase the strength of stabilized peat soil samples up to several times with the cement-slag admixture showed the highest long term strength gain and improvement in stabilized peat when it was preloaded from 7 days to 1 year as illustrated in Fig. 17. According to Ahnberg (2006), it is not the magnitude of the initial load itself that governs the increase in strength, but the amount of compression resulting from loading. The void spaces between the binder grains and the solid soil particles in peat would be reduced by the compression that occurs under preloading. With the increasing preloading, the compression increases resulting in the decrease of initial density of the stabilized soil and time lapse between mixing and loading (Ahnberg, 2006). Furthermore, the compression will increase in the laboratory with decreasing sample height or similarly, with the distance to permeable soil layers or the ground surface in the field (Hayashi *et al.*, 2005).

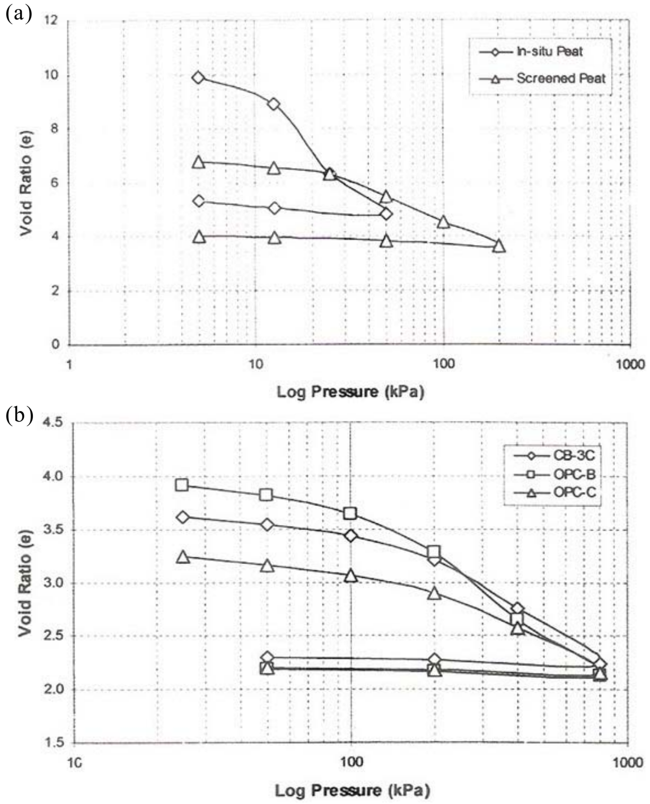
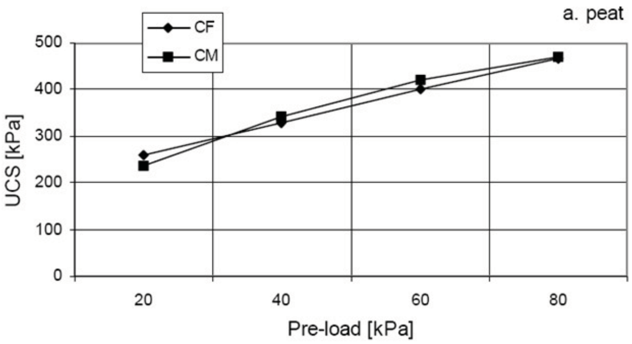


Fig. 15: Void ratio-consolidation pressure curves of (a) untreated Banting peats (b) stabilized Banting peats with sand (Alwi, 2008)

Similar finding was discovered from the study on the effect of initial loading on the cement-stabilized Ballydermot peat by Hebib and Farrell (2003). The preloading of the stabilized peat immediately after mixing appears to be a critical factor in terms of the mechanical behavior achieved after stabilization (Hebib and Farrell, 2003). In the study of Hebib and Farrell (2003), two cement-stabilized Ballydermot peat specimens, each at a binder dosage of 250 kg m^{-3}, were prepared for unconfined compression tests, one preloaded under 18 kPa initial pressure and another without preloading. Both test specimens were cured for 90 days in water. The test specimen subjected to the preloading exhibited significantly higher unconfined compressive strength as compared to that without preloading as shown in Fig. 18. Furthermore, there was barely any increase in strength with curing time after 7 days for the specimens that were not preloaded, whereas for preloaded specimens, the strength achieved at 90 days curing time was almost five-fold higher than that achieved at 7 days (Hebib and Farrell, 2003).

With the addition of binder in peat, the density of the soil would increase, and this lead to the decrease of its void ratio and water content as the soil undergoes the process of stabilization. There will be further increase and decrease respectively, in these properties, with increasing compression caused by the initial loading (Ahnberg, 2006). Fig. 19 shows measured strength versus the water content of various types of stabilized peat after 28 days of curing. Fig. 19 also indicates that a correlation between the strength of the stabilized soil and its water content would give a clear indication that the strength decreases with the increasing water content. The amount of water content of the stabilized soil is governed by the initial compression and binder quantity added to the soil. It can also be observed from Fig. 19 that different types of binder in the stabilized soil would give different measured soil strength with increasing water content. However, the relationship between the water content and the soil strength can be expected to change with time in different ways depending on the type of binder (Ahnberg, 2006).



Binder symbols: C = cement; M = blast furnace slag from Sweden; F = Finnstabi®-gypsum

Fig. 16: Effect of preloading on stabilized peat from Kivikko, Finland (EuroSoilStab, 2002)

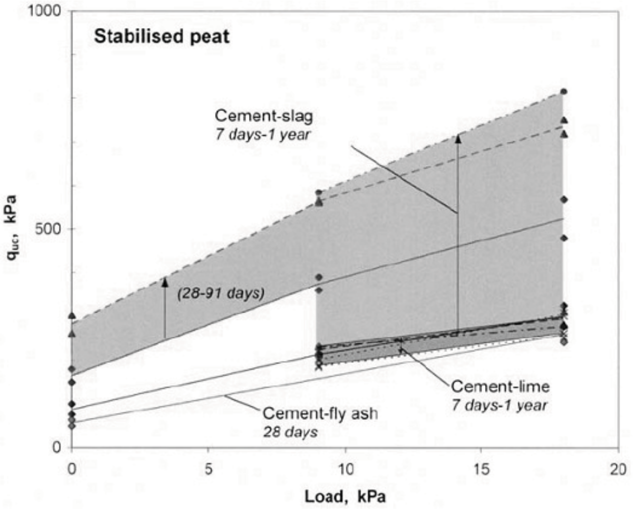


Fig. 17: Measured unconfined compressive strength in stabilized peat samples with preloads of 0, 9 and 18 kPa with binder quantity of 200 kg m^{-3} (Ahnberg, 2006)

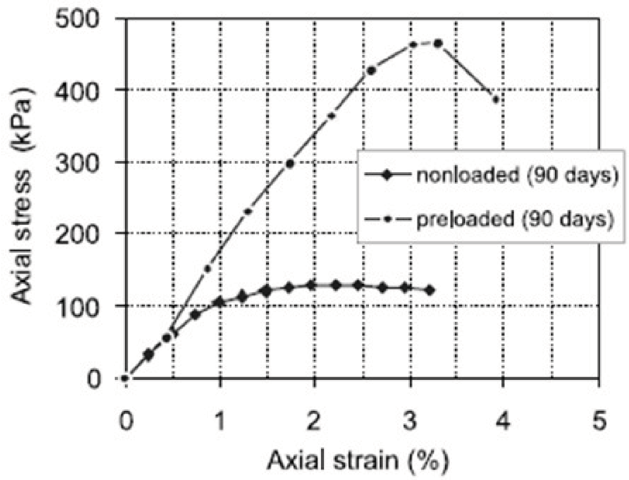


Fig. 18: Stress-strain curves for unconfined compression tests on both preloaded and non-preloaded cement-stabilized Ballydermot peat specimens (250 kg m^{-3}, 90 days) (Hebib and Farrell, 2003)

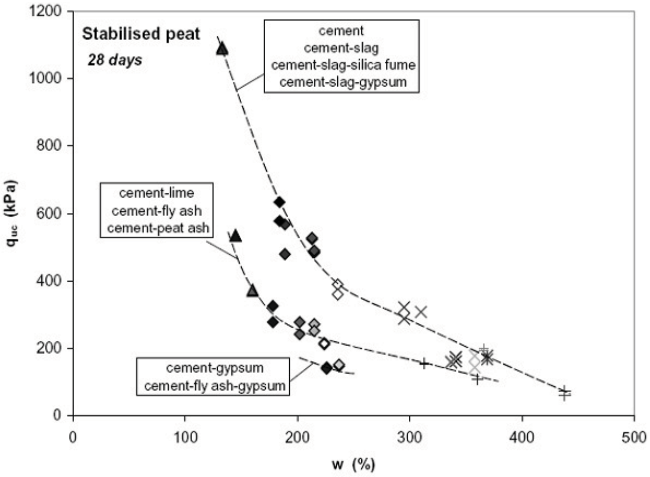


Fig. 19: Measured unconfined compressive strength versus water content in peat samples stabilized with different binders, initial load and loading delay (Binder quantity = 100 - 300 kg m^{-3}; Preload = 9 to 18 kPa; Loading delay = 0.75 to 24 hours) (Ahnberg, 2006)

Conclusion:

It can be concluded that the effectiveness of binder type and dosage on the stabilization of peat is very site specific since the properties of peat differ from site to site. Therefore, different type of peat reacts with different type of binder at certain binder dosage to achieve effective stabilization. Based on the review of various experimental investigations of stabilized peat, it was found that the unconfined compressive strength gain of the stabilized soil increased with an increase in binder dosage, silica sand, preloading and time of curing in water. This is because the stabilized peat became denser with the increase of preloading and silica sand in addition to the formation of more calcium silicate hydrates, the major cementing products in the stabilized soil with higher dosage of binder and prolonged curing time in water. The cementing products actually bond the soil and sand particles together in the stabilized soil to form a load sustainable stabilized material. Basically, the high strength stabilized peat exhibited low permeability and compressibility as a result of its cementation and hardening effects.

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