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Experiences of dry soil mixing in highly organic soils

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Soil mixing, or soil stabilisation, is a method of enhancing the geotechnical properties of suitable host soil through the addition of cementitious and/or pozzolanic binders in either dry or slurry forms. In dry soil mixing, the binder is injected into the soil in powder form using compressed air. Published laboratory experiences of stabilising highly organic soils in dry soil mixing laboratory trials are collated in this paper. A large database of stabilised strengths is compiled from which it emerges that cement and a cement/ground granulated blast furnace slag combination are the most suitable binders for peat soils, and that the ratio of mass of water to mass of binder and the von Post classification H value are important indicators of stabilised strength. The data provide a useful frame of reference for practitioners wishing to select an appropriate binder type and content for mixing trials in peat. Stabilised strength gain over time is discussed, as are issues such as soil temperature, binder temperature sensitivity and prestressing.

1. Introduction

Soil stabilisation/mixing is a form of ground improvement in which cementitious and/or pozzolanic materials are introduced to a soil, with the goal of improving strength and deformation characteristics (e.g. EuroSoilStab, 2001) or confining/remediating contaminated soils (e.g. Al-Tabbaa *et al.*, 2009). Stabilisation can be achieved using either the dry mix method, with air as the medium used to carry the binder, or the wet mix method, where water is the transport medium.

Dry soil mixing (DSM), the focus of this paper, is implemented in the field using either of two main methods: deep dry soil mixing (DDSM) and mass stabilisation. DDSM is a relatively new process developed in Sweden and first used in the 1970s (Bredenberg, 1999) in which stabilised columns are created in soft clays, peats and other weak soils. Using a rig similar to that shown in Figure 1, compressed air is used to inject a binder material into the soil in a dry powder form through holes in a purpose-built mixing tool mounted on a rotating kelly bar, which mixes the binder with the parent soil. The natural water content of the soil initiates the chemical reactions of the hydration process, leading to increased shear strength and reduced compressibility and permeability of the soil mass. Typically, columns have diameters between 0·5 m and 1·0 m in European practice and columns up to 1·5 m in diameter have been formed in Japan; they can be constructed as single units, in rows or in interlocking panels. Treatment depths have exceeded 30 m in Europe and treatment to 70 m has been achieved in Japan. In recent years, mass stabilisation has emerged as an efficient means of stabilising large areas of soft ground to shallow depths of up to 5 m. Stabilisation is carried out in blocks using a mixing tool mounted on the end of an excavator's arm, with mixing occurring horizontally as well as vertically (EuroSoilStab, 2001). In the same way as DDSM, the binder is fed to the mixing tool from a shuttle unit tailing the excavator. Mass stabilisation can also be used in combination with DDSM, for example, where a soft soil profile is particularly soft at shallow depths requiring complete treatment (EuroSoilStab, 2001).

Organic soils comprise a significant portion of the land area of some European countries, for example 17·2% of Ireland and 33·5% of Finland are covered by peat (Hobbs, 1986). Stabilisation offers an alternative solution to 'dig and replace' methods of ground improvement in these soils. However, the stabilisation of organic soils is more challenging than that of inorganic soils, given their inherent variability and the tendency of humic acids to hinder the hydration processes and related reactions required for the development of strength following stabilisation (Axelsson *et al.*, 2002). Although the results of many laboratory dry mixing trials have been published, there is little collated guidance to be drawn upon by geotechnical engineers planning a stabilisation scheme in organic soils and it is generally necessary to resort to site-specific pre-contract binder trials for each new project to

Figure 1. Keller Geotechnique's DDSM rig

appraise technical and economic feasibility. As a first attempt to improve this process, existing European and Japanese laboratory experiences in stabilising highly organic (mainly peat) soils are summarised, primarily from conference proceedings (Bredenberg *et al.*, 1999; Kitazume and Terashi, 2009; Rydell *et al.*, 2005), journal publications and published data from the Swedish Deep Stabilisation Research Centre (SDSRC). In particular, a large database of laboratory trials is used to investigate some of the factors that influence stabilised strength, thereby providing additional guidance for the design of stabilisation schemes.

2. Peat properties and characteristics

Those with experience of testing peat soils will be familiar with the irregularity in classification and property determination owing to the material's natural variability and the high level of subjectivity that is commonly encountered when trying to use seemingly straightforward classification systems. Two different laboratories may classify the same peat in two different ways. With this in mind, some of the most relevant characteristics of peat are discussed in this section.

2.1 Peat humification

Peat is a highly organic soil type, with a substantial natural water content, formed by the decay of the dead remains of organic material rich in carbohydrates into humus (referred to as humification). Hartlén (1996) classifies peat into three simple categories.

(*a*) Fibrous peat which has a low degree of humification. This form will have a distinct plant structure and will produce a brown to colourless, cloudy to clear water when squeezed.
(*b*) Pseudo-fibrous peat has a mid to high degree of humification. The plant structure is now less identifiable and a mushy mass will be extruded when squeezed.
(*c*) Amorphous is the classification used for the most highly humified peat. Very little, if any, of the plant structure remains and on squeezing no free water is released.

More detailed classification systems include the von Post (1922) classification and the Canadian classification proposed by Radforth (MacFarlane, 1969). von Post (1922) provides a very detailed classification based on a range of characteristics, including degree of humification, water content and fibre type and content. Von Post's degree of humification, H, is a scale ranging from H1 (least humified) to H10 (most humified); with fibrous peat in the range H1–H4, pseudo-fibrous in the range H5–H7 and amorphous between H8 and H10. The exact classification of H value can be subjective, and can vary locally within a sample. Hobbs (1986) provides a detailed description of the classification and suggests an extension to include tensile strength, plasticity, organic content, smell and acidity, thereby acknowledging the role that soil science can play in characterising a material that is not easily characterised by traditional engineering parameters.

Humic decay may be either aerobic, that is organic matter is oxidised in the presence of oxygen, or anaerobic, that is material is broken down under conditions of no oxygen. Aerobic decay occurs at a higher rate than anaerobic decay; this is evident in that humification of the acrotelm, that is the upper 0·1 m–0·6 m of a peat profile, occurs at a higher rate than that of the oxygen-deficient catotelm beneath it. After full decomposition there will be no evidence of the original plant structure; all the organic matter will have been broken down and the peat will now have a granular rather than a fibrous form. The rate of humification is higher in peats with higher temperatures (optimum 35–40°C) and a basic nature (that is, $\mathrm{pH} > 7{\cdot}0$), as the organisms that break down the organics are more active under these conditions (Hobbs, 1986).

2.2 Water content

The standard geotechnical definition of natural water content w_i is shown in Equation 1 where m_w and m_s are the mass of water and solids respectively

$$w_{\mathrm{i}}(\%) = 100\,\frac{m_{\mathrm{w}}}{m_{\mathrm{S}}} \tag{1}$$

The value of w_i for peat can range up to many hundreds and even thousands of per cent, as evident in the database summary in Table 1, and can vary within a single peat sample. Fibrous peats with low degrees of humification have higher water contents than more humified granular amorphous peats (Hobbs, 1986). Within a peat, water is stored in three ways (Hartlén, 1996): (i) within large cavities in the peat, (ii) within smaller cavities but held by capillary action, and (iii) held by the physical, chemical and osmotic processes. The proportions of water held by each will depend upon the degree of decomposition of the peat. Fresh peats have high void ratios, with values up to 25 reported (MacFarlane, 1969) and water is found within cavities, whereas amorphous peat void ratios are lower and water mainly exists bound to the particles within the peat. If a peat is dried out, significant shrinkage will occur and oxidation of the peat results in a permanent change to the material. Shrinkage is not as significant in fibrous peats as in amorphous peats, as the fibres act to resist against shrinkage. A peat will not return to its original water content nor will further decomposition occur if it is re-submerged in water.

Another difficulty in comparing moisture contents from different reports is that there is little consensus on the oven temperature to be used in determining the moisture content. General practice for determining the moisture content of a soil is to dry the soil at 105°C ± 5°C (ASTM, 2007; BSI, 1996) but drying organic soils at these temperatures can result in charring and oxidation of the organics, resulting in a higher apparent moisture content (O'Kelly, 2005). Skempton and Petley (1970) endorse the use of 105°C but O'Kelly shows from a series of tests on organic soils, ranging from organic silts to peat (3% to 93% organics), that a temperature of 80°C provides reductions similar to those seen in inorganic soils (evaporation of water rather than charring of organics). Notwithstanding this uncertainty, moisture content is considered to be a primary indicator of changes in peat state as bulk density is notoriously difficult to determine accurately; pore water can be lost owing to the forces applied in sampling, loss of pore gas results in reduced volumes and disturbances can arise in storage and transportation of the sample to the laboratory (Landva *et al.*, 1983).

2.3 Shear strength

In terms of its shear strength, fibrous peat does not act like other soil types. Fibres in the peat act to reinforce the soil and their

Reference	Location	Soil type	w_i: %	ρ: kg/m^3	OC: %	von Post H	pH	Source:
Raheenmore	Raheenmore, Ireland	Peat	1200	1075	98–99	2	5·3	(Hebib and Farrell, 2003)
Ballydermot	Ballydermot, Ireland	Peat	850	1125	94–98	6–9	4·9	(Hebib and Farrell, 2003)
Hernandez	Ireland	Moss Peat	210, 500, 1000	294, 446, 1014	94	6	–	(Hernandez-Martinez and Al-Tabbaa, 2005)
Hömla	Hömla, Sweden	Gyttja	220	1230	10	–	8·5	(Åhnberg and Johansson, 2005)
Söderhamn	Söderhamn, Sweden	Peat	869	–	89	–	5·8	(Lahtinen *et al.*, 1999)
Arlanda (T3)	Arlanda, Sweden	Peat	442	1000	73	8	–	(Axelsson *et al.*, 2002)
Örebro (T1)	Örebro, Sweden	Peat	1308	1000	99	2–3	–	(Axelsson *et al.*, 2002)
Örebro (T2)	Örebro, Sweden	Peat	1413	1000	97	2–6	–	(Axelsson *et al.*, 2002)
Örebro (G1)	Örebro, Sweden	Gyttja	151	1200	8	–	–	(Axelsson *et al.*, 2002)
Arlanda (G2)	Arlanda, Sweden	Gyttja	205	1200	17	–	–	(Axelsson *et al.*, 2002)
Örebro 2	Örebro, Sweden	Peat	1350	980	99·1	–	–	(Axelsson *et al.*, 2002)
Örebro 3	Örebro, Sweden	Peat	1290	980	98·9	–	–	(Axelsson *et al.*, 2002)
Dömle P1	Dömle, Sweden	Peat	1600	950	97	5–7	4·3	(Åhnberg and Holm, 1999)
Adria	Adria, Italy	Peat	375	1070	72	6	6·9	(Cortellazzo and Cola, 1999)
Correzzola	Correzzola, Italy	Peat	690	1075	71	5	4·6	(Cortellazzo and Cola, 1999)
Kivikko	Kivikko, Finland	Peat	668	–	95	–	4·7	(Lahtinen *et al.*, 1999)
Grimsäs	Grimsäs, Sweden	Peat	1022	970	98	4-6	4·3	(Åhnberg and Holm, 2009)
Quigley	Mayo, Ireland	Peat	1019	1000	98	7–8	–	(Quigley and O'Brien, 2010)

Table 1. Compiled data on the stabilisation of peat and gyttja soils and their properties

horizontal orientation provides shear resistance in the vertical direction. In addition, a fresh peat with a high fibre content coupled with a sufficiently high moisture content can have a density below that of water.

Although research in the 1950s by Hanrahan suggested that remoulded peat was purely cohesive (that is, a friction angle of zero), subsequent testing by Hanrahan and Walsh disproved this initial theory by showing that peat was in fact frictional (Long, 2005). The effective friction angle was shown to increase with reducing water content. Long (2005) concludes that the friction angle of peat when tested in triaxial compression ranges widely from 40° to 60°, but that lower angles are obtained from ring shear and direct simple shear tests, noted to be as a result of the reinforcing effect of fibres with a horizontal orientation. Mesri and Ajlouni (2007) provide a table of friction angles for fibrous peats tested in triaxial tests; all are shown to fall between 40° and 60°.

2.4 Gyttja

Gyttja is the Swedish term used for an organic mud-like soil formed in lakes and seas from the deposition of the remains of plants and animals with a high fat and protein content, as opposed to the carbohydrate-rich origin of peats (Hartlén, 1996). Depending upon its origin it can be grey, reddish-grey or greenish-grey when formed in nutritious waters. Organic contents are typically less than 20% with 50% considered as the upper limit (Hansen, 1959). Values of w_i for gyttjas are lower than those seen in peats, lying typically below 300%. Like peat, this soil type shrinks when dried and forms hard clumps. Although gyttjas do not hold the same international interest as peats, some stabilised strength data are available which are included in the strength database to help put some context on the peat results.

3. Binders and stabilisation issues

3.1 Binders

In the early days of DSM, lime was the first binder used but cement binders became popular owing to the greater strength gains achievable. Today, many binders including various cements, ground granulated blast furnace slag (GGBS), gypsum, fly ash and even fillers such as silica sand and limestone are used in soil stabilisation with binder contents ranging between 100 kg/m^3 and 300 kg/m^3 (and greater) depending upon the soil type.

When cement is mixed with an organic soil it reacts with the water within it, starting the hydration process in which calcium (C; CaO) silicate (S; SiO_2) hydrate (H; H_2O) ($C_3S_2H_4$ (CSH)) is formed during hydraulic reactions (Janz and Johansson, 2002). The CSH gel binds the soil particles together, filling voids and becoming stronger and denser with time. Initially the rate of strength gain will be controlled by the temperature; the higher the temperature, the more reactions that take place, leading to better strength gains. In time, the CSH gel formed will hinder the rate of strength gain as the gel slows the release of calcium ions. The ratio of tricalcium silicate (C_3S) to dicalcium silicate (C_2S) within the cement affects the rate of hydration; a high ratio results in greater CSH production and hence greater strengths. Also, the gypsum content of the cement will serve to delay the setting process.

Two forms of lime are used in stabilisation; quick lime (calcium oxide (CaO)) and hydrated lime (calcium hydroxide ($Ca(OH)_2$). When mixed with water, quick lime will react to form hydrated lime but this will not result in any strength gain. The hydrated lime then reacts with the pozzolanic material in the soil and more water to produce CSH, which contributes to strength gain. Lime provides an initial dewatering effect and an increase in pH, but stabilisation results can be poor as humic acids inhibit strengthening reactions. In some cases, failure of the stabilised mass to solidify has been observed (Hayashi and Nishikawa, 1999).

GGBS is a by-product of iron and steel manufacturing processes. It contains a certain amount of lime but requires activation, generally by cement or lime. This allows the latent hydraulic reactions to begin, after which its own lime content provides the calcium hydroxide required for the reactions. The temperature generated during these reactions is low, resulting in slow strength gains, and changes in the temperature of the soil mass can affect the rate of reactions. Thus, initial strengths can be lower than those of mixes using other binders but long-term strengths can be significant. Pulverised fly ash (PFA) is obtained from flue gas in coal-fired power generation plants. PFA, like GGBS, requires activation owing to its low calcium oxide content, achieved using either cement or lime, and is also a temperature-sensitive binder. Its reactivity depends upon its fineness, vitreosity and rate of cooling following manufacture. The calcium hydroxide provided by the added cement or lime reacts with water and the pozzolanic material present in the PFA to start the strengthening process. Reaction rates are low and depend on the amount of calcium hydroxide available and CSH gel with a low tricalcium silicate content is formed, resulting in lower strengths than other binders.

Filler binders such as silica sand and limestone can be used to increase the stiffness of the soil but unlike other binders are practically inert and do not provide any strengthening reactions. They reduce the amount of costly binders required and when used in peat soils they augment the number of solid particles available to be bound together (Axelsson *et al.*, 2002). However, checks need to be carried out to ensure that the increased density of the soil profile and the resulting higher stress states do not lead to excessive subsidence or heaving problems in neighbouring untreated soils. Geosynthetic fibres offer an alternative binder additive to improve strength gains. In a series of laboratory tests Kalantari and Huat (2008) used Portland cement and 12 mm long polypropylene fibres at an optimum 0·15% content in the stabilisation of a H4–H5 peat. Stabilised sample strengths with fibres were observed to be slightly higher than those stabilised without fibres.

3.2 Effect of organics

The organic contents (OC) of peats and gyttjas reported in the literature are given in Table 1. During the stabilisation of organic soils, calcium hydroxide reacts with the humic acids to form insoluble products which coat the particles in the soil. Hebib and Farrell (2003) and Hernandez-Martinez and Al-Tabbaa (2005) inspected stabilised peat samples under an electron microscope and found that there was little or no interaction between the strengthening products created during hydration and the organic material of the stabilised peat. Finnish studies have proposed a binder threshold below which no increase in strength will occur (Axelsson *et al.*, 2002). It is suggested that once this threshold is passed, there is enough binder to cause the pH to increase, neutralising the acids present. Hebib and Farrell (2003) noted the minimum binder quantity for strength improvement to be 150 kg/m^3 for two Irish peats.

Hebib and Farrell (2003) also showed that for a given binder type and content, stabilised strengths can differ from one peat to another; samples from Raheenmore (H2) stabilised with cement showed higher strengths than those from Ballydermot (H6–H9). Likewise, when a GGBS–gypsum binder was used, Raheenmore samples showed excellent strengths reaching nearly 1200 kPa after 28 days with a 250 kg/m^3 content, whereas very poor results were obtained for the Ballydermot peat. The differences in strength of the peats were attributed by the authors to the differences in their extents of decomposition.

3.3 Temperature

Axelsson *et al.* (2002) report that some binders are temperature sensitive, that is the temperature of the soil mass to be stabilised can have a significant effect on the number of reactions that take place and the rate of strength gain. This is not an issue with cement or lime binders, where significant heat is created during the cementitious and pozzolanic reactions; Halkola (1999) reports a temperature of 70°C temperature in lime columns and CIRIA C573 (CIRIA, 2002) notes surprisingly high temperatures of 300–400°C recorded in the centre of lime columns created using the Japanese method up to 3 hours after mixing. Binders such as GGBS produce less heat during the exothermic reactions, and are consequently more susceptible to temperature changes in the soil being stabilised, resulting in fewer reactions and lower initial strengths.

Kido *et al.* (2009) measured the strength of peat stabilised using cement with a high gypsum content and a blast furnace slag cured at temperatures between -20°C and 20°C. Samples cured below 0°C showed little strength improvement using either binder, while samples tested above 0°C showed good strength improvements, especially at 20°C. Analysis of the amount of ettringite formed after 7 days showed very small amounts at low temperatures but large amounts of longer crystals at higher temperatures. Åhnberg and Holm (1999) showed that high curing temperatures can result in lower strength gains. Cement–lime and cement–slag samples cured at 40°C were found to have lower strengths than samples cured at 20°C. They suggest that this may be due to humification under the increased temperatures as gyttja stabilisation under similar conditions showed increasing strength with increasing temperatures.

3.4 Prestress loading

In the field a layer of fill, up to 1 m deep, is generally placed over the stabilised area to compact and remove air entrained in the soil during mixing. Investigations carried out by Åhnberg *et al.* (2001) on the effect of prestress loading on a stabilised peat showed that loading of the freshly stabilised soil was vital in attaining good strength improvements. Samples stabilised with cement–lime and cement–slag at 100 kg/m^3 were loaded with 0 kPa, 9 kPa, and 18 kPa at 45 min (standard delay), 4 h and 24 h after mixing. It was observed that the samples with delayed loading had reduced strengths – in the region of 25% after 45 min and 75% after 24 h when compared to the samples loaded immediately. One possible reason for this is that when the loading is delayed, bonds are created between the soil particles and the effect of the prestress in compressing the void is reduced. Voids will still remain within the stabilised mass, although some will be filled with products from the reactions mentioned earlier. It was also noted that lower strengths were observed in samples with larger diameters and heights than in smaller sized samples from the same stabilised batch. This was thought to be attributable to the larger sample volume and the high variability of peat.

Hebib and Farrell (2003) showed from tests on Irish peats that the permeability of the stabilised samples was reduced by prestressing, whereas the permeability of samples not subjected to prestress was the same as that of the parent peat.

3.5 Laboratory against field results

In most cases, strengths achieved in laboratory tests will not be representative of strengths achieved in the field. In the case of laboratory testing, the unstabilised mass will be mixed to create a uniform homogeneous mass which may not represent the in situ soil throughout its depth. Moreover, any mismatch between the water content of the soil used in the laboratory and that in situ at the time of stabilisation will result in strength differences. In most laboratory tests, the curing temperature used will be in the region of 20°C but the field curing temperature may be much lower, depending upon the location. The lower temperature of the ground to be stabilised will result in a lower reaction rate between the binder and soil; as mentioned earlier, this may have a significant effect on certain binder blends.

Hayashi and Nishikawa (1999) conducted a series of stabilisation tests on a peat soil using various mixing times and rates, and showed that with increased mixing levels, better strength uniformity can be achieved. The authors detailed the ratio of laboratory to field strengths to lie in the range 2–5, with 3 used as the average ratio in practice. Increased mixing in laboratory tests resulted in a closer correlation between laboratory strengths and the evaluated field strengths.

4. Stabilised strength database

4.1 Unconfined compressive strength and moisture contents

Unconfined compressive strength (UCS) is the most commonly used gauge of the strength of stabilised soil samples in the laboratory. The authors have developed a database comprising almost 600 measurements of the UCS of laboratory stabilised peats and gyttjas which have been cured for periods of between 7 and 365 days and at various temperatures.

The largest and most useful subset of this data is reproduced in Figure 2, which presents UCS values measured at 28 days, UCS_{28} (and cured at either 20°C or 21°C under an 18 kPa prestress)

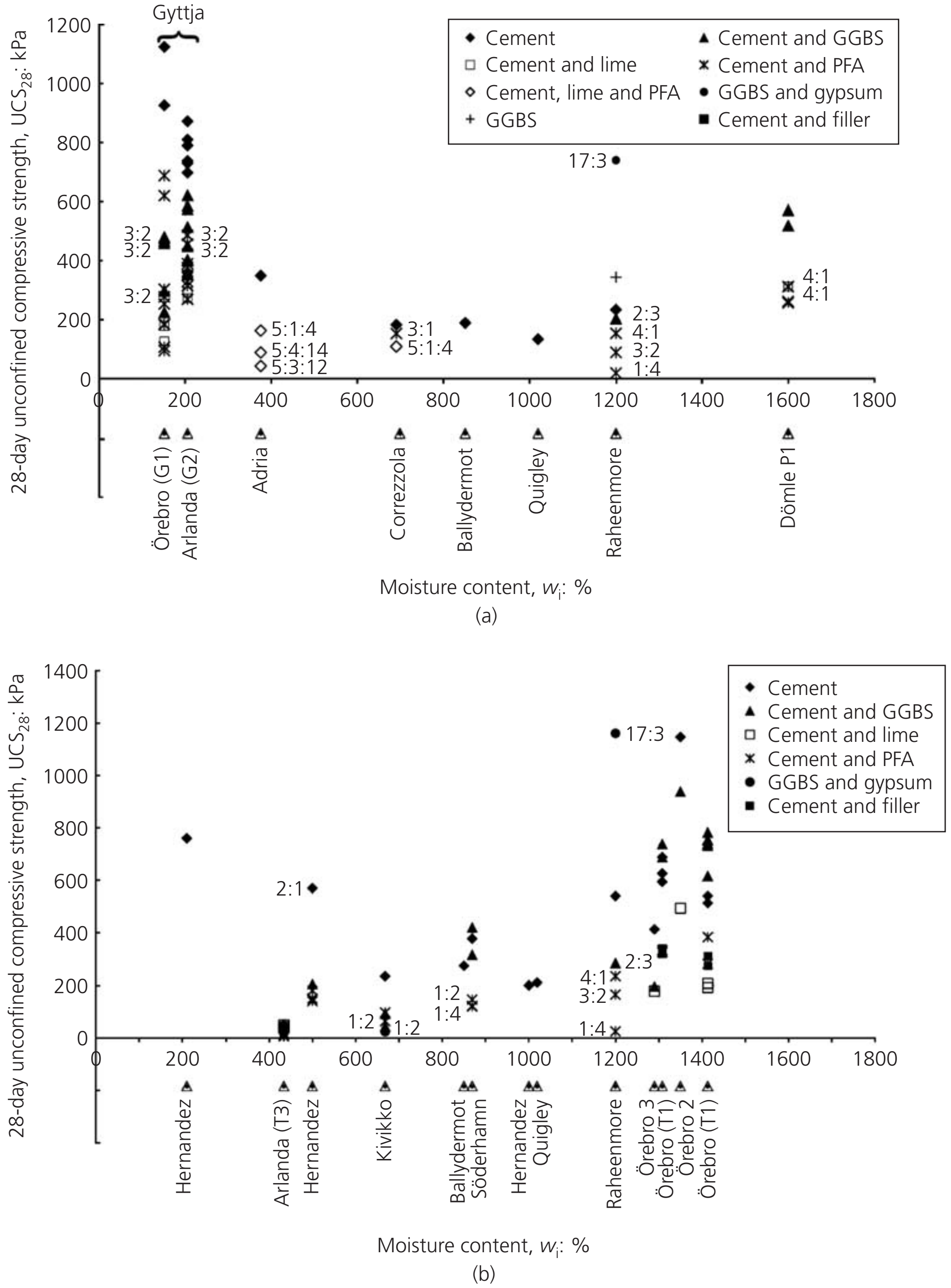

Figure 2. Graphs of unconfined compressive strength against moisture content (a) at 200 kg/m^3 after 28 days' curing; (b) at 250 kg/m^3 after 28 days' curing. Note: all compound binder proportions are split evenly, except where otherwise detailed

plotted as a function of w_i. Two popular binder dosage rates are shown: 200 kg/m^3 Figure 2(a) and 250 kg/m^3 (Figure 2(b)). The sites from which the data have been sourced are annotated on Figures 2(a) and 2(b) and may be cross-referenced with Table 1. All data represent stabilised peats with the exception of those marked as gyttja in Figure 2(a). A careful examination and comparison of these figures reveals the following.

(*a*) UCS$_{28}$ values of stabilised peat and gyttja of up to and beyond 1 MPa are achievable.
(*b*) Higher UCS$_{28}$ values are obtained by using higher binder contents, as expected.
(*c*) Cement and cement–GGBS binders produce consistently higher UCS$_{28}$ values when mixed with peat than other binders. Cement–lime and cement–PFA binders yield poorer strengths.
(*d*) The lower organic content of gyttjas results in higher stabilised strengths, and the database confirms that lower binder contents are sufficient; cement binders appear to be most effective, followed by cement–GGBS blends (Figure 2(a)).

The apparent increase in UCS$_{28}$ with w_i in Figure 2(b) is perhaps misleading as the data for the four highest moisture contents all derive from the same (Örebro) site. Taking the Arlanda and Örebro data from Figure 2(b) in isolation, Axelsson *et al.* (2002) concludes that an increased strength with moisture content may be attributable to the ample availability of water in the soil, allowing for a larger proportion of the binder to be utilised. However, as expected, the general consensus differs; Hernandez-Martinez and Al-Tabbaa (2005) showed reducing strength with increasing moisture content for cement-stabilised Irish moss peat tested at $w_i = 210\%$ and further induced moisture contents of 500% and 1000%. Likewise Hayashi and Nishimoto (2009), who tested three peats of varying moisture and organic contents, demonstrated reducing strengths with increasing moisture and organic content. It appears from Figures 2(a) and 2(b) that moisture content on its own is insufficient as a predictor of stabilised UCS.

4.2 Water to binder ratio

An alternative parameter, the water to binder ratio (η), is defined in Equation 2 as the mass of water per unit volume (m_w) divided by the mass of (active) binder per unit volume (m_b). The mass of water is a function of w_i for DSM as no additional water is added during mixing. Using trials for which w_i, the density of the peat (ρ) and the mass of binder per unit volume (m_b) were all available, η values were calculated using Equation 2 and plotted against respective UCS$_{28}$ values in Figure 3(a) for binders incorporating cement and/or GGBS. For the few data points where the stabilised soil contained some inactive binder content, no adjustments were made to the values of ρ or w_i for calculating η. The references for the data in Figure 3(a) are provided in Table 2

$$\eta = \frac{m_w}{m_b} = \frac{\rho}{m_b[1 + (1/w_i)]} \quad (2)$$

Figure 3(a) shows a prevalence of η values in the range 4 ± 1; indicative of the most popular mixing proportions. Importantly, a general trend for UCS$_{28}$ to reduce with increasing η (for $\eta > 3$ approximately) is apparent for both cement and cement–GGBS mixes; the trend for the cement-GGBS (50:50) mixes is the better defined of the two. From this exercise, it is clear that η is a better indicator of stabilised strength than w_i.

4.3 von Post classification

The data in Figure 3(a) having von Post H values are reproduced in Figure 3(b) to investigate the extent of humification on the UCS$_{28}$ values. The data are grouped according to the H1–H4, H5–H7 and H8–H10 categories defined in Section 2.1; however, two intermediate groups are created for data where the degree of humification range quoted in the literature spans two of those categories. Figure 3(b) shows an approximate yet noteworthy tendency (given the variables involved) for UCS$_{28}$ to decrease with increasing humification. In particular, it is clear that stabilising peats with highest H values (i.e. Axelsson *et al.* (2002) at Arlanda, Quigley and O'Brien (2010), and Hebib and Farrell (2003) at Ballydermot) is most challenging, with stabilised strengths generally falling below 200 kPa.

It is clear that the von Post H value is another important variable. Figures 3(a) and 3(b) used in combination provide a useful means of estimating the UCS$_{28}$ values to be expected from pre-contract trials on peaty soils.

4.4 Statistical analysis

Minitab statistical software was used to perform a regression analysis to investigate the significance of η, organic content and von Post H on the UCS$_{28}$ values with H values included on Figure 3(a). The natural log of the UCS was taken so as to condense the numerical range of the data, and statistical p values were used to test the strength of the relationship between the predictor and response (p values lie between 0 and 1 with values closer to 0 indicative of stronger correlation). The results of the analyses are shown in Table 3, and these must be considered in the context of the following limitations

(*a*) the limited dataset for which all three of the aforementioned variables were available
(*b*) the need to take an average H value where only a range was quoted
(*c*) the absence of information on other relevant parameters, such as mixing energy and the temperature used in ascertaining w_i.

Where more than one UCS$_{28}$ value was available for a given mix, an average was taken.

An analysis on all the data (without distinction between binders) showed H to be the least significant parameter. However, when carried out on cement data alone, the analysis gives η a very high significance with equal significance for organic content and

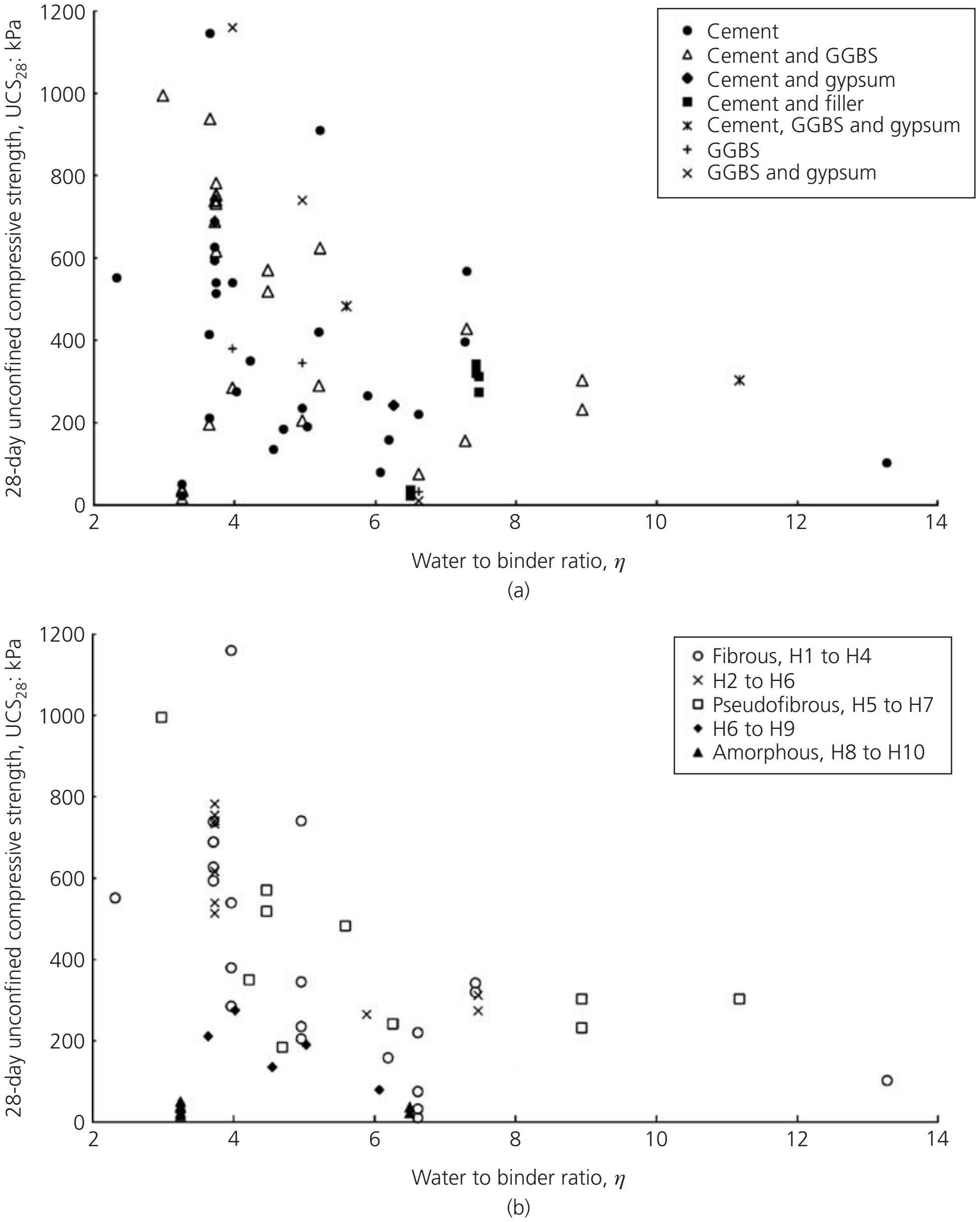

Figure 3. Graphs of unconfined compressive strength against water binder ratio: (a) for cement and GGBS binders in peat; (b) with von Post classification

von Post H; with a coefficient of regression $r^2 = 0{\cdot}548$. When carried out on the cement/GGBS binders equally high significances were seen across η, organic content and von Post H with a higher coefficient of regression $r^2 = 0{\cdot}926$; this stronger correlation is expected given the stronger trend noted between UCS_{28} and η in Figure 3(a). The authors feel that it is inappropriate to provide regression equations given the stated limitations of the analysis; however, this work shows potential for future correlations if adequate and accurate data can be captured from future trials.

4.5 Strength gain over time

Available data showing UCS gain over time (in the form of UCS normalised by the UCS_{28}) are shown in Figure 4. It can be seen that cement and cement-GGBS continue to exhibit strength gain well beyond 28 days, whereas the strength gain from lime is virtually complete after 28 days. Although the cement binders show greater continued strength gain long term, the UCS_{28} values for the cement–GGBS mixes were in fact very high (e.g. UCS_{28} of nearly 1000 kPa was reported for Dömle P1B1 300 kg/m^3). However, there is a need for further data tracking strength gain over time.

Authors' reference:	Binder: (1:1 unless stated)	Quantity: kg/m^3	UCS$_{28}$: kPa	η	Authors' reference:	Binder: (1:1 unless stated)	Quantity: kg/m^3	UCS$_{28}$: kPa	η
Adria1	Cement	200	350	4·22	Arlan T3-4	Cement and GGBS	250	38	3·25
Arlan T3-1	Cement	250	50	3·25	Arlan T3-4	Cement and GGBS	250	15·4	3·25
Arlan T3-1	Cement	250	22	3·25	Arlan T3-6	Cement and GGBS	250	38	3·25
Bally 1	Cement	200	190	5·03	Arlan T3-6	Cement and GGBS	250	34	3·25
Bally 2	Cement	250	275	4·03	Dömle P1 C	Cement and GGBS	200	571	4·47
Corr 1	Cement	200	184	4·69	Dömle P1 B1	Cement and GGBS	100	303	8·94
Grimsås1	Cement	150	265	5·89	Dömle P1 B1	Cement and GGBS	100	232	8·94
Oreb T1-1	Cement	70	102	13·27	Dömle P1 B1	Cement and GGBS	200	519	4·47
Oreb T1-1	Cement	150	158	6·19	Dömle P1 B1	Cement and GGBS	300	995	2·98
Oreb T1-1	Cement	250	626	3·72	Oreb T1-3	Cement and GGBS	250	738	3·72
Oreb T1-1	Cement	250	688	3·72	Oreb T1-3	Cement and GGBS	250	688	3·72
Oreb T1-1	Cement	400	552	2·32	Oreb T2-4	Cement and GGBS	250	754	3·74
Oreb T1-5	Cement	250	594	3·72	Oreb T2-4	Cement and GGBS	250	752	3·74
Oreb T2-1	Cement	250	514	3·74	Oreb T2-5	Cement and GGBS	250	740	3·74
Oreb T2-1	Cement	250	540	3·74	Oreb T2-5	Cement and GGBS	250	616	3·74
Oreb2-1	Cement	125	568	7·30	Oreb T2-7	Cement and GGBS	250	782	3·74
Oreb2-1	Cement	175	910	5·21	Oreb T2-7	Cement and GGBS	250	732	3·74
Oreb2-1	Cement	250	1146	3·65	Oreb2-2	Cement and GGBS	125	428	7·30
Oreb3-1	Cement	125	396	7·28	Oreb2-2	Cement and GGBS	175	624	5·21
Oreb3-1	Cement	175	420	5·20	Oreb2-2	Cement and GGBS	250	938	3·65
Oreb3-1	Cement	250	414	3·64	Oreb3-2	Cement and GGBS	125	156	7·28
Quig1	Cement	150	79	6·07	Oreb3-2	Cement and GGBS	175	290	5·20
Quig2	Cement	200	135	4·55	Oreb3-2	Cement and GGBS	250	196	3·64
Quig3	Cement	250	211	3·64	Rah 6	Cement and GGBS (2:3)	150	75	6·62
Rah 4	Cement	150	220	6·62	Rah 6	Cement and GGBS (2:3)	200	205	4·96
Rah 4	Cement	200	235	4·96	Rah 6	Cement and GGBS (2:3)	250	285	3·97
Rah 4	Cement	250	540	3·97	Arlan T3-3	Cement and filler	250	36	3·25
Corr 4	Cement and Gypsum (3:1)	200	242	4·69	Arlan T3-3	Cement and filler	250	22	3·25
Rah 5	GGBS	150	32	6·62	Oreb T1-2	Cement and filler	250	342	3·72
Rah 5	GGBS	200	345	4·96	Oreb T1-2	Cement and filler	250	320	3·72
Rah 5	GGBS	250	380	3·97	Oreb T2-3	Cement and filler	250	274	3·74
Rah 7	GGBS and Gypsum (17:3)	150	10	6·62	Oreb T2-3	Cement and filler	250	312	3·74
Rah 7	GGBS and Gypsum (17:3)	200	740	4·96	Dömle P1 F	Cement, GGBS and gypsum (2:2:1)	100	303	8·94
Rah 7	GGBS and Gypsum (17:3)	250	1160	3·97	Dömle P1 F	Cement, GGBS and Gypsum (2:2:1)	200	483	4·47

Table 2. Unconfined compressive strength and water to binder ratio for stabilised peats

In 2001, 'EuroSoilStab: Development of design and construction methods to stabilise soft organic soils' was published – the result of collaborative research between six European countries to investigate the stabilisation of organic soils and provides details of the design, testing and construction of soil stabilisation projects in organic soils. The findings of this work provide further support to those detailed in Table 6·1 of EuroSoilStab (2001).

5. Conclusions

Peat soils are problematic in terms of their low strength, high compressibility and high moisture and organic contents. DSM

Binder	No. of data	r^2	p-values		
			η	OC	H
All binders	39	0·329	0·013	0·003	0·776
Cement only	14	0·548	0·021	0·157	0·152
Cement/GGBS only	12	0·926	0·000	0·000	0·001

Table 3. Regression analysis results using Figure 3(b) data

provides an alternative approach to the conventional dig and replace methods used today, with the potential for improved strength and settlement properties, as well as ground remediation in contaminated soils. Conclusions drawn in the paper from a review of previous literature and a new stabilised strength database will assist in the selection of an appropriate binder and binder content in pre-contract mixing trails, which are routinely conducted to ascertain the feasibility of soil stabilisation in organic soils. The conclusions are summarised below.

(*a*) The compiled laboratory results show that stabilisation of organic soils is possible and that significant strength increases can be achieved with cement and cement–GGBS binders, even beyond 28 days. Samples stabilised with lime and fly ash binders show lesser strengths gains than those seen with cement and GGBS binders.

(*b*) 28-Day UCS values of between 100 and 1200 kPa are achievable with stabilisation, providing ample strength for many engineering purposes such as foundations for roads, railways and so on.

(*c*) There is no obvious correlation between 28-day UCS and initial moisture content alone.

(*d*) The 28-day UCS shows some correlation with the ratio of the mass of water to the mass of binder in the mix, and therefore is a more suitable basis for estimating expected strengths at design stage. Highest strengths (within the limits of the database) are achieved at water to binder ratios of $\approx$4.

(*e*) The database has also been used to confirm and quantify (for the first time to this scale) the influence of the degree of humification (as measured by von Post's H classification) on the stabilised UCS value. The difficulties in achieving high stabilised UCS values in highly humified peats emerge; these peats are most likely to have low UCS values to begin with.

(*f*) The trends identified in (*d*) and (*e*) have been confirmed with a statistical analysis of the data, and are encouraging given that it has not been possible to compare mixing energies for the various studies collated. If sufficient care is taken to report the relevant variables in future trials, it may be possible to develop simple design equations to estimate expected stabilised strengths. Other factors are clearly relevant in laboratory testing, such as prestress during curing, host soil temperatures and curing temperatures. Evidence from laboratory and field trials shows strengths achieved in the laboratory will be greater than those obtained in the field owing to factors such as the amount and quality of mixing and uniformity of the soil profile.

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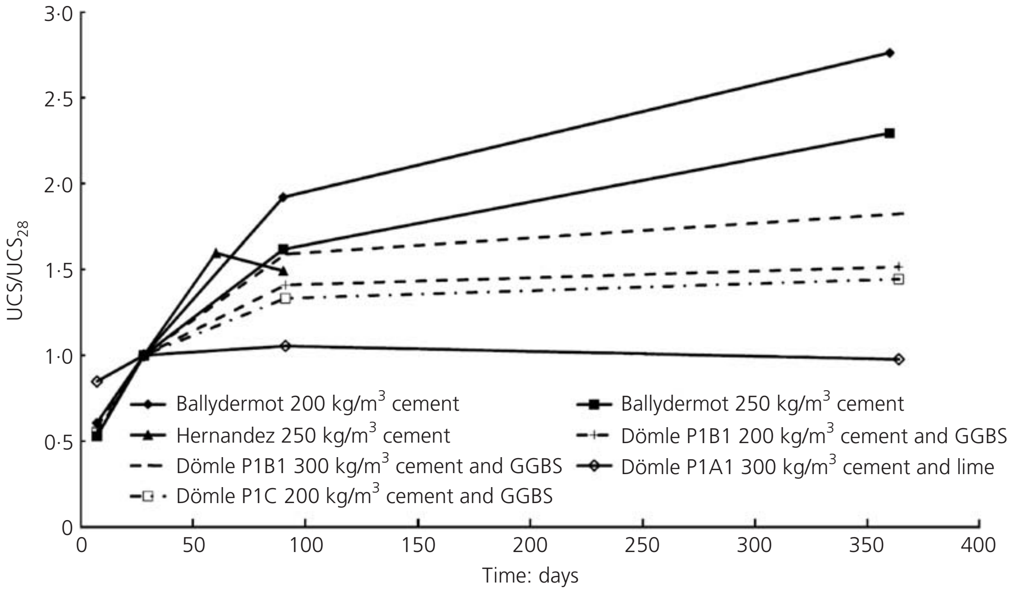

Figure 4. Graph of unconfined compressive strength against time for a number of test data

provided by Dr Dan Adams of Keller Geotechnique in the compilation of this paper.

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