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Laboratory Push-In Resistance Tests (PIRT) in a cement-stabilised pseudo-fibrous peat

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ABSTRACT: Deep dry soil mixing (DDSM) is a form of ground improvement in which dry binders are injected and mixed *in situ*, forming individual columns, rows or interlocking panels, thereby improving the geotechnical characteristics of the host soil. *In situ* strength verification is required to validate designs and is typically achieved using the Push-In Resistance Test (PIRT). Guidance on PIRT bearing factors is almost exclusively based on Scandinavian experience which has limited confidence in the technique internationally; this has prompted a comprehensive suite of laboratory-scale PIRT verification tests in cement-stabilised clay/silt at NUI Galway (Timoney and McCabe 2017). Given that peat soils can be successfully stabilised and that very little of the collective PIRT experience to date pertains to peat, a small supplementary study of PIRT in stabilised peat was carried out, the results of which are reported in this paper. The PIRT bearing factors inferred for stabilised peat are in keeping with those obtained for clay/silt at comparable stabilised strengths.

KEY WORDS: Push-in Resistance Test (PIRT), Kalk-Pelar-Sondering (KPS), stabilisation, deep dry soil mixing, cement, peat.

1 INTRODUCTION

Dry soil mixing (DSM) is a form of ground improvement in which dry cementitious and/or pozzolanic binders (*e.g.*, cement, lime, pulverised fuel ash, gypsum or ground granulated blast-furnace slag in suitable combinations) are injected and mixed *in situ*. Deep Dry Soil Mixing (DDSM) facilitates the construction of stabilised columns (in single units, rows or interlocking panels), while Mass Stabilisation allows for the complete stabilization of a zone of soil, with both versions suited to a wide range of geotechnical and geo-environmental engineering applications [1].

In DSM, binder hydration reactions are initiated by the natural moisture content of the host soil, resulting in a stronger, stiffer and less permeable composite mass. DSM is typically deployed in soils with moisture contents in excess of 40% [2], for example soft clays/silts, peats, dredged sediments and other weak soils. In spite of their high moisture contents, there is plenty of evidence that peat soils can be stabilised effectively [*e.g.* 3,4]; cement or cement-GGBS binders are recommended, at dosages of 150-300 kg/m^3 [1].

Site-specific laboratory trials are routinely used to estimate the stabilised strengths that will be achieved in the field. However, it can be difficult to replicate field conditions in the laboratory [5], given the myriad of technical considerations involved, such as soil and binder characteristics, and mixing and curing conditions [6,7]. Therefore, *in situ* strength verification is essential; for DDSM the most commonly used method is the Push-In Resistance Test (PIRT). Guidance on inferring column strengths from PIRT relies almost exclusively on Scandinavian experience, *e.g.* [8-12], prompting Timoney and McCabe [13] to carry out a laboratory-scale study of PIRT on stabilised organic clay/silt, aimed at offering independent verification to satisfy international interest in the test. Given the potential of peat soils for stabilisation and that very little of the collective PIRT experience to date pertains to peat soils, a small study of PIRT in stabilised peat was carried out as a supplement to the Timoney and McCabe [13] study and is reported in this paper. Bearing factors inferred for stabilised peat are compared with those for clay/silt [13] at comparable stabilised strengths. This work will be of interest to geotechnical engineers in light of recent evidence that stabilised peat can sequester CO$_2$ [14,15,16]; the on-site environmental impact of soil mixing is therefore lower than excavate-and-replace solutions which lead to CO$_2$ release from peat.

2 PUSH-IN RESISTANCE TEST

The Push-In Resistance Test, also known as Kalk-Pelar-Sondering (KPS) in Scandinavia, involves the measurement of the force as a winged penetrometer is advanced through a stabilised column at a constant rate of 20±4 mm/s. Typically, the width of the penetrometer is 75% of the column diameter; a 400mm wide penetrometer is shown in Figure 1.

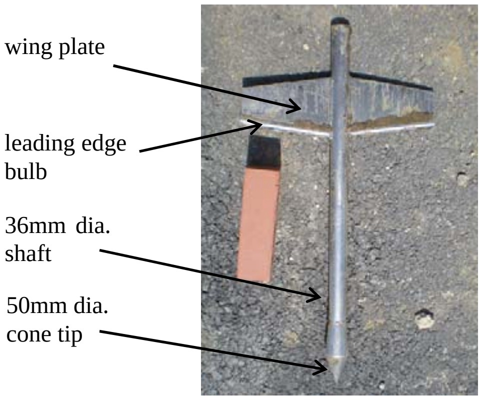

Figure 1. 400 mm-wide PIRT penetrometer

The leading edge has a circular bulb shape to reduce friction along the vertical plate sections of the wing; this is typically 15 or 20 mm in diameter, while the wing thickness is 5 mm less than the leading edge. The cone tip is typically 50 mm in diameter and the sounding rod diameters are between 36 mm and 44 mm diameter. Swedish guidelines [11,12] allow for pre-drilling of columns to reduce the risk of the penetrometer deviating from vertical and exiting the column. Typically, this is applied to columns longer than 6-8 m or with undrained shear strengths (c_u) in excess of 300 kPa. Timoney and McCabe [13] also encountered penetrometer deviation in their reduced-scale tests and predrilling enabled successful testing.

The profile of c_u with depth for a stabilised column is estimated using Equation 1 [17], where P is the PIRT probing force (kN) corrected for sounding bar friction, A is the plan area of the penetrometer in contact with the column (m^2) and N is a dimensionless bearing capacity factor.

$$c_u = \frac{1}{N} \times \frac{P}{A} \qquad [1]$$

Timoney and McCabe [13] have summarised PIRT N values reported in the literature, which range between 8 and 20. The only data relevant to peat soils are attributed to Wiggers and Perzon [18] who backfigured an N value of 20 for overlapping columns in poorly-decomposed peat with clayey interlayers, stabilised with 300 kg/m^3 blast-furnace slag-cement, having c_u values in the range 100-300 kPa.

In their reduced-scale PIRT series on stabilised clay/silt columns under controlled laboratory conditions, Timoney and McCabe [13] found N values to lie in the range 8-13 and established a clear influence of both column confinement and undrained shear strength on N.

3 LABORATORY TESTING

3.1 Peat Properties

Peat is a highly organic soil covering 17.2% (1.2m hectares) of Ireland's land area; blanket bogs (formed over 4,000 years ago) are the most common type in the country, with thicknesses ranging from 1 to 6m [19]. The peat used in this study was taken from a depth of 2-3m at a blanket bog near An Spidéal, Co. Galway. The peat was pseudo-fibrous, classifying as H5-H6 on the von Post [20] humification scale, with natural moisture contents (determined at 105^0C) in the range 775-915%. The characteristics of this peat are provided in Table 1.

Table 1. Characteristics of the An Spidéal peat

Parameter	Value
Natural moisture content (%)	775 – 915
Bulk density (kg/m^3)	955
Loss on ignition (%)	94 – 97
Fibre content (%)	36
Von Post degree of humification	H5 – H6
pH	4.9 – 5.1

3.2 Binder Trials

Binder trials were carried out in accordance with EuroSoilStab [10] protocols for mass stabilisation and further recommendations made by Timoney [21]. For consistency with the work of Timoney and McCabe [13], cement was also used, at dosages of 150 kg/m^3, 200 kg/m^3, 250 kg/m^3 and 300 kg/m^3.

The raw peat was initially mixed in a pan mixer, after removing large roots and fibres, to homogenise the mass. The binder was added and mixed with the peat until the sample was visually homogeneous (after approx. 5 minutes). The mix was then compacted, in 30-40 mm layers, into 65mm diameter and 320 mm high cylindrical moulds and a loading cap placed at the top of the sample. The moulds were mounted vertically into a rack within a curing basin (water at 20°C), with an 18kPa pre-stress (approximating 1m of fill material) placed on each loading cap. At 7 and 28 days, samples were carefully removed from their moulds and 2 no. 130mm high samples were subjected to Unconfined Compression Strength (UCS) testing. A plot of E_{50} (the Young's modulus at a stress corresponding to $c_u = 0.5q$, where q is the UCS value) against c_u for the different binder/time combinations (Figure 2) suggests that E_{50}/c_u lies consistently between 120 and 142 (each point represents the average of two UCS tests). These values are in keeping with those for other stabilised Irish peats [4]. Based on the binder trial results, a cement content of 300 kg/m^3 was selected for use in the subsequent PIRT test series.

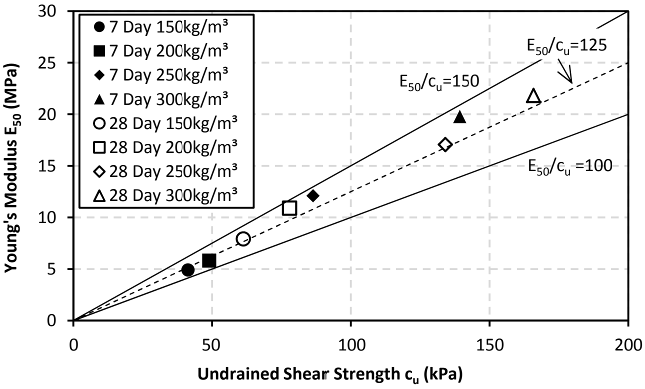

Figure 2. Variation of E_{50} with c_u for stabilised peat binder trials

3.3 Reduced-Scale Penetrometer and Curing Basin

The peat-cement columns were tested using the PIRT facility developed by Timoney and McCabe [13]. The 150 mm-wide reduced-scale penetrometer used was a bespoke one-quarter scale version of a standard 600 mm wide penetrometer (Figure 3). The curing basin consisted of a high-density polyethylene (HDPE) pipe, 0.75 m in diameter and 1.0 m high, sealed at the base with an HDPE base plate, intended to accommodate a centrally-located 0.2 m diameter column (modelling 0.8 m diameter columns at one-quarter scale).

3.4 PIRT Column Construction

Three mixes were required to construct each column; these were generated using the same procedures as used for binder trials. Initial peat moisture content ranges are given in Table 2. The column was constructed as follows (see Figure 4):

(i) Two semi-circular halves of 200mm diameter, 375mm long form pipe were bound together and placed vertically on a thin clay base (raw peat did not provide enough stability for the pipe and column); Figure 4(a).

(ii) A 13 mm diameter steel rod was pushed into the basin floor and maintained central and vertical within the pipe. The peat/cement mix was added to the form pipe in 50mm layers, with each layer compacted using a 65 mm diameter tamping bar and a 96 mm diameter custom-made ram until the form pipe was filled (Figure 4(b)). The surfaces of layers were scarified with an extended fork to aid inter-layer binding.

(iii) The 375 mm form pipe was then carefully removed and replaced with a 800 mm long version. Layers were added to the pipe until the final column height was reached. The form pipe was then gently removed exposing the full length of the stabilised column; Figure 4(c).

(iv) The column was then surrounded with raw peat, added in 60-80mm layers and compacted using a 65mm tamping bar (Figure 4(d)) until the top level of the stabilised column was reached.

Figure 3. 150 mm-wide scale PIRT penetrometer
(inset: wing profile with its 6 mm dia. leading edge bulb)

Table 2. PIRT test details

		PI-A	PI-B	PI-C
Peat initial moisture ct. (%)		743-844	740-767	771-872
Average curing temp. (^{0}C)		19.6	20.2	20.0
Time of PIRT (days)		1.95	6.99	13.85
Time of UCS test (days)		2.28	7.46	14.22
Push-in rate (mm/sec)	P1	12.4	19.6	21.8
	P2	17.8	18.6	22.0

During curing, the basin was stored at a temperature of between 18°C and 21°C (average values in Table 2). The top of the basin was covered with plastic between construction and testing to avoid moisture loss. A small stress was applied to the top of the basin to aid in the curing process.

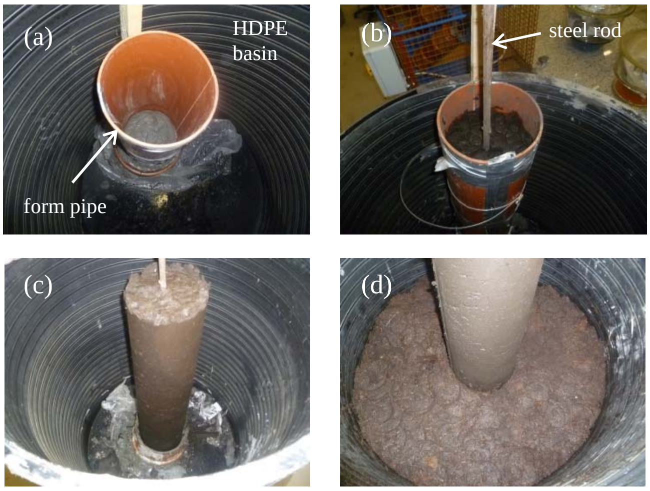

Figure 4. Timeline of PIRT column construction

3.5 PIRT Column and UCS testing

Once the designated curing period was complete, the steel rod was removed from the centre of the column (thereby replicating a pre-drilled hole in the column) and the basin was centred under the PIRT rig (an adaptation of the NUI Galway CPT rig) as shown in Figure 5.

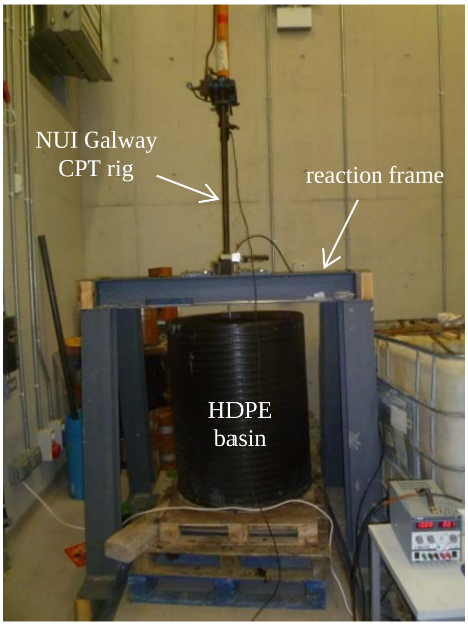

Figure 5. NUI Galway PIRT rig

The PIRT penetrometer was attached to the bottom of the push rod, which in turn was attached to the ram of the CPT rig. A load cell and draw-wire gauge connected to a data acquisition system enabled a force-depth profile to be recorded (Figure 6(a)). The penetrometer was advanced into the column (Figure 6(b)) at the rates shown in Table 2 until the clay base beneath the column was reached (P1 represents the first push before pausing temporarily at $\approx$300 mm depth to facilitate the addition of a second sounding bar; P2 represents the second push). Three PIRTs were carried out on stabilised peat (PI-A, PI-B and PI-C) with nominal curing times of 2, 7 and 14 days, respectively (the exact test times are shown in

Table 2). A fourth PIRT was conducted in the raw peat surrounding the column for comparison.

After each test, the stabilised column was carefully exhumed and laid flat for inspection; see Figure 6(c). Cylindrical specimens, approximately 50mm in diameter and 100-120mm long, were obtained from the column where possible (avoiding areas of cracking) for UCS testing in accordance with EuroSoilStab [10] (Figure 6(d)). Exact UCS test times are also provided in Table 2.

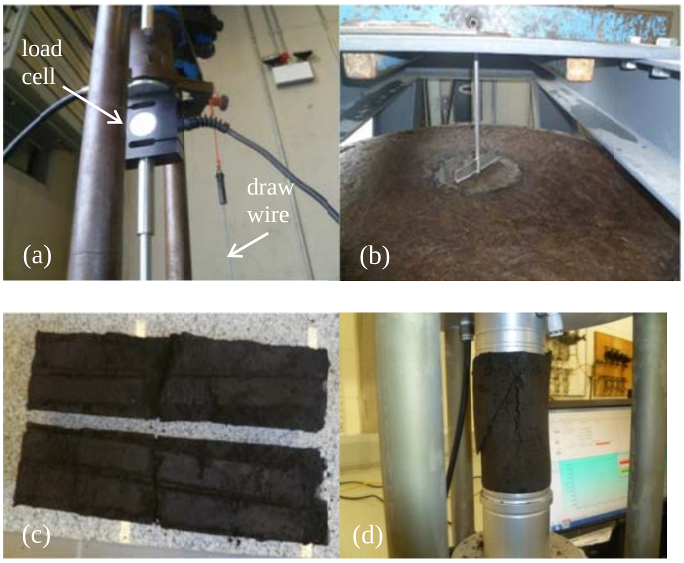

Figure 6. (a) Instrumentation (b) Pre-test set up (c) Exhumed column for inspection/sampling (d) UCS test on 2-day old specimen

4 RESULTS

4.1 *Penetration Force profiles*

The profiles of penetration force (P_u) with depth are shown in Figure 7 for the stabilised peat PIRTs and the single PIRT in unstabilised peat. The P_u profiles for PI-A (2 days) and PI-B (7 days) clearly reflect their different strengths, a function of the curing period, but P_u profiles for PI-B (7 days) and PI-C (14 days) are much closer in magnitude. For PI-B and PI-C, large P_u values were observed upon initial penetration into the column, followed immediately by a sharp drop as a crack propagated ahead of the penetrometer. The increasing jaggedness of the curves (from the unstabilised PIRT, to PI-A, to PI-B and PI-C) reflects a progression in column brittleness (illustrated by [22] using strains at failure), giving rise to increased cracking ahead of the penetrometer. This jaggedness is also reflected in the Wiggers and Perzon [16] data. Similar observations on cracking were made by Timoney and McCabe [13] for stabilised silt/clay.

4.2 *Unconfined Compression Strength testing*

The expected increase in q with curing time is shown in Figure 8. The q values are relatively consistent with depth, given the variability in the host peat and the mixing process. From Figure 9, it can be observed that the dependence of E/c_u on c_u is slightly more pronounced than in the binder trials (Figure 2), possibly due to the different compaction methods applied to mould samples and the column.

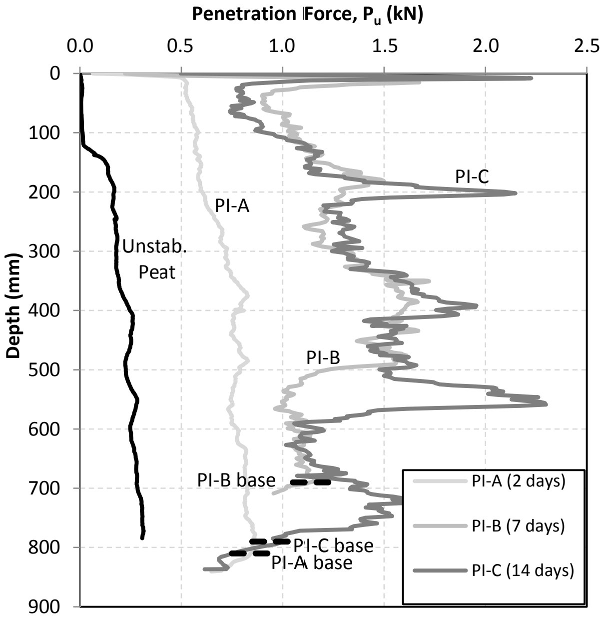

Figure 7. Penetration force (P_u) variation with depth in columns

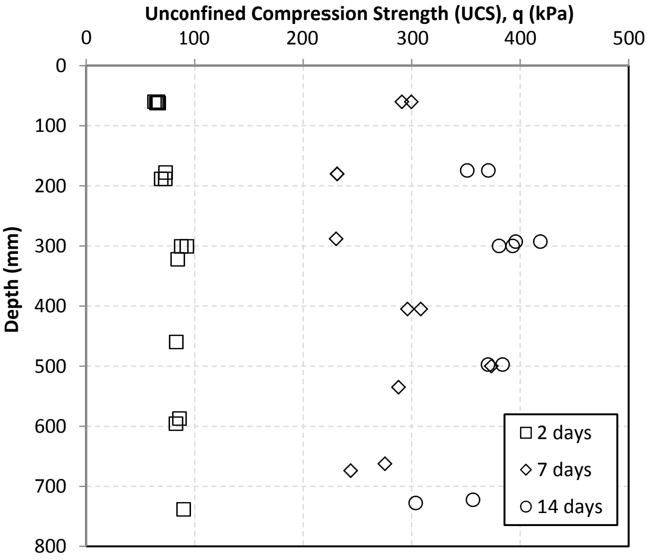

Figure 8. UCS profile with depth (column samples)

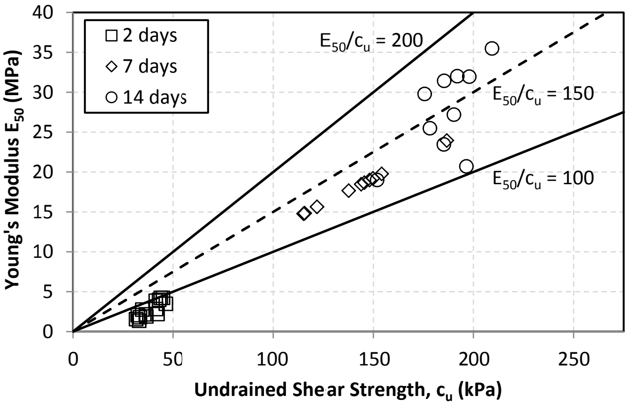

Figure 9. Variation of E_{50} with c_u (column samples)

5 INTERPRETATION OF N VALUES

5.1 Corrected Penetration Force Profiles

Timoney and McCabe [13] performed cone-only tests enabling the frictional contribution of the cone and sounding bar to be deducted from the overall PIRT force profile, as *P* in Equation 1 relates to the contribution of the penetrometer only. No cone-only tests were conducted for the peat series described here. However, examination of the data produced by Timoney and McCabe [13] indicated that the contribution of the cone plus sounding bar consistently amounted to 6-9% of the total penetration force. A cone plus sounding bar contribution of 7.5% was assumed for this peat series.

5.2 Corrected UCS values for time-equivalence

The UCS tests (Figure 8) were unavoidably performed a number of hours after the corresponding PIRT as evident in Table 2. Therefore, a correction to the q value of each sample (to that at the time of the PIRT test) was required to enable accurate N value calculation. Timoney and McCabe [13] proposed a graph of q normalised by water-to-binder ratio against temperature-corrected time as a framework for unifying all data for this purpose. In this instance, the moisture contents and average curing temperatures were very consistent among the three samples (Table 2), so the simpler plot of q against curing time was deemed sufficient. A piece-wise linear relationship was assumed between successive points on this plot, allowing a corrected UCS (q_{cor}) at the time of the PIRT to be estimated (the corrections to UCS ranged from 2% to 17%).

5.3 PIRT N Values

N values were calculated for each individual sample retrieved from the column using Equation 1 with $P = 0.925P_{u,avg}$ (where $P_{u,avg}$ is the average P_u in Figure 7 (calculated over length of the sample) and $c_u = c_{u,cor} = 0.5q_{cor}$. A profile of N with depth is shown in Figure 10. In keeping with previous research [11], a small number of N values were omitted at shallow depths, where cracking ahead of the penetrometer (due to low confining forces from the peat surrounding the column) was believed to have resulted in abnormally low P values. The individual values of N are plotted against corresponding $c_{u,cor}$ in Figure 11, and again indicate that N may be strength-dependent, as found for clay/silt [13].

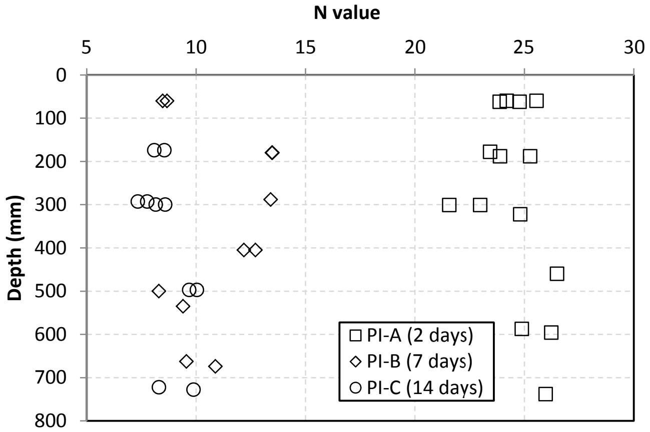

Figure 10. Variation of N value with depth

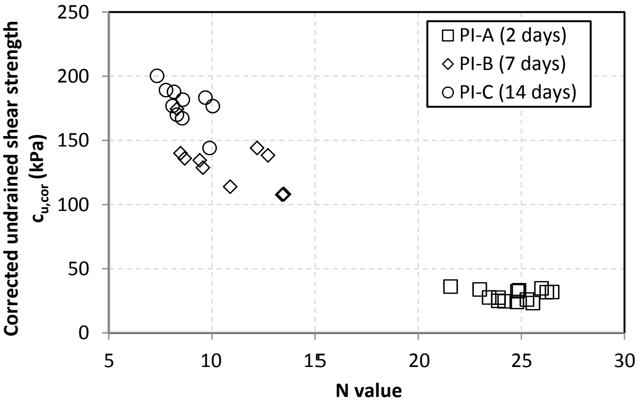

Figure 11. N value variation with corrected undrained strength

In Figure 12, average N values for each of the three stabilised peat columns plotted against the corresponding average corrected strengths $c_{u,cor,avg}$, are superimposed upon the corresponding clay/silt data derived using the same experimental arrangement [13]. The average N value for PI-A (24.6) is higher than those for unstabilised clay/silt values in Figure 12. Given that the strength of this column is relatively low, it is postulated that the fibres may have provided some tensile resistance to passage of the 6 mm diameter penetrometer bulb, thereby inflating P_u values. In general, the graph indicates that the N value may be more closely related to strength than host soil type, at least for $c_u > 50$ kPa. This is a potentially significant finding but requires substantiation through further research.

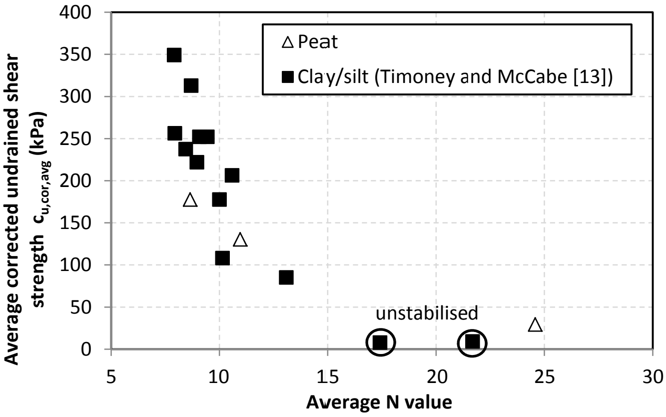

Figure 12. Average N value variation with average corrected undrained shear strength – peat and clay/silt

The N value of 20 quoted by Wiggers and Perzon [18] for stabilised peat in the strength range c_u = 100-300 kPa is significantly greater than the values established for this work, and no strength dependence has been suggested by those authors. The additional confinement around the penetrometer (overlapping columns were used to create a stabilised mass at the Lekkerkerk site, as opposed to single columns in this research) and an alternative means of determining c_u (direct shear testing) may explain the discrepancy between their N value and the more typical values derived from this study and in other published field data.

6 CONCLUSIONS

It is clear from this study that Dry Soil Mixing is an effective method of stabilising peat soils, although binder contents required are typically greater than those needed to stabilise soils (*e.g.* clays/silt) with lower moisture and organic contents.

The PIRT *N* values derived show some scatter as expected, given the inherent natural variability of the peat and the mixing process. The individual values from three columns tested at different curing times lie in the range 7-26, showing the same strength dependence as found for PIRT on clay/silt columns using the same apparatus [13]. Furthermore, the combined peat and clay/silt dataset suggests that the *N* value (corresponding to a particular strength) may be independent of the host soil type, but further research is warranted to investigate this preliminary finding. In addition, further research is required to confirm the applicability of reduced-scale model data to field scale.

7 ACKNOWLEDGEMENTS

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