Exploring the Use of Rock Flour for Sustainable Peat Stabilisation

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ABSTRACT

This paper aims to investigate the mechanical behaviour of peat stabilised with glacial rock flour for foundation construction. Peat, a natural organic soil, presents challenges for construction due to its high compressibility and low bearing capacity. This is an especially acute problem in Scotland (UK) where 25% of the territory is covered by peat. Glacial rock flour, a fine-grained powder produced by the crushing of stone in the construction industry, has been identified as a potential stabiliser for peat. This study evaluates the effect of varying percentages of glacial rock flour on the mechanical properties of peat, considering the Unconfined Compression Strength (UCS). The findings indicate a significant improvement in UCS_{28} of the mixture with the addition of up to 15% rock flour. Hence, it is concluded that peat stabilisation with glacial rock flour can be an alternative, cost-effective, and sustainable solution to the typically used excavate-and-replace technique in peatlands in the UK.

INTRODUCTION

Construction on peatlands

Peat, which is a soft and organic soil, is challenging to access as the water table is usually at or above the ground surface. Due to its low strength and high compressibility, peat is known for its poor mechanical properties, and it is prone to deformation under load. Therefore, when constructing on such soil, geotechnical problems including insufficient bearing capacity or excessive settlement must be considered (Timoney et al., 2012). Ideally, it would be best to avoid building on peat, but in many regions of the world, including Scotland or Malaysia, where peatlands are widespread, avoidance may not be feasible (Bernal-Sanchez et al., 2021).

Constructing roads, housing, or windfarms on peat requires some form of foundation. Typically, three types of foundation exist: a) removing the peat entirely and replacing it with aggregate fill, b) improving the soil (leaving the peat in place), and c) transferring the load through the peat layer to lower level, load-bearing soil/rock layers (Huat et al., 2014). In Scotland (and the rest of the UK), the favoured foundation option for housing has typically been to excavate the peat, particularly in areas where the depth is not greater than 3-4 m, and replace it with a suitable fill to provide a stable base. However, excavating the peat dries sections of the peatland, which has a detrimental effect on the carbon stored in the peat (Evans et al., 2017). This is because drained peat allows stored carbon to decompose readily due to the created aerobic conditions. As a result, Green House Gas (GHG) missions resulting from this method are significantly high (Lindsay et al., 2014), particularly when high volumes of peat are replaced by fills. Bernal-Sanchez and Gaspari (2023) found that alternative approaches to a total peat removal could have a significant abatement effect on the carbon emissions.

Peat-left-in-place techniques

Instead of removing peat, it is possible to use foundation options that leave the peat in place. In Scotland, floating solutions with the use of geogrids to ensure the peat stability are commonly used for constructing access roads to onshore wind farms (NatureScot, 2015). For housing foundations, techniques such as trench fill and conventional driven piling have been utilised in situations where stability of nearby buildings needed to be ensured (Munro, 2004).

Alternatively, mass stabilisation is commonly used in Scandinavia and Japan (Juha et al., 2018), for road and railway embankments and for stabilising dredged materials in land reclamation and erosion control. This technique has also been introduced recently in the UK (ICE, 2020). This option works by injecting suitable dry or wet cementitious and pozzolanic binders into the ground that are mechanically mixed into the peat by means of a mechanical tool (EuroSoilStab, 2010). As a result, it creates a homogeneous mass; either for the whole peat layer or in the form of deep columns, which hardens via curing over time strengthening the ground and reducing any potential settlement. Environmental considerations favour the use of mass stabilisation because its use reduces the need to excavate the peat and avoids any subsequent drainage effects of the surrounding peat (Bernal-Sanchez et al., 2021).

Dry Soil Mixing (DSM) is the main interest of this research paper. DSM normally takes place by adding any cementitious and pozzolanic binders in a dry state to the hosting peat. However, other forms of DSM include the injection of non-reactive binders, e.g. sand, rock flour, etc. The latter are the binders herein studied with a view to minimise the environmental impact.

Timoney et al. (2012) compiled a database of stabilised peat from various locations (i.e. Ireland, Sweden, Finland and Italy) showing Unconfined Compression Strength after 28 days of curing (UCS_{28}). The data includes various cementitious binders such as cement, Ground Granulated Blast Furnace Slag (GGBS), pulverised fuel ash (PFA), and gypsum along with other composite stabilisers utilised in previous studies by other authors. The findings from the study demonstrate that higher UCS values can be achieved with greater binder contents. Cement and cement/GGBS are shown to be the most effective pozzolanic binders to stabilise peat, reaching strength values between 200 and 1200 kPa, sufficient to ensure the foundation stability. The binders are also seen to be more effective as the moisture content of peat is lower. The UCS_{28} values that are provided by this database are of interest as they can be compared to the stabilised strength of the peat mixed with rock studied herein.

Alternatively, Joraf et al. (2013) proposed peat stabilisation with a non-reactive binder (i.e., quartz sand), and they conducted an experimental investigation via the injection of columns. The main advantage of using sand was to avoid any curing time, unlike it occurs with cementitious materials, and its shear strength properties remaining constant over time. It was also observed that Sivakumer et al. (2011) followed a similar column injection methodology to stabilise soft clay formations. The approach was found to promote good drainage in the peat soil which in turn decreased its moisture content over time. The study also showed how the interlocking of the fibres in the peat through consolidation with sand led to enhanced shear strength parameters.

Using as a reference for this paper, other experimental investigations have studied the mechanical behaviour of soils mixed up with rock flour. Ene and Okagbue (2009) discovered that for a lateritic soil, the shear strength and California Bearing Ratio (CBR) improved with increasing a pyroclastic rock dust content. However, it was noted that the initial addition of 2% by mass of rock flour resulted in a destabilising effect which led to a decrease in CBR and UCS values. Adding pyroclastic dust content of 8% by mass resulted in the optimum mechanical behaviour of the studied clay. A prime curing time of 7 days was also noted for the soil mixture when an unsoaked CBR value of 23% was achieved with a corresponding UCS value of 90 kPa. The authors discovered that, as in previous studies undertaken on lateritic soil and lime mixtures, higher quantities of pyroclastic dust beyond the optimum percentage led to a decrease in the bearing capacity of the soil, consistent with previous research undertaken by Bell (1993).

Scope of this study

The study will focus on a specific location of a construction site in Bishopbriggs, Glasgow (United Kingdom), designated as open space. While the northern section contains an active peat bog that requires protection, the degraded southern section offers the potential for residential development. A regional constructor proposed developing the southern section while safeguarding the existing active peat. The presence of a significant amount of degraded peat, with depths of up to 4.9m, in the southern section of the 20ha site was highlighted during the first site investigation. The proposed foundation technique, adopting the aforementioned excavate-and-replace, has been deemed too environmentally damaging due to the volume of soil involved (about 210k m^3). Hence, the Scottish Environmental Protection Agency (SEPA, 2017) objected its construction and asked for alternative (more sustainable) forms of construction. Thus, this paper seeks to evaluate the mechanical behaviour of stabilised peat with an abundant by-product in Scotland, i.e. rock flour, to demonstrate its potential use for foundation construction in peatlands.

Materials

Peat core analysis was undertaken at four localities across the Bishopbriggs site using a Russian auger to extract 0.5m sections which were then laid out to provide a peat depth profile. The consistency of the peat was compared to the conditions described in The Von Post Scale of Humification to provide an estimation regarding the degree of decomposition and to distinguish the different layers present within the ground. Boreholes (BH) 1, 2 and 4 were located within the southern marshy grassland area (where development is being considered) and they were classified as moderately to well decomposed according to the Von Post scale. Whilst BH3 was located within the raised bog, and it was identified to be undecomposed.

A trial pit investigative technique was then selected as a mode of breaking the ground and exposing the underlying peat at each borehole location (BS 5930, 2020). From each trial pit, representative bulk samples of the peat formation were collected and placed into sealed polythene containers to conserve their natural moisture state.

Regarding the peat stabiliser, glacial rock flour was utilised, and it was obtained from Cloburn Quarry in South Lanarkshire, Scotland. Physio-chemical properties were ascertained as a low-carbon Supplementary Cementitious Material (SEM) in the production of concrete. The rock flour is a microgranite by nature having a particle size distribution ranging between 0.038 – 0.125mm with a relatively high moisture content of 61.2%. The potential chemical (i.e. pozzolanic) reaction provided by rock flour is the main reason why this by-product is considered in this study, with the benefit of the significantly lower embodied carbon in comparison with traditional binders, i.e. cement.

Sample preparation

The test specimens incorporated in the mechanical test procedures of this research paper were prepared and formed with reference to the relevant BS 1377-1 (2022) and BS EN 12390-1 (2021) technical standards. Eurosoil-stab (2001) was also followed in this methodology.

The mechanical behaviour of the unstabilised and re-moulded peat was studied prior to the introduction of the binder to provide baseline values representing the host soil. Cubical samples of 100mm side were prepared using the four peat formations obtained from BHs 1, 2, 3 and 4. The virgin peat was placed in the cubical mould in three consecutive layers. Each layer was compressed with 25 blows of the tamping rod to prevent voids in the peat sample. Cling film was used over the exposed face of the specimen to conserve its natural moisture state.

Peat samples from BH1 to BH4 were selected for the experimental investigation of re-moulded and stabilised samples to provide an insight into the stabilisation effects on both active and degraded peat formations. The mixing bowl was then placed on the ‘Hobart’ mixer, the rock flour weighed to the desired % of dry soil and then introduced to the baseline peat. It was then left to mix before the completion of the dry mixing stage.

Testing programme

A test regime was outlined for the unstabilised peat to obtain a benchmark for the compressive strength of each formation. This was undertaken in compliance with the guidance provided by BS 1377-7 (1990) regarding the UCS of civil engineering soils. A maximum value equivalent to 20% vertical strain was interpreted in this study as the specimen ultimate failure point, as in the literature (Timoney et al., 2012), which was also outlined by the technical guidance.

The unstabilised and stabilised specimens were placed onto the ‘Instron 3367’ universal testing machine, and the steel load platen lowered until it was in contact with the leading surface. A plastic load platen was utilised for specimens that lacked stability. Upon test completion, the specimen was removed from the machine and the final volumetric dimensions were measured to provide a means of assessing the deformation and strength samples.

The testing programme consisted of 18 UCS experiments. Initially, four tests were done on the unstabilised peat. Then, seven tests were conducted at 5, 10 and 15% by mass of rock flour after seven days of curing based on two boreholes, one representing degraded peat (BH1) and the other characterising active peat (BH3). Finally, seven more tests were completed on BH1 and BH3 to test the commonly used in the literature UCS_{28}, representing the strength of any re-moulded peat specimen after 28 curing days. The latter will be used to compare it with previous studies focused on the determination of UCS of stabilised soils with other binders.

RESULTS

Immediate test on unstabilised peat (Baseline)

Moisture content was the main parameters studied to ascertain the physical properties of the "baseline" peat. The volumetric dimensions of each specimen were also recorded for shrinkage assessment. Based on the peat's humification, variable moisture content values were achieved in the experimental investigation. As initially interpreted, the active peat (i.e. BH3) appeared to have the highest moisture content of 1127%. This is due to the active nature of the peat as it is still undergoing significant decomposition and humification. Degraded peat samples appeared to have the lowest moisture content with 629% and 646% for boreholes BH1 and BH4, respectively. BH2, also classified as degraded peat, had a relatively high moisture content of 1105%, similar to BH3, the active formation.

The mechanical properties of the baseline peat were assessed through compressive strength testing. A vertical deformation (i.e. strain) of 20% with respect to the original height was viewed as the ultimate failure point of the peat specimens, therefore 5%, 10% and 15% strains were also utilised for analysis. Referring to Figure 1, the active undecomposed peat sample (BH3) showed the lowest compressive strength at 10-15% strain, with values of 2.4 and 3.2 kPa, respectively. Reflecting on one degraded peat samples (i.e. BH1), there is a 47% compressive strength differential (3.5 kPa to 4.7 kPa) in the range between 10% and 15% strain.

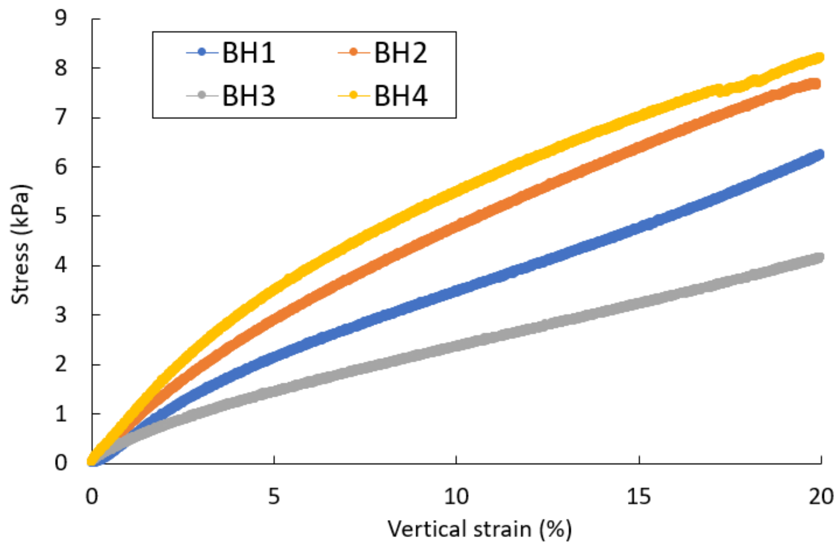
Indeed, the degraded peat specimens (BH1, BH2 and BH4) show in general higher immediate UCS than the active peat (BH3), without significant curing time, which can be expected due to their granular and drier nature. In terms of mechanical strength, Hobbs (1986) also stated that peat with low degrees of humification tends to show greater moisture content than more degraded granular amorphous formations. The degraded specimen taken from BH4 showed the highest values of strength with an UCS of 5.5-6.9 kPa obtained from mechanical testing at 10-15% strain, respectively. Based on the 10% strain criteria, there is more than a two-fold difference in compressive strength between BH4 and BH1, demonstrating the variance in strength of the degraded peat within the same site depending on the peat's humification. A similar observation can be seen in Fig 1 from the 15% strain criteria, where a 100% differential in strength is experienced between BH4 and BH1.

Test on stabilised peat – 7 days curing (UCS_7)

The mechanical properties of both active and degraded peat were calculated by considering the UCS of various samples. For that, boreholes BH3 (active) and BH1 (degraded) were used. Compression tests were thus conducted after 7 days curing at 5, 10 and 15% binder contents (Fig. 2). The physical and mechanical properties are here reviewed.

From the initial 7-day tests, volumetric shrinkage was experienced in all specimens to varying degrees. The vertical shrinkage for all BH1 and BH3 specimens ranged between 36 - 42% for all tested peat cubes. Due to the volumetric shrinkage and curing, significant changes were also experienced in the moisture content of peat specimens. For the stabilised BH1 specimens (i.e., 5 - 15% rock flour), the reduction in moisture content ranged between 70 - 75% after the 7-day curing period. For the active BH3 peat with greater baseline moisture, the specimens withheld water more efficiently for lower binder contents. At 5% binder, a moisture content reduction of 62% was recorded. However, at 15% addition, this reduction increased up to 80%, setting a range of 62 – 80% moisture reduction for the active specimens with respect to the unstabilised.

Figure 1. Stress vs strain for unstabilised peat from BH 1, 2, 3 and 4



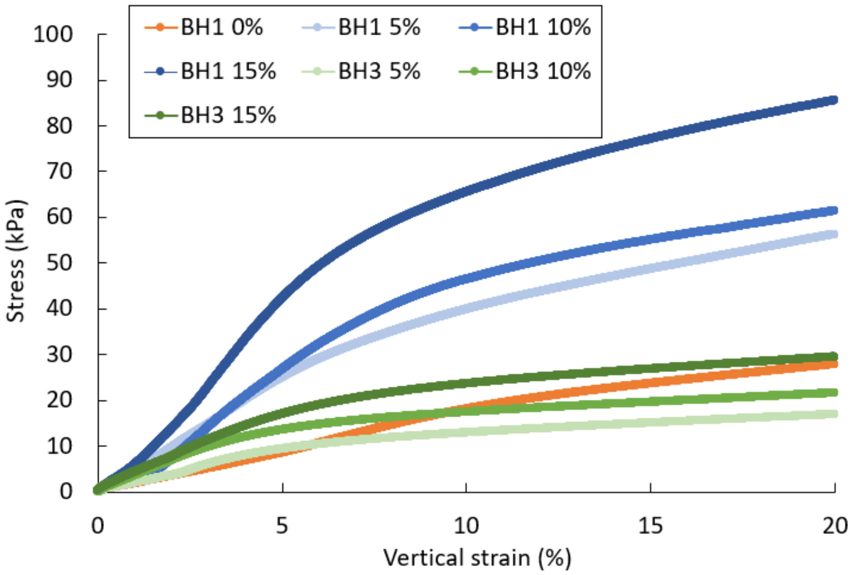
With regards to the mechanical properties after 7 days, an unstabilised (without binder) BH1 peat specimen was tested to assess whether the rock flour provided additional stabilisation. Fig 2 shows all unstabilised and stabilised peat specimens using soil from BH1 and BH3. In comparison to the immediate tests (Fig. 1), it is noted that the shrinkage showed in BH1 peat was responsible for a five-fold increase in the UCS at 10-15% deformation. Hence, the obtained stress values were 17.9-23.5 kPa after 7 days curing, moving from 3.5-4.7 kPa observed after the immediate test. The latter demonstrates the improvement in mechanical strength due to solely the change in moisture content and the evident sample shrinkage.

An increase in UCS is exhibited for the 5 - 15% rock flour addition in both formations, BH1 and BH3 (Fig. 2). For 5% rock flour addition in BH1, an over two-fold increase was experienced in compressive strength at 10% and 15% strains when compared to the cured unstabilised peat. For the 15% rock flour addition in BH1, a nearly four-fold increase is experienced in compressive strength at 10% strain and an over three-fold improvement for 15% deformation. Moreover, a nineteen-fold increase was noted at 10% strain and a sixteen-fold increase for 15% deformation when this value is compared to the baseline peat (Fig 1).

For the BH3 formation, a cured unstabilised specimen was not incorporated due to a lack of material. However, the results can be compared to the ones provided after the immediate testing. Adding 5% rock flour, a five-fold increase was discovered when referring to the baseline BH3 peat's compressive strength at 10% - 15% axial strain. For 10% binder quantity, a further enhancement in mechanical strength was recorded. For 10% - 15% strain, a thirteen-fold increase was exhibited in comparison with the baseline peat value. For the 15% rock flour addition, an over seven-fold increase was discovered for 10% axial strain and a six-fold increase for 15% deformation when referring to the baseline BH3 peat's compressive strength.

In other words, the results point to a slight improvement of the mechanical strength due to the shrinkage effects. However, it is here demonstrated that a significant increase in UCS comes from the reaction between the rock flour and the host peat. This improvement is more significant in the case of the degraded peat (BH1) compared to the active peat (BH3). This is likely attributed to the amorphous condition of degraded peat in combination with the lower moisture content shown in the soil (Timoney et al., 2012).

Figure 2. Stress vs strain after 7 days curing. Peat specimens from BH1 and BH3



Test on stabilised peat – 28 days curing (UCS_{28})

To compare active and degraded peat, samples from BH1 and BH3 were newly utilised. 28-day tests were conducted on BH1 and BH3 at 5, 10 and 15% binder contents (Fig. 3). The findings in terms of physical and mechanical properties are here reviewed.

From the 28-day stabilised peat tests, additional shrinkage was encountered than to those from the 7-day specimens. Similar to the observations made after 7 days, for the degraded peat (BH1), the shrinkage appeared to reduce with increasing rock flour content in the peat. In the 28-day instance, this also holds true for the active peat (BH3) unlike the increase in volumetric shrinkage that was noted at 7 days. The volumetric shrinkage for the BH1 stabilised specimens after 28 days ranged between 65 – 70% when compared to their initial dimensions. In its entirety for 28 days, the shrinkage for all BH3 specimens ranged between 63.5 – 72% when compared to the initial specimen dimensions.

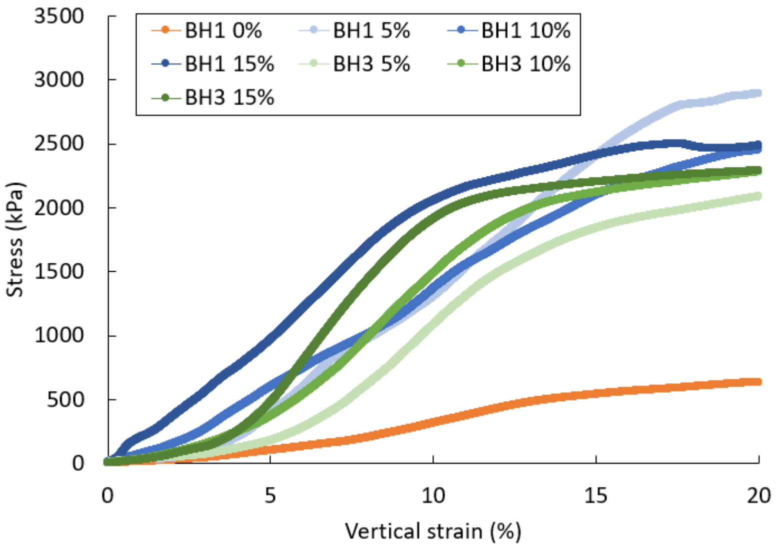
Due to additional volumetric shrinkage and curing, greater alterations were experienced in the peat's moisture content. After the 28-day curing period, all specimens had almost reached a solid state. The degraded formation (BH1) appeared to withhold the greatest amount of moisture over the 28 days. The unstabilised and cured BH1 specimen experienced the greatest reduction in moisture content with a 99.99% moisture loss after four weeks. This observation is similar for the active peat (BH3), where the moisture content also decreased with increasing rock flour additive. Based on its initial moisture content, there was a reduction of over 99.99% over all three soil mix quantities. This is, amongst other factors, the reason why there is such a significant change in the mechanical behaviour of cured peat specimens as explained below.

An unstabilised but cured degraded peat specimen (BH1) was newly incorporated to assess whether the rock flour provided stabilising properties after 28 days, and to exclude the strength gain obtained through the specimen shrinkage. In comparison to the baseline specimen (Fig. 1), it was noted that the specimen's shrinkage was mainly responsible for a ninety-four-fold increase in UCS at 10% strain and over a hundred and fourteen times increase at 15% axial (Fig. 3). By comparing the cured but unstabilised values of BH1 with the stabilised trends, there is an evident increase in UCS with additional rock flour regardless of the volumetric shrinkage. For the 15% rock flour addition in BH1, an over six-fold increase is experienced in compressive strength at 10% strain and a nearly four and half times increase for 15% deformation. This finding is key in the investigation as it verifies that the rock flour does indeed have pozzolanic properties which led to a change in the mechanical behaviour of peat. When compared to the baseline BH1 peat (Fig 1), the UCS improved by more than three hundred and seventy-four times for 10% strain and by five hundred and sevenfold for 15% deformation.

Similar to the observation made at 7 days, the degraded peat (BH1) yielded higher UCS when compared to its BH3 counterpart. Timoney et al. (2012) found that for stabilised peat, the UCS value at 28 days decreases with increasing humification which verifies this observation. For nearly all cases for both formations the compressive strength increased whilst increasing the binder content, with 15% exhibiting the highest compressive strength.

For the BH3 formation, a cured and unstabilised specimen was not incorporated due to a lack of material. For this active peat, the compressive strength increased by 37% between 5 and 10% rock flour addition corresponding to 10% strain and by a strength enhancement of 15% at 15% vertical strain. When the 15% binder quantity parameters (Fig. 3) are compared to the baseline peat (Fig. 2), this equates to an eight hundred and six-fold increase in mechanical strength for 10% strain and a six hundred and eighty-eight-fold enhancement for 15% deformation.

Figure 3. Stress vs strain after 28 days curing. Peat specimens from BH1 and BH3



DISCUSSION

An improvement in compressive strength of peat with rock flour has been observed in Figs. 1-3 with most significant changes occurring between 0-5% rock flour and 10-15% additive. An increase in UCS is also observed at greater deformation levels, characteristic of loose soils, where no obvious peak strength is exhibited by most specimens here studied.

Therefore, unlike it occurred in the literature (Borthakur and Singh, 2014; Ene and Okagbue, 2009), no optimum value has been found in this study in the UCS_7, with a gradual increase in strength with binder contents of up to 15%. This suggests that additional amounts of rock flour could be added in order to further increase the compressive strength of the stabilised peat. After 28 days, the same occurs in the 5-10% vertical strain range, where the UCS is greater as more rock flour is added. However, there appears to be an optimum range around 5% rock flour at larger deformations (15-20% strain), from where the UCS decreases after adding 10-15% rock flour. Given the lack of additional tests, this could be also due to issues in sample preparation and more testing is required to confirm the reached peak strength.

From Timoney et al. (2012), a database of stabilised strengths after 28 days of curing was gathered. The data includes various cementitious binders such as cement, GGBS and gypsum along with other composite stabilisers utilised in previous studies by other authors.

For the unstabilised and cured BH1 specimen, a stress of 635 kPa was achieved. This strength would nearly equate the stabilisation trial that utilised 250 kg/m^3 of Ordinay Portland Cement (OPC) as a binder, where a UCS of 626 kPa was found. A similar mechanical strength of 614 kPa was attained by adding OPC and GGBS in a mix ratio of 1:1 with a binder quantity of 175 kg/m^3. Hence, the high UCS from the unstabilised BH1 specimen after 28 days demonstrates the high influence of the exhibited shrinkage on the mechanical properties of the specimen, as it showed similar compressive strength of peat stabilised with OPC and GGBS binders.

For 5% rock flour additive, a significant increase in UCS was experienced when a value of 2890 kPa was obtained at 20% strain. This mainly demonstrates the pozzolanic properties that the rock flour is adding to the mixture and its impact on the stabilised degraded peat. This equates to an over four-and-a-half-fold increase in UCS when compared to the OPC and GGBS stabilised peat mixtures. At 15% rock flour, an increase in strength was further exhibited when compared to 10% additive, when a UCS_{28} equivalent to 2488 kPa is reached. This translates in a nearly four-fold increase in mechanical strength in relation to other pozzolanic binders.

It is thus observed that the Scottish peat stabilised with glacial rock flour in this paper provides higher unconfined compressive strength values at 28 days in comparison to other stabilising binders. When considering this, it must be noted that the sample preparation and testing methodology has a major influence on this occurrence. Realistically, it would be expected that rock flour binder would not provide the same mechanical strength in stabilised peat as traditional cementitious binders. However, if only relative comparisons are considered between the baseline peat (Fig. 1) and the enhanced (stabilised) peats (Figs. 2-3), it is extensively demonstrated that the addition of rock flour can lead to changes in the mechanical behaviour.

CONCLUSIONS

In regions such as Scotland, where the use of alternative foundation construction methods on peatlands sometimes becomes inevitable, it is crucial to explore environmentally sustainable alternatives to the damaging excavate-and-replace technique. Rock flour, a by-product generated during the production of aggregates through rock crushing, is abundantly available and presents an attractive option for stabilising peat soil. To investigate the mechanical behaviour of re-moulded and stabilised peat with rock flour, a series of unconfined compression strength tests were conducted. The following key findings were obtained:

- Under immediate loading conditions, there was considerable variability in the unconfined compression strength (UCS) among the four unstabilised peat specimens from the same construction site. The degraded peat specimens (BH1, BH2, and BH4) exhibited higher immediate UCS values than the active peat (BH3), which was expected due to their granular and drier nature. All peat specimens demonstrated an increase in UCS with deformation.
- After 7 and 28 days of curing, an improvement in UCS was observed in the unstabilised degraded peat (BH1). This suggests that the shrinkage experienced by all peat specimens contributed to an improvement in their mechanical behaviour. However, both degraded

(BH1) and active (BH3) peat samples stabilised with rock flour exhibited significantly higher UCS values compared to the unstabilised specimens. This improvement can be attributed to the pozzolanic properties imparted by rock flour when mixed with peat.

These results indicate that rock flour presents a viable and more sustainable alternative for foundation construction in peat-dominant areas. It was observed that the cubical specimens exhibited shrinkage during the curing period when subjected to air drying. To address this limitation, an alternative curing regime could be implemented. Additionally, employing a direct shear box test would be appropriate for assessing shear strength parameters. These recommendations will be further explored in subsequent academic papers.

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