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Cement and Silica Fume Treated Columns to Improve Peat Ground

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Abstract Peat layers are weak; much weaker and more compressible than inorganic soils, and thus do not provide suitable support for most engineering structures. The usual methods have been either to remove peat and replace it with suitable soil or to pass piles through it to the stronger soil layers below. On the other hand, research has been carried out to discover ways to strengthen peat deposits by deep stabilization. Peat was reinforced with precast columns stabilized with cement and silica fume. Unconfined compressive strength, Rowe cell consolidation test and plate load test were carried out to evaluate the increase in strength. The compression index (C_c) of peat samples, upon use of stabilized precast columns, was found to reduce by 36 % using only 5 % cement. Further, when 10 % silica fume was added along with cement, the C_c decreased by 42 %. Plate load test results indicated that the bearing capacity of peat can be improved significantly by over 84.6 % when 15 % cement is used, and also the use of silica fume with cement further increased it to 107.7 % compared with untreated peat. The precast stabilized columns (stabilized with cement and silica fume) can be used successfully to improve the engineering behaviour of soft peat deposits and as a result improve its strength and bearing capacity. Finite element analysis was carried out to understand the distribution of stresses in peat as well as in the stabilized column.

Keywords Peat · Cement · Silica fume · Precast column · Compression index · Recompression index · Plate load test

الخلاصة

طبقات الجفث ضعيفة ، وأكثر ضعفا وانضغاطية من التربة غير العضوية ، ولذا لاتوفر الدعم المناسب لمعظم المنشآت الهندسية . وكانت الطريقة المعتادة إما بإزالة الجفث واستبداله بتربة مناسبة أو بتمرير خوازيق خلالها إلى التربة القوية تحتها . من ناحية أخرى ، تم إجراء أبحاث لاكتشاف سبل تعزيز وتقوية رواسب الجفث بوساطة التثبيت العميق . وقد تم تسليح الجفث بأعمدة مسبقة الصب يتم تثبيتها بالإسمنت وغبار السيليكا . ثم إجراء اختبار الضغط غير المحصور ، واختبار خلية رو واختبار لوح التحميل وذلك لتقييم الزيادة في القوة . وقد وجد أن مؤشر الضغط (C_c) لعينات الجفث وعند استخدام أعمدة التثبيت سابقة الصب قد تقل بـ36 % باستخدام 5 % من الإسمنت . كذلك ، عند إضافة 10ف% من غبار السيليكا إضافة إلى الإسمنت فإن الـ C_c تتناقص ب42 % . ودلت نتائج اختبار لوح التحميل على أن قدرة التحمل للجفث يمكن تحسينها بشكل كبير بأكثر من 84.6 % عند استخدام 15 % من الإسمنت وايضا استخدام غبار السيليكا مع الإسمنت أدت الى زياده إضافية مقدارها 107.7 % بالمقارنة مع الجفث غير المعالج . ويمكن استخدام أعمدة التثبيت السابقة الصب (المثبتة بالاسمنت مع غبار السيليكا) بنجاح لتحسين السلوك الهندسي لرواسب الجفث الناعم ، وكنتيجة يحسن من قوتها وقدرة تحملها . كما تم أيضاً إجراء تحليل العنصر المحدد ، وذلك لفهم توزيع الإجهادات في الجفث إضافة إلى الأعمدة المثبتة .

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1 Introduction

Peat represents the extreme form of soft soil. It is an organic soil consisting of more than 70 % of organic matters. Peat deposits are found where conditions are favourable for their formation. In US and Canada, the land covered by peat is around 39 % and in Malaysia, some three million hectares of land is covered with peat [1–4]. The term 'peat' refers to highly organic soil derived primarily from plant materials. It has a dark brown to black colour, a spongy consistency, and organic odour. Usually the plant fibres are visible, but in the advanced stage of decomposition they may not be evident. Peat often occurs in bogs, which are pits filled with organic materials. Among the three types of peat, namely fibric, hemic, and sapric, the fibric or fibrous peat is the most compressible of all [3].

Peat layers are weak; much weaker and more compressible than inorganic soils and thus do not provide suitable support for most engineering projects [5–10]. The most usual methods among engineers so far to deal with peat deposits have been either to remove peat and replace it with suitable soil or to pass piles through it to the stronger soil layers below.

On the other hand, research has been carried out to discover ways to strengthen peat deposits. These methods include peat stabilisation using a mixture of various binders such as cement or lime, and different admixtures such as fly ash and blast furnace slag [11]. The behaviour of peat has been improved by stabilisation techniques where the binders are mixed with the in situ peat to create columnar reinforcement in the ground [1,12].

Black et al. [13] used peat, cement and sand to produce cast-in-situ columns to strengthen peat deposits. Organic deposits have been mixed with inorganic soils also, such as silt and clay, producing a soil that is not as unstable as peat although less stable than inorganic deposits [4]. Forrest and MacFarlane [14] had carried out field studies on the response of plate load test on peat and reported that the stresses applied to peat result in developed pore pressures greater than the increase in vertical stresses. The authors concluded that the occurrence of large strains, with their nonlinear effects, invalidates the linear theory of elasticity used to calculate the stresses in organic soils.

Also, strengthen peat deposits, precast stabilised peat columns that were made of the in-situ peat added with cement with or without additives have been used. These were formed outside the ground in different mould sizes and then placed in the pre-drilled ground boreholes and evaluated for their shear strength [8].

Silica fume is extremely fine and dusty, with a typical particle size equal to 1.016×10^{-4} mm and surface area equal to 19 m^2/g. Cement and silica fume mix shows a much higher strength, compared with when used alone. This siliceous material, which in itself possesses little or no cementitious property, but in finely divided form and in the presence of moisture, it will chemically react with calcium hydroxide to form compounds possessing cementitious properties [15,16]. Detwiler and Metha [17] had observed that cement reacts with water to form calcium silicate hydrate and calcium hydroxide. Silica fume reacts with the calcium hydroxide in the presence of water to form calcium silicate hydrate. This can be attributed to, the authors reported, the silicon dioxide in silica fume, which forms a calcium silicate compound in its hydrate gel state. The reaction of silicon dioxide with calcium hydroxide lowers the alkalinity of the pore solution because of cement hydration resulting in a reduction in the amount of available calcium hydroxide. The increase in calcium silicate hydrate gel results in a reduction in capillary pores in the cement paste, and this seems to be the main factor for increased strength and a reduced permeability.

The consolidation behaviour of peat is extremely complex because of the fact that this peat is highly compressible and may undergo a strain of 50 % and a very large reduction in hydraulic conductivity under very small stress. The consolidation process is also complicated by the occurrence of secondary compression which appears to extend indefinitely, although it is realized that the settlement must ultimately cease [18,19].

Fleri and Whetstone [15] have discussed the life cycle aspects of in-situ stabilization. Toutanji et al. [20] have reported the role of silica fume in increasing the strength of cement-based materials. It can be concluded that secondary compression, rapid changes in hydraulic conductivity and the large strain have a significant influence on the consolidation behaviour of peat. Since the composition of natural peat deposits may vary considerably among different sites, as to so their mechanical properties, the analysis becomes very site specific [15].

Modeling the consolidation behaviour of peat by Karunawardena and Kulathilaka [21] was not very successful due to extreme variation in the coefficient of consolidation with the applied stress. The reason for this was primarily the large changes in the coefficient of hydraulic conductivity and a reduction of void ratio during the consolidation process. Lea [22] and Forrest and MacFarlane [14] also reported similar results. Tan and Oo [23] have successfully modelled stone column installed in soft clay using finite element method.

In the present model study, precast stabilised peat columns with ordinary Portland cement, with and without the addition of silica fume, have been investigated for their compressibility behaviour when they are used in peat. To fulfil this purpose, consolidation tests using Rowe cell apparatus were used. Two important parameters, compression (C_c) index and recompression (C_r) index, which are crucial in compressible behaviour of plain peat as well as plain peat reinforced with columns, were investigated in this research. These parameters were found for undisturbed plain peat as well as for peat reinforced with precast stabilised peat columns. Also, to investigate the bearing capacity of precast stabilized peat columns plate load test has been conducted on plain peat, as well as peat reinforced with stabilized columns.

Finally, finite element analysis using PLAXIS was carried out using the shear strength parameters of peat and stabilized columns obtained from the triaxial test. These shear strength parameters were used to simulate the behaviour of the plate load test to evaluate the effective stresses in peat and the precast stabilized columns.

2 Test Materials

Peat used in the study was collected from various locations in Kampung Jawa, in the western part of Malaysia, and its properties are presented in Table 1.

Ordinary Portland cement (herein after called cement) was used as the binding agent. Silica fume (SF) is used as the additive in the present study. Silica fume is an extremely fine product of high amorphous silica content arising from the condensation of rising vapour given off in the manufacture of ferrosilicon and metallic silicon in high-temperature electric arc furnaces. Silica flume was used as an additive to increase the resistance of the column to compression. Silica fume is a proven pozzolanic material and its pozzolanic activity is estimated at 120–200 % that of cement [16]. The physical and chemical properties of the silica fume are shown in Table 2.

Table 2 Physical and chemical properties of silica fume

Properties	Values
Specific gravity	2.25
Particle size (average)	0.1 μm
Bulk density	2.247 Mg/m^3
SiO_2	93.38 %
CaO	0.67 %
Al_2O_3	0.15 %
Fe_2O_3	0.21 %
MgO	0.10 %
SO_3	0.37 %
Loss on ignition (LOI)	1.46 %

3 Experimental Program

Before examining the effect of precast stabilised peat columns on the compressibility behaviour of peat, routine tests were carried out to determine the index properties, strength and compressibility behaviour of peat. The tests carried out were water content, liquid limit, plastic limit, organic content, fibre content, compaction, unconfined compressive strength, hydraulic conductivity and triaxial (consolidated undrained). Rowe cell consolidation test was also carried out on the undisturbed peat as well as on peat reinforced with stabilized peat columns.

The precast columns used in this study were made of peat with different amounts of ordinary Portland cement (herein after called cement) as well as peat added with cement and silica fume (at its optimum dose). The optimum dose of silica fume is defined as the amount that gives the maximum strength for the stabilised soil. The samples of peat with cement, or peat with cement and silica fume were prepared at their respective optimum moisture contents. The experimental programme consisted of the determination of the index properties of peat, compaction tests, moulding the stabilized columns, drying the columns, inserting the columns into the pre-drilled holes in the undisturbed peat, soaking the samples in water till completely saturated and conducting Rowe cell consolidation test.

3.1 Optimum Silica Fume Percentage Determination Tests

In order to determine the optimum percentage of silica fume to be used in the columns, unconfined compressive strength

Table 1 Properties of peat

Properties	Standard specifications	Values
Depth of sampling		0.05–0.65 m
Moisture content	ASTM D2216	198–417 %
Bulk unit weight		10.23–10.4 kN/m^3
Classification	ASTM D5715	Fibrous
Classification	von Post	H_1–H_4
Liquid limit	BS EN 1997-2: 2006	160 %
Plastic index	ASTM D424-59	Non plastic
pH	BS EN 1997-2: 2006	6.81
Organic content	ASTM D2974	80.23 %
Optimum moisture content	AASHTO T 180-D	130 %
Maximum dry unit weight, $\gamma_{d(max)}$	AASHTO T 180-D	4.89 kN/m^3
Permeability	ASTM D2434-68	0.018 m/day
Initial void ratio, e_0	BS EN 1997-2: 2006	12.55
Compression index, C_c	BS EN 1997-2: 2006	3.64
Recompression index, C_r	BS EN 1997-2: 2006	0.490
Cohesion (effective), c'_u	ASTM D 4767	0.1 kPa
Friction angle (effective), φ'_u	ASTM D 4767	36.64°

(UCS) tests were carried out on the samples stabilized with different amounts of cement and silica fume and air cured for 3 months. The results are shown in Fig. 1.

It is observed that the UCS of peat samples with 10 % silica fume is higher (320 kPa) than for the samples with 5 % silica fume (295 kPa); although the cement content was same at 5 %. Similar behaviour was observed for the samples when the cement content was increased to 15 %. However, this trend of higher UCS with 10 % silica fume showed a reversal when the cement content was more than 15 %. For samples with 25, 40 and 50 % cement, the UCS was higher for samples containing 5 % silica fume.

Hence, for samples with up to 15 % cement, 10 % silica fume gives higher percentage increase in the UCS. On the other hand, for the samples with cement content of 25 % and above, 5 % silica fume gives better results in the UCS test. Although 10 % silica fume gave marginal increase in UCS compared with 5 % silica fume, the authors are of the view that the 5 % silica fume mix will be more economical since silica fume is an expensive material. Based on the results presented in Fig. 1, the precast columns were prepared using the optimum dose of cement and silica fume, for the Rowe cell tests.

3.2 Amount of Cement and Silica Fume to Make Precast Peat Columns

In order to investigate the effect of precast stabilised peat columns on the settlement behaviour, a total of four different amounts of cement was chosen, i.e., 5, 15, 30 and 50 % by weight of wet peat. The doses of 5 and 15 % cement are considered lower dosages and the other two (30 and 50 %) are considered higher dosages. The amount of silica fume added was 5 and 10 % of the weight of the cement added to the samples.

Based on the results obtained from optimum silica fume percentage determination tests, silica fume used for lower dosages of cement was 10 % and for the higher dosages was 5 %. However, the authors are of the view that silica fume being an expensive material, a lower doze should be used wherever possible.

3.3 Soaking Time for Complete Saturation

In order to investigate the time for the complete saturation of the samples, samples of undisturbed peat with a precast column made of peat, 50 % cement and 5 % silica fume at its centre were submerged in water for 2 weeks. The samples were weighed every day for increase in weight until a constant weight was reached and no further weight increase was recorded, indicating the time for the complete saturation of the samples. This particular combination of peat, 50 % cement and 5 % silica fume was chosen for the determination of the time required for complete saturation because this combination showed the highest per cent increase in UCS among all the combinations used.

The result of this test indicated that the sample became fully saturated at the end of 6 days of soaking as no further weight increase occurred thereafter. Therefore, all the undisturbed peat samples with or without precast columns were soaked in water for 6 days prior to being tested in Rowe cell apparatus.

3.4 Compaction Test

For the compaction test, the procedure of gradual drying of peat samples prepared with different amounts of cement and silica fume was adopted in this study. The modified compaction tests were performed, following the procedure mentioned in AASHTO T 180-D, to find out the optimum moisture content (OMC) for the each combination of cement and silica fume. The dry density versus moisture content curves of peat with cement only are shown in Fig. 2a and with cement and silica fumes are shown in Fig. 2b.

The maximum dry density of peat was 0.49 Mg/m^3 at a moisture content of 130 %. The dry density was observed to increase with a corresponding decrease in moisture content when the amount of cement in peat was increased for the

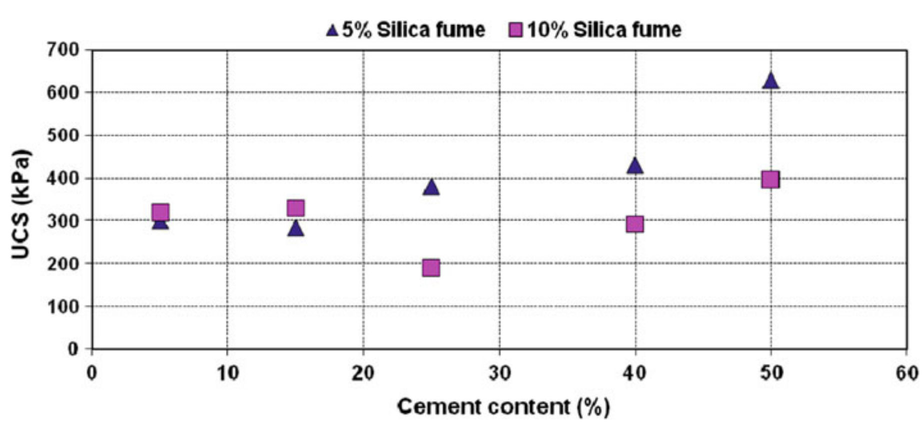

Fig. 1 Strength increase in UCS versus cement

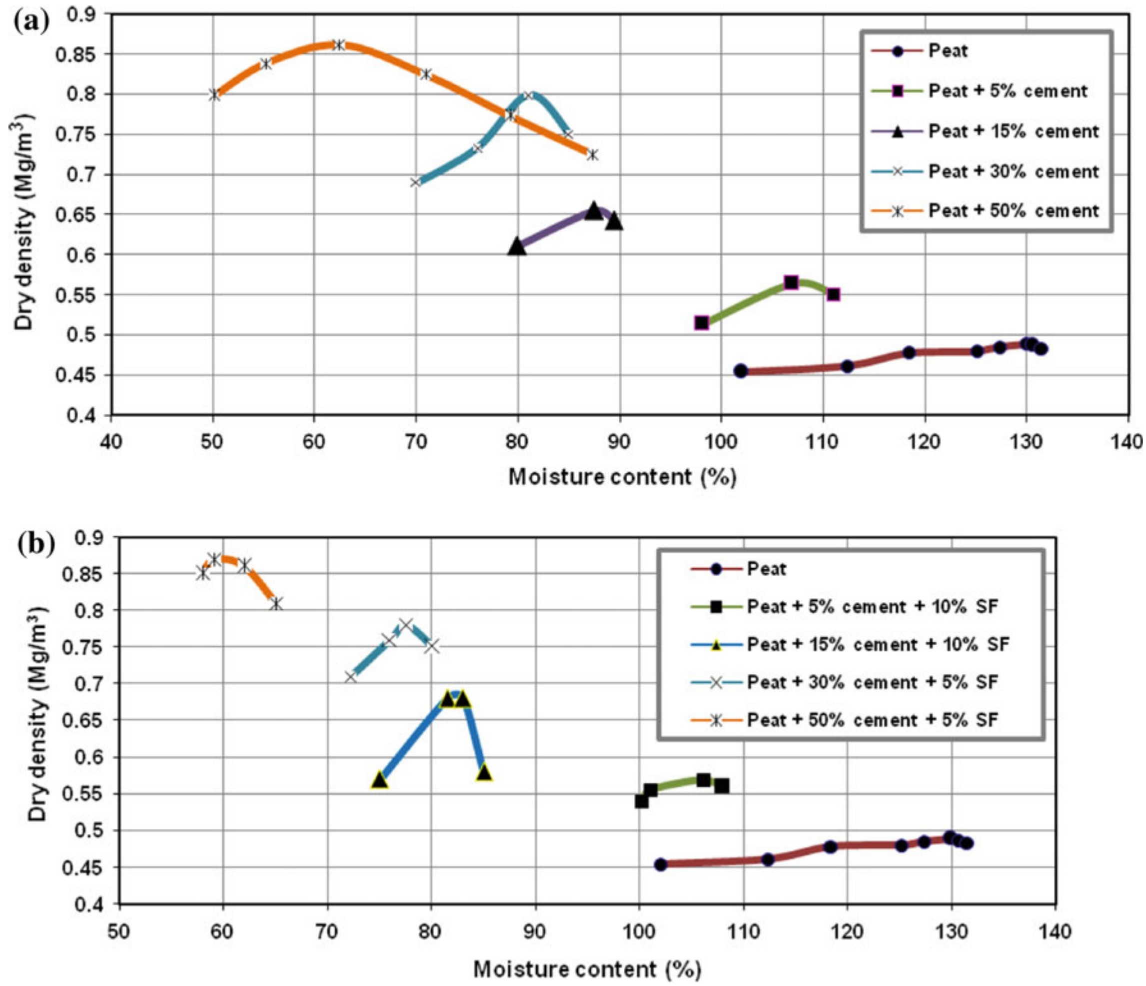

Fig. 2 Dry density versus moisture content curves; **a** peat with cement, **b** peat with cement and silica fume (SF)

entire range of cement studied. A similar trend in increase in dry density and a decrease in moisture content was also observed when silica fumes were added along with cement for the entire range of silica fume added.

The OMC obtained from dry density–moisture content relationship (Fig. 2) was used to prepare precast stabilised peat columns, which were then placed in the centre of the undisturbed peat samples for carrying out the consolidation tests.

3.5 Consolidation Using Rowe Cell

The Rowe cell consolidation apparatus was developed to overcome the disadvantages of the conventional oedometer apparatus while performing consolidation test on non-uniform deposits, such as fibrous peat. It has several advantages over the conventional oedometer apparatus, mainly the hydraulic loading system, the control facilities, the ability to measure pore water pressure and the capability of testing samples of a large diameter [24].

Peat samples used in Rowe cell apparatus were 150 mm in diameter and 50 mm high. The Rowe cell was connected to a computer using the software GDSLAB v 2.2.7, and was capable of recording time, deformation and pore pressure during the progress of the test. The load increment ratio was one (LIR = 1) for the samples and each loading and unloading process was continued for 24 h. The samples were loaded from an initial 20 kPa to a maximum of 320 kPa. After 5 days of loading (20, 40, 80,160 and 320 kPa), each sample was unloaded from 320 to 40 kPa. The drainage, for all the samples, was allowed from one side only. Time, deformation and pore pressure parameters during the test were recorded every 15 s by the computer.

3.6 Preparation of Samples with Precast Columns

The precast columns, made of specified amounts of cement, with or without silica fume, were prepared by compacting them at optimum moisture. The columns were 50 mm in diameter and 50 mm long, and had an area ratio of the 0.11.

The British Standards (BS8006:1995) suggest the optimal spacing between the columns to be in the order of 2.5–3.5 *D* (*D* is the diameter of the column), and in this study the column spacing of 3 was chosen (150/50). The prepared mixture was then transferred into the mould in five layers, and each layer was compacted in accordance with AASHTO T 180-D. The samples along with their moulds were air dried at normal room temperature (30 ± 5° C) and relative humidity (80 ± 5 %). For preparing the samples with a precast column, the mould (150 mm in diameter) was filled with undisturbed peat and a thin-walled steel tube (50 mm in diameter) was pushed carefully into the peat to remove the soil from within the steel tube. The steel tube was then removed and the annular space so created was filled back with the already prepared stabilized column.

Figure 3 depicts the procedure followed to prepare the samples with a precast column at its centre, and afterwards were soaked in water to make it fully saturated, before placing in Rowe cell for testing.

The undisturbed peat was taken in a container. A thin-walled metal cylindrical was pushed quickly in peat to minimize any disturbance. The peat from inside the cylinder was cored out to form an annular opening for placing the column. Afterwards, peat with the additives (stabilized peat) was placed in this annular opening to act as the stabilized column.

The procedure followed for preparing the samples and conducting the tests were same for all the samples of untreated peat, as well for peat treated with stabilized columns. The samples were loaded from 20 to 320 kPa, with a load increment ratio (LIR) equal to one. After each load increment, the sample was allowed to consolidate for 24 h. After reaching the final load of 320 kPa, the sample was unloaded in one step to 40 kPa.

The compression (C_c) and recompression (C_r) indices of undisturbed peat and peat stabilized with precast column were calculated from the results of Rowe cell test and are presented in Fig. 4.

The change in void ratio of peat and stabilized peat samples was evaluated for a wide range of pressure. The pressure applied to the samples ranged from 20 to 320 kPa. The void ratio versus pressure (e-log p) diagram of untreated peat, peat with 15 % cement, and peat with 15 % cement and 10 % silica fume is presented in Fig. 5.

The change in stress at failure due to addition of cement and silica fume was evaluated and the results in terms of stress–strain curves of selected samples are shown in Fig. 6. The samples were loaded up to a strain of 14 %; the curves became almost asymptotic after 10 %.

3.7 Plate Load Test

In order to evaluate the bearing capacity of peat stabilized by precast columns, plate load test (PLT) was carried out in a specially designed and fabricated circular steel test tank, 0.6 m in diameter and 1.5 m high, as shown in Fig. 7a.

Fig. 3 Column installation procedure: **a** Undisturbed peat sample. **b** Thin-walled metal tube cutters inserted in the undisturbed peat. **c** Sample with hole prepared for the column. **d** Stabilized peat column inserted in the undisturbed peat sample

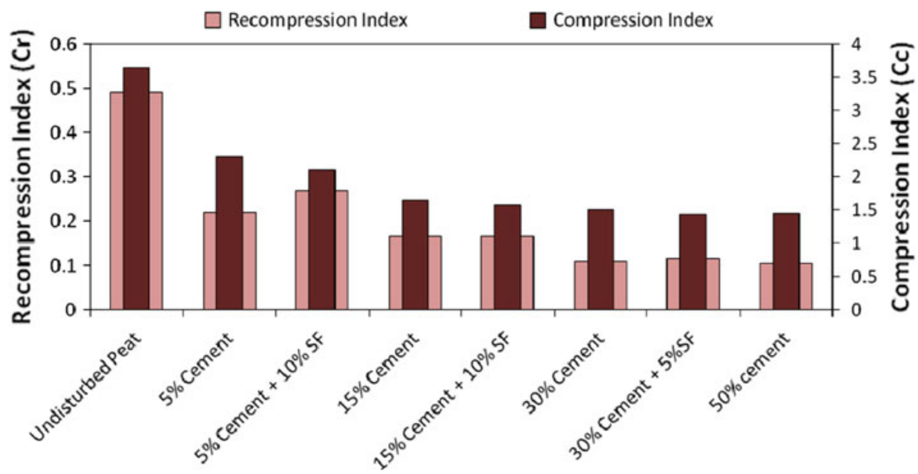

Fig. 4 Compression and recompression index of peat and stabilized peat samples

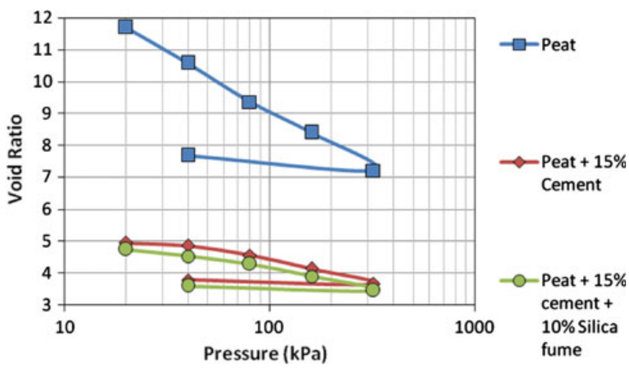

Fig. 5 Void ratio versus pressure diagram: **a** peat, **b** peat with 15 % cement and **c** peat with 15 % cement and 10 % silica fume

For carrying out the plate load test, the tank was filled with peat up to a depth of 1.0 m. It had a provision to apply the load using a loading plate of 0.6 m diameter and the load was measured using a load cell. The displacement of the loading plate was measured using linear variable displacement transducers (LVDTs), and these, along with the load cell were connected to a data logger. A preliminary estimate of the ultimate capacity was carried out and the loads were applied in ten steps. In accordance with ASTM D1194, an initial estimate of the ultimate load capacity was required to estimate the magnitude of load increments to be applied. ASTM D1194 mentions, "Apply the load to the soil in cumulative equal increments of not more than 1.0 ton/ft^2 (95 kPa), or of not more than one tenth of the estimated bearing capacity of the area being tested". The load-deformation response during unloading phase was not carried out as the main concern was the evaluation of bearing capacity of peat with stabilized column.

The procedure adopted to prepare the columns was identical to the making of columns for Rowe cell tests. Figure 7b shows a precast stabilized column prior to installation in the test tank, which is filled with remoulded fibrous peat at a bulk density equal to that in the field. Prior to carrying out the plate load test, the content of test tank (reconstructed peat and column) was saturated for 24 hours as shown in Fig. 7c. To prevent any leakage from the test tank, it was lined from inside with a plastic sheet, and at the same time it was also useful in reducing the friction between peat and the test tank when the test was ongoing.

A total of three sets of plate load tests were carried out with the following descriptions:

- Remoulded fibrous peat having the same bulk density as in the field.
- Peat with precast column (diameter = 200 mm, and length = 1,000 mm) made of peat and 15 % cement.
- Peat with precast column (diameter = 200 mm, and length = 1,000 mm) made of peat, 15 % cement and 10 % silica fume.

The load-displacement curves are shown in Fig. 8. The load-settlement curve for untreated peat was observed to be a straight line, implying a punching type failure. The load at 90 mm settlement was 5.2 kN. When 15 % cement was added to the stabilized column, the load-carrying capacity increased by 84.6 % (from 5.2 to 9.6 kN) at a settlement of 90 mm. Similarly, when 10 % silica fumes were added in addition to 15 % cement, the load-carrying capacity increased to 107.7 % (from 5.2 to 10.8 kN) at the same settlement.

4 Finite Element Analysis

The shear strength parameters of peat and stabilized columns were obtained from the results of the triaxial test on samples specially prepared for this test and are presented in Table 3. The parameters so calculated were utilized to simulate the

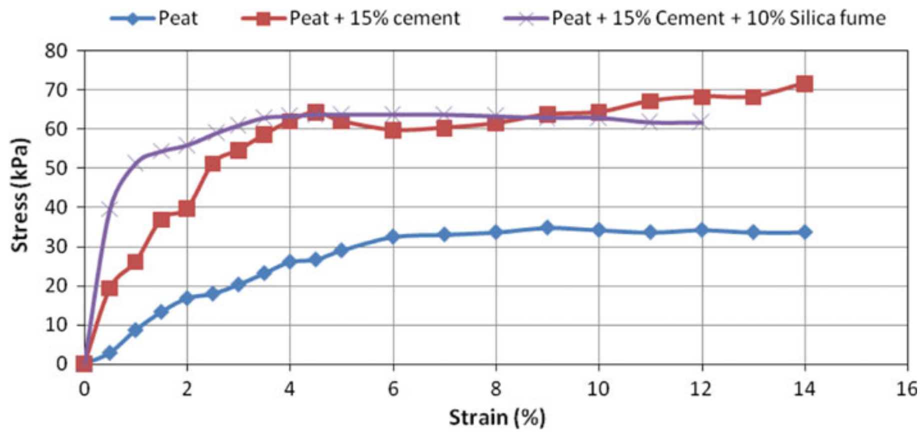

Fig. 6 Stress–strain curves of peat and peat with additives

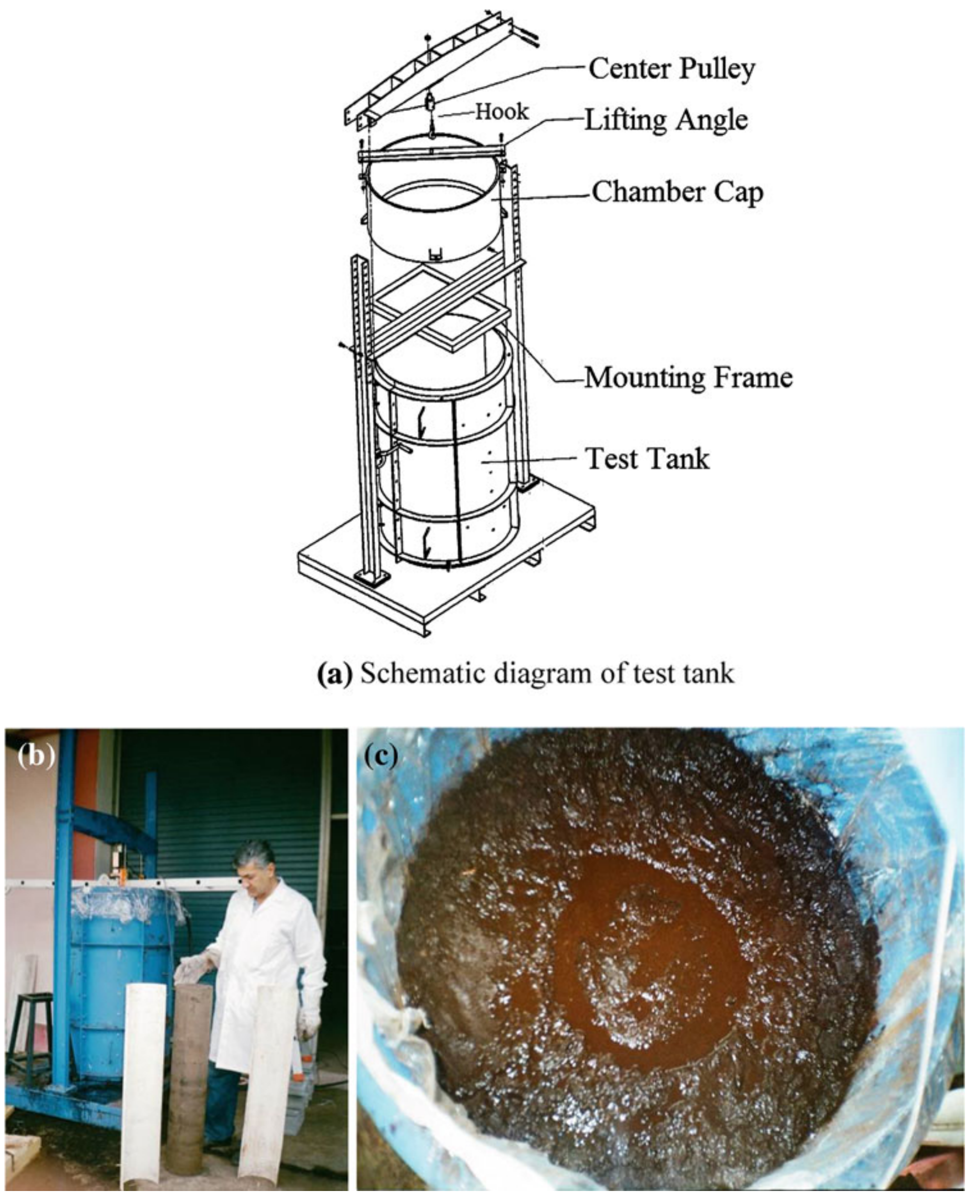

Fig. 7 Plate load test: **a** schematic diagram of test tank, **b** precast stabilized column, **c** precast column after being installed in the test tank

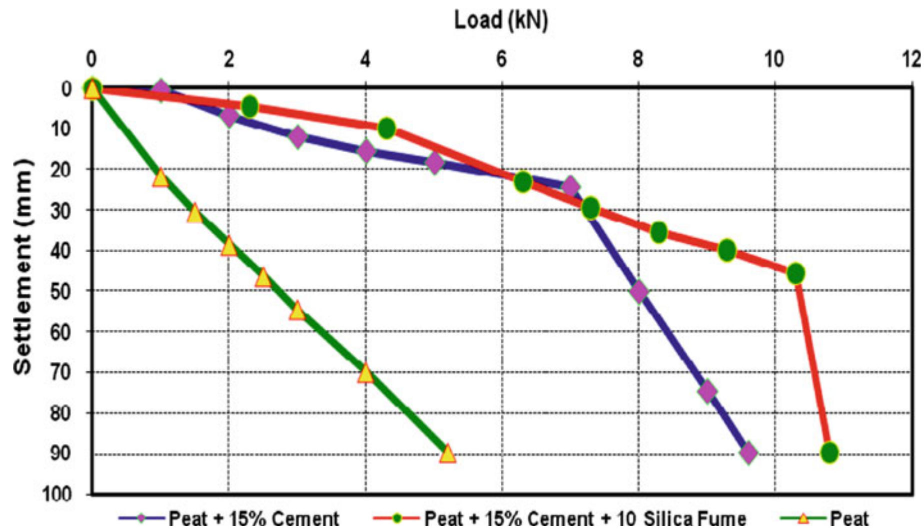

Fig. 8 Load-displacement curves

Table 3 Shear strength parameters of peat and stabilized columns

Description	Values	
	c (kN/m^2)	φ (°)
Peat	10	13
Peat + 15 % cement	43	19
Peat + 15 % cement + 10 % silica fume	46	23

Table 4 Parameters of peat

Parameter	Value	Unit
Unsaturated unit weight of peat (γ_{unsat})	9.8	kN/m^3
Saturated unit weight of peat (γ_{sat})	11.7	kN/m^3
Modified compression index (λ^*)	0.117	–
Modified swelling index (κ^*)	0.031	–
Modified creep index (μ^*)	0.001	–
Cohesion (c_{ref})	0.01	kN/m^2
Friction angle (φ)	10	°

plate load test and thus enabling us to have an idea about the effective stresses in peat and the stabilized columns under plate load test.

An axisymmetric analysis was carried out using soft soil creep model for peat and Mohr–Coulomb's criterion for stabilized columns. The parameters required for peat were unit weight (γ), modified compression index (λ^*), modified swelling index (κ^*), modified creep index (μ^*), cohesion (c), friction angle (ϕ), and dilatancy angle (ψ), and these are presented in Table 4. The parameters modified compression index (λ^*), modified swelling index (κ^*) and modified creep index (μ^*) were obtained by an oedometer test. When plotting the logarithm of stress as a function of strain, the plot can be approximated by two straight lines. The slope of the normal consolidation line gives the modified compression index (λ^*), and the slope of the unloading (or swelling) line is used to compute the modified swelling index (κ^*). The modified creep index (μ^*) was obtained by measuring the volumetric strain on the long term and plotting it against the logarithm of time. The shear strength parameters were obtained from the triaxial test.

The parameters required for stabilized columns, presented in Table 5, were unit weight (γ), Poisson ratio (ν), Elastic modulus (E), cohesion (c), friction angle (ϕ) and dilatancy angle (ψ). These parameters were obtained from the results of the triaxial test. The angle of dilatancy was taken as null for all the materials, as recommended in Brinkgreve and Vermeer [25].

The effective stresses for untreated peat, peat with 15 % cement, and peat with 15 % cement and silica fume are shown in Fig. 9. It was observed that the maximum effective stress in peat is 11.9 kN/m^2. The maximum effective stress in peat with 15 % cement increased to 54.0 kN/m^2, and further increased to 66.7 kN/m^2 when 10 % silica fumes were added along with 15 % cement.

5 Results and Discussion

Figure 1 shows the results of UCS tests of samples with 5 and 10 % silica fume, when used with various amounts of cement and air cured for 90 days. It is observed that the 10 % silica fume gives higher UCS with up to 15 % cement, whereas as the cement content is increased to 25 % and higher, a lower dose of silica fume at 5 % gives higher UCS result.

The reason for this phenomenon is due to the fact that silica fume, which is a pozzolanic additive, gives a higher strength along with cement [16]. The pozzolanic reaction in the short-term strength is lower. However, the long-term strength is increased by replacing a part of the cement with silica fume. Similar results were also reported by Janz and Johansson [26].

Table 5 Parameters of stabilized columns

Parameter	Values	
	Peat + 15 % cement	Peat + 15 % cement + 10 % silica fume
Unsaturated unit weight of peat (γ_{unsat})	11.0 kN/m^3	11.2 kN/m^3
Saturated unit weight of peat (γ_{sat})	15.4 kN/m^3	15.8 kN/m^3
Poisson's ratio (υ)	0.2	0.2
Elastic modulus (E)	1,300 kN/m^2	1,500 kN/m^2
Cohesion (c)	250 kN/m^2	280 kN/m^2
Friction angle (ϕ)	22°	26°

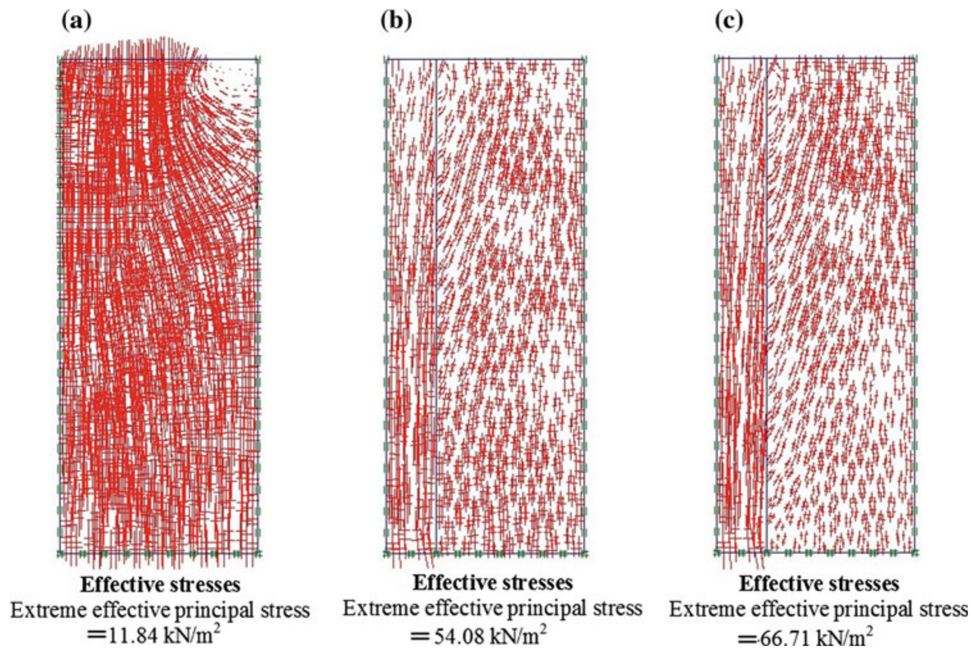

Fig. 9 Effective stress diagrams: **a** peat, **b** peat with 15 % cement and **c** peat with 15 % cement and 10 % silica fume

Two crucial parameters that are important in compressibility behaviour of saturated soft soil such as peat are compression (C_c) and recompression indices (C_r). As and when any of these indices are reduced in saturated soft soils, for any reason whatsoever, the settlement will reduce by proportional amount [27–30]. In this study, C_c and C_r values for peat, and peat with stabilized columns were evaluated using Rowe cell test and are presented in Fig. 4. It was observed that the two indices decrease with an increase in the cement content. The C_c reduced from 3.64 for undisturbed peat to 1.44 for peat stabilized with 50 % cement and to 1.42 with 30 % cement and 5 % silica fume. It also showed a good reduction to 2.3 with only 5 % cement. Similarly, the C_r of undisturbed peat was 0.49 and it reduced to 0.218 with 5 % cement, 0.105 with 50 % cement, and 0.117 with 30 % cement and 5 % silica fume. It is apparent from the results that the C_c can be reduced to a large extent with the use of cement and silica. Further, silica fume played an important role as the C_c of samples with 30 % cement with 5 % silica fume was less than that of samples with 50 % cement. This indicates that cement and silica fume together is more effective than cement alone in reducing the compression index. Although in some cases, 10 % silica fume gives better C_c and C_r parameters compared with cases with 5 % silica fume, a lower dose should be used whenever possible.

When precast stabilised peat columns with 5, 15, 30, and 50 % cement were installed in undisturbed peat samples, the C_c dropped by 36.8 % (3.64–2.3), 55.2 % (3.64–1.63), 58.8 % (3.64–1.5), and 60.4 % (3.64–1.44), respectively, in comparison with undisturbed peat. The addition of silica fume to the mixture of peat and cement for the columns further reduced the C_c and the percentage reduction was 42.3 % (3.64–2.1) with 5 % cement and 10 % silica fume, 56.6 % (3.64–1.58) with 15 % cement and 10 % silica fume, and 61 % (3.64–1.42) with 30 % cement and 5 % silica fume. This can be attributed to the fact that the pores in peat and cement mix are filled up by the silica fumes, leading to smaller and fewer voids.

The results of recompression indices, as shown in Fig. 4, indicate that the recompression index (C_r) of the undisturbed peat decreased with an increase in the cement content of the columns. The percentage reduction in C_r was 55.5, 66.1, 77.6, and 78.6 % with cement content as 5, 15, 30, and 50 %, respectively.

The addition of silica fume increased marginally the C_r, as compared with samples with cement only. The percentage increases in C_r was 5 % (from 0.218 to 0.268) with 5 % cement and 10 % silica fume, 0.1 % (from 0.166 to 0.167) with 15 % cement and 10 % silica fume, and 0.7 % (from 0.110 to 0.117) with 30 % cement and 5 % silica fume.

The reduced values of C_c and C_r can be attributed to the increase in strength as a result of the increased calcium silicate hydrate gel in the cement paste due to hydration and agree well with the reported results [3,15,26]. Further, silica fume as a pozzolanic additive gives a higher strength, density, and durability when used along with cement [16]. Detwiler and Metha [17] observed that cement reacts with water to form calcium silicate hydrate and calcium hydroxide. Silica fume undergoes the same type of pozzolanic reaction. The strength gain then is very slow but the effect of pozzolanic reaction on long-term strength can be considerable [11,26].

The void ratio versus pressure (e-log p) diagram of peat, peat with 15 % cement, and peat with 15 % cement and 10 % silica fume are presented in Fig. 5. The void ratio of peat decreased sharply from 11.7 at 20 kPa to 7.2 at 320 kPa. When 15 % cement was added, it decreased from 4.95 to 3.65; and with 15 % cement and 10 % silica fume, it decreased from 4.75 to 3.45 for the same pressure range. This behaviour of peat with additives is due to the fact that peat particles are bonded together leading to a decrease in the initial void ratio as well as a small reduction in void ratio upon increase in pressure.

The stress–strain curves of peat and peat with the additives are presented in Fig. 6. The stress level reached at 5 % strain is 29.5 kPa for peat without any additives. This showed a sharp increase to 58.4 kPa with the addition of 15 % cement and further increased to 65.7 kPa when 10 % silica fume was added along with 15 % cement. This increase in stress level with the addition of cement and silica fume is expected due to the increase in the stiffness of the samples because of the hydration and other reactions taking place as explained earlier. Toutanji et al. [20], Chen and Wang [31], and Kalantari [32] have also reported an increase in strength of cement-based materials, with a corresponding reduction in compressibility.

Results obtained from plate load tests are shown in Fig. 8. It is observed that in case of peat only, there is a punching failure. Comparing the load at a settlement of 40 mm (20 % column diameter), the load was 2.2 kN for peat only, 7.4 kN for peat with 15 % cement and 9.1 kN for peat with 15 % cement and 10 % silica fume. It is obvious that the load-bearing capacity increased with the precast column, and at the same time, there is also a further increase in the bearing capacity with the addition of silica fume.

A finite element analysis of the behaviour in the plate load test showed good agreement between the simulated and the experimental behaviour. The results of the finite element analysis in the form of effective stress diagram are presented in Fig. 9. It is observed that the effective stress for peat is 11.84 kN/m^2. It showed a very large increase to 54.06 kN/m^2 when 15 % cement was added to form the stabilized column. This shows the reason why peat stabilized with cement can take higher load because of increased stiffness of the column. When silica fume was also added with cement to form the stabilized column, the effective stress increased to 66.71 kN/m^2, indicating a higher bearing capacity. The results obtained agree well with the findings of Forrest and MacFarlane [14] and Tan and Oo [23] who also reported a similar increase in the strength of soil due to reinforcement with columns.

6 Conclusions

In the present model study, precast stabilised peat columns with ordinary Portland cement, with and without the addition of silica fume have been investigated for their compressibility behaviour when they are used in peat. Based on the study, the following conclusions can be drawn:

- The precast stabilized columns can be used successfully to improve the engineering behaviour of soft peat deposits, and as a result improve its strength and bearing capacity.
- The load bearing capacity of peat can be improved significantly by a factor of more than four when 15 % cement is used to prepare the column, and also the use of silica fume would increase the load-bearing capacity of the column by about 35 %.
- The results obtained from Rowe cell tests showed that with only 5 % cement, the settlement of peat deposit will reduce by over 36 % (C_c of undisturbed peat reduced from 3.64 to 2.30). Moreover, when 10 % silica fume was also added, the reduction in the settlement of peat was even higher (42 %).
- The presence of any type of small particle (known as particle packing or micro filling) will improve the strength in the presence of cement.
- Finite element analysis can be carried out to understand the distribution of stresses in peat as well as in the stabilized column.

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