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# Shear Strength of Organic Soils Modified by Mineral Materials

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**Abstract:** The paper presents the test results of the shear strength of composite materials, in which the base material was peat. The materials modifying the mineral part of the peat ground skeleton were fly ash and hydrated lime. The research was carried out for two groups. In group 1, the ratio of the mass of the peat skeleton to the mass of fly ash was equal to one, and in group 2, it was two. Hydrated lime content in the unit mass of the composite in group 1 was 2.4, 4.8 and 9.2%. In the second group, it was 1.6, 3.2 and 6.4%. The test results showed that the materials from group 1. (P/FA = 1) are characterised by the highest shear strength compared to materials from group 2. (P/FA = 2), regardless of the content of hydrated lime. It should also be noted that the shear strength of the materials of group 1 was significantly higher than the shear strength of the base material, which was peat.

**Keywords:** shear strength, peat, fly ash, hydrated lime, soil composites

## 1. Introduction

In the area of Żuławy Elbląskie, local organic soils are used for modernisation and reconstruction of flood embankments classified as III and IV class of hydrotechnical structures (Borys 1993, Olchawa 2003, Olchawa & Przewłócki 2013). The use of these soils results from the lack of mineral soils in Żuławy. The possible use of mineral soils would make it necessary to transport them from areas outside Żuławy and often to build technological roads, increasing investment costs by roughly 300% (Liziński & Olchawa 1997).

Flood embankments of organic soils produce lower stresses in the ground than those of the same structure but are made of mineral soils. This facilitates the foundation of these embankments on low-bearing ground in the Żuławy region (Olchawa 2003). For these reasons, ways of modifying organic soils are sought to increase their shear strength, reduce water permeability, and reduce the susceptibility to structural changes and mineralisation of organic matter. To obtain such properties, modification of the mineral part of the soil skeleton in organic soils is often used. Such modification involves putting mineral materials such as cement, lime, fly ash into the soil and, less frequently, granulated blast furnace slag. Mixtures of mineral materials in optimally selected weight ratios are often used (Ahnberg & Holm 1999, Cortellazzo & Cola1999, Lahtinen et al. 2005, Pousette et al. 1999, Axelsson et al. 2002, Hebib & Farrell 2003, Filipiak 2006, Quigley & O'Brien 2010, Timoney et al. 2012, Filipiak 2013). Using modified soil and mineral materials ensures longer operation of embankments compared to embankments of the same structure but made of organic soils only. The average service life of embankments made of organic soils in Żuławy is about thirty years, whereas embankments made of mineral soils can withstand at least one hundred years (Olchawa 2003).

Considering the Investor's financial resources (State Water Management Company – Watershed of Elbląg), it is necessary to make practical use of local organic soils modified with available mineral materials. Soils modified in this way can be used as a construction material for flood embankments and, most often, for their revitalisation.

The soil science laboratory of the Academy of Applied Sciences in Elbląg tested the geotechnical properties of soils, such as compactability, hydraulic conductivity, and edometric compressibility. The results of these tests were published in the earlier paper (Brzeziński et al. 2023).

In the second stage of the research, shear strength tests of the modified soils were performed to determine the shear strength parameters necessary for the embankment stability analysis. Based on the test results, an attempt was made to determine the correlations between the strength parameters and the composition of modified organic soils, i.e., peat, fly ash and hydrated lime (P, FA, HL).

The statistical correlation between the composition of the modified soils and their strength parameters will enable the design of the soil composition with the assumed strength properties. The article presents the shear strength test results of soil composite materials. The authors recommend that the results presented in the paper be treated as a pilot study.

## 2. Materials and Methods

### 2.1. Test material

The base material for soil testing of composite materials was peat collected from the depression area of Żuławy Elbląskie in Komorowo Żuławskie, in the immediate vicinity of the Elszka River, in the basin of Lake Druzno. The collection area was selected based on the data from the Żuławy Research Center of the Institute of Land Reclamation and Grasslands in Elbląg, as well as based on available publications (Borys et al. 2002, Borys & Rycharska 2004, Olchawa 2003).

The tests of the collected soil showed a high organic content of 62.9% (tested by thermogravimetric method), density of $9 \cdot 10^2$ kg/m$^3$, moisture content of 350% and porosity of 0.70. The degree of decomposition on the Van Post scale was rated as H4-H5 (Post 1922), and the determined concentration of hydrogen ions was 6.5 (Brzeziński & Iskra 2016, Brzeziński 2017, Brzeziński 2020). Considering the performed test and macroscopic evaluation, the collected peat can be classified as fibrous peat, turning into pseudofibrous.

The peat subjected to derivatographic examination (Figure 1) presents the test results in the form of derivatograms (Thermogravimetric Analyzer SDT Q600), where the TG and DTA curves are shown. In the TG curves shown in the figures, we can notice the mass losses of the samples that occurred due to the temperature. In Figure 1, a sharp drop in mass can be seen on the TG curve at about 373.15 K (100°C), which should be associated with the dehydration process, i.e., the evaporation of hygroscopic water and water bonded to the solid phase of the mineral part of the soil. The mass loss in the peat sample at the temperature of 923.15 K (650°C) corresponds to the earlier thermogravimetric tests related to organic matter content.

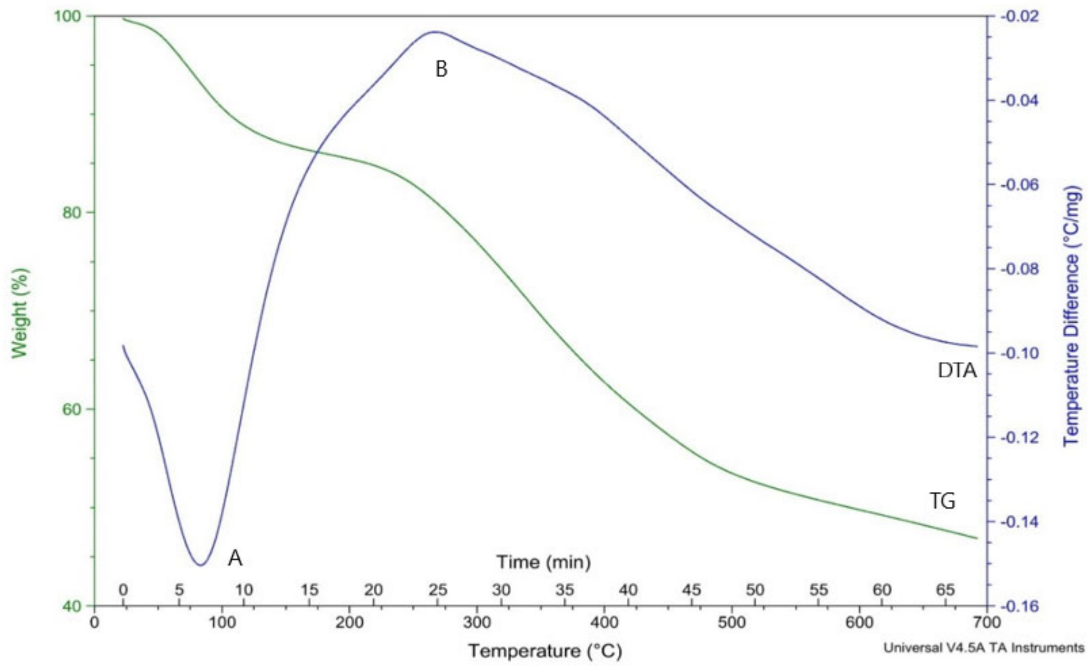



**Fig. 1.** Peat derivatogram

The mineral materials modifying the mineral part of the soil skeleton of the peat were hydrated lime (HL) and fly ash (FA). Widely available hydrated lime, referred to as building lime, was used as a first component. The relative density of hydrated lime is 2240 kg/m$^3$ at 293.15 K (20°C) and the pH value for a saturated solution at 293.15 K (20°C) is 12.4 (Karta charakterystyki Wapno budowlane EN 459-1CL 90-S). The fly ash used for the test, with a density of 2298.32 kg/m$^3$ and a specific surface area of 364.78 m$^2$/kg, was characterised by the high content of silicon ($SiO_2$) and aluminium ($Al_2O_3$), which qualifies it to silicate ashes, and based on roasting losses to category A (PN-EN 450-1:2012).

Complementary tests of fly ash, such as leachability of heavy metals, hydrogen ion content and determination of radioactivity, were carried out, as demonstrated in the earlier papers (Brzeziński 2020, Brzeziński & Iskra-Świercz 2021, Brzeziński et al. 2023). They showed complete safety and harmlessness of this material for the natural environment.

The mineral materials and peat were used to make six mixtures, referred to later in the article as soil composite materials marked with the symbol C. The composition of soil composite materials determined by the content of peat skeleton, fly ash and hydrated lime per unit mass of the mixture is shown in Table 1.

The materials were prepared by manually mixing naturally moisturised peat and mineral materials. After that, a mechanical stirrer was used to increase the homogenisation of the mixture. This sample preparation method follows the recommendations from the literature (Ahnberg & Holm 1999, Pousette et al. 1999, Ahnberg & Holm 2005). The composites were placed in sealed containers to redistribute humidity. The storage time of the composites in such conditions was 10 days at a temperature of 278.15 K (52°C).

**Table 1.** The mass content of peat skeleton, fly ash and hydrated lime in a unit mass of soil composite

| Materials of the composites | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| | Group 1 | | | Group 2 | | |
| Peat, kg | 0.488 | 0.476 | 0.454 | 0.654 | 0.644 | 0.624 |
| Fly ash, kg | 0.488 | 0.476 | 0.454 | 0.327 | 0.322 | 0.312 |
| Hydrated lime, kg | 0.024 | 0.048 | 0.092 | 0.016 | 0.032 | 0.064 |
| Hydrated lime, % | 2.4 | 4.8 | 9.2 | 1.6 | 3.2 | 6.4 |

## 2.2. Research methods

In the first stage of the research, the so-called "Proctor test" was performed to assess the compactability of the materials. Having determined the relationship between the volumetric density of the soil skeleton and water content, it was possible to ascertain the moisture of the composite at which the material can be compacted to the value of $I_s > 0.92$. Relative compaction, index $I_s = 0.92$, is the minimum compaction value for earth masses required for embankments classified as class III and IV of hydrotechnical structures (PN-97/B-12095).

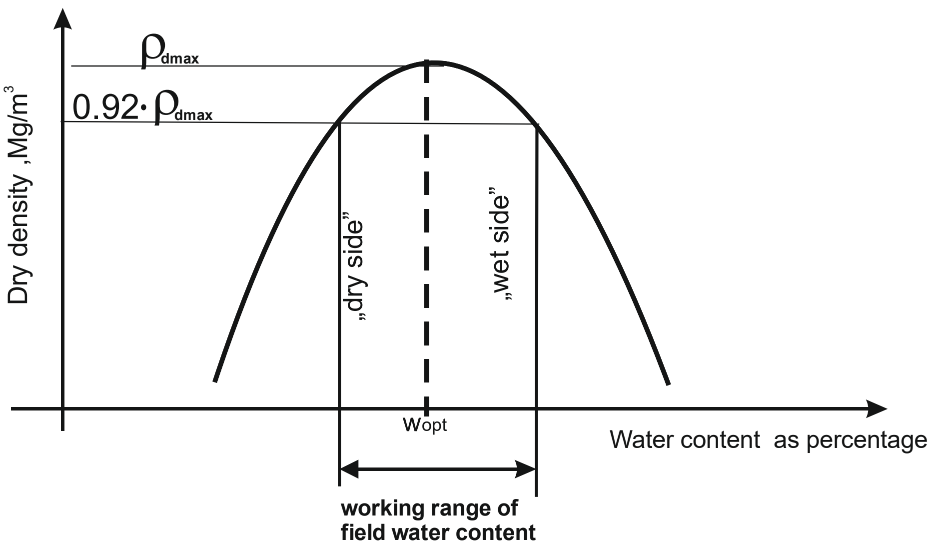



**Fig. 2.** Working range of field water content

The composites were compacted with their compaction index, $I_s$ greater than 0.92 (Figure 2). After the compaction process was completed, samples of 60 x 60 mm or 80 x 80 mm were cut out from the lower cylinder of the Proctor apparatus. The cut samples were transferred to the direct shear apparatus (Brzeziński et al. 2023). Figure 3 shows the method of collecting samples from the cylinder of the Proctor apparatus.

**Fig. 3.** Scheme of taking a composite material by cutter from the lower cylinder of the Proctor apparatus

Strength tests were carried out in a box apparatus produced by the Department of Scientific Equipment of the Jagiellonian University in Cracow. The test procedure followed the PN-88/B-04481 standard, p. 7.2.2.4. Plastic-yielding failure was adopted as the shearing criterion (Whitlow 2001). The shear strength was calculated from the formula:

$$\tau_f = \frac{Q_{10}}{0.9 \cdot a^2} \quad (1)$$

where:
$\tau_f$ – shear strength, kPa,
$Q_{10}$ – shear force at relative soil sample deformation $\epsilon = 10\%$, kN,
a – sample side length, m.

The normal stresses used were $\sigma_n$ = 25, 50, 75, 100, 125, 150 kPa. The least squares method calculated the functional relationships τf = τf (σn). The strength parameters of composite materials, i.e., the angle of internal friction and cohesion, were marked with φ and c, respectively, without u indexes. According to the authors, using indexes in PN-81/B-03020 is unjustified because for $c_u$ = const, always $\varphi_u = 0$.

Tests of strength parameters were performed in three replications for peat and each composite. The angles of internal friction and cohesions presented in the figures are the arithmetic averages of the three measurements.

## 3. Test Results

Estimated parameters of the regression equation $\tau_f = \sigma_n \cdot tg\varphi + c$ for composite materials C1, C2, C3, C4, C5 are C6 are shown in Table 2. Figures 4, 5 and 6 present the graphical function relationships $\tau_f = \tau_f(\sigma_n)$ (Draper 1973). Figures 7, 8, 9 and 10 present the influence of mineral materials content in composites on their strength parameters.

**Table 2.** Shear strength parameters and statistics for regression lines

| Composite symbol | Shear strength parameter | | Statistic parameters | |
|---|---|---|---|---|
| | φ in degrees | *c*, kPa | $R^2$ | F* |
| C1 | 0.313 | 17.52 | 0.99 | 667.40 |
| C2 | 0.842 | 19.04 | 0.98 | 677. 60 |
| C3 | 0.423 | 45.00 | 0.95 | 667.40 |
| C4 | 0.266 | 27.00 | 0.95 | 157.30 |
| C5 | 0.206 | 31.70 | 0.97 | 281.64 |
| C6 | 0.311 | 8.08 | 0.91 | 74.40 |

$F_{kr}$ ($\alpha = 0.05$, 1.4) = 7.71, * Fisher–Snedecor distribution (Aczel 1996)

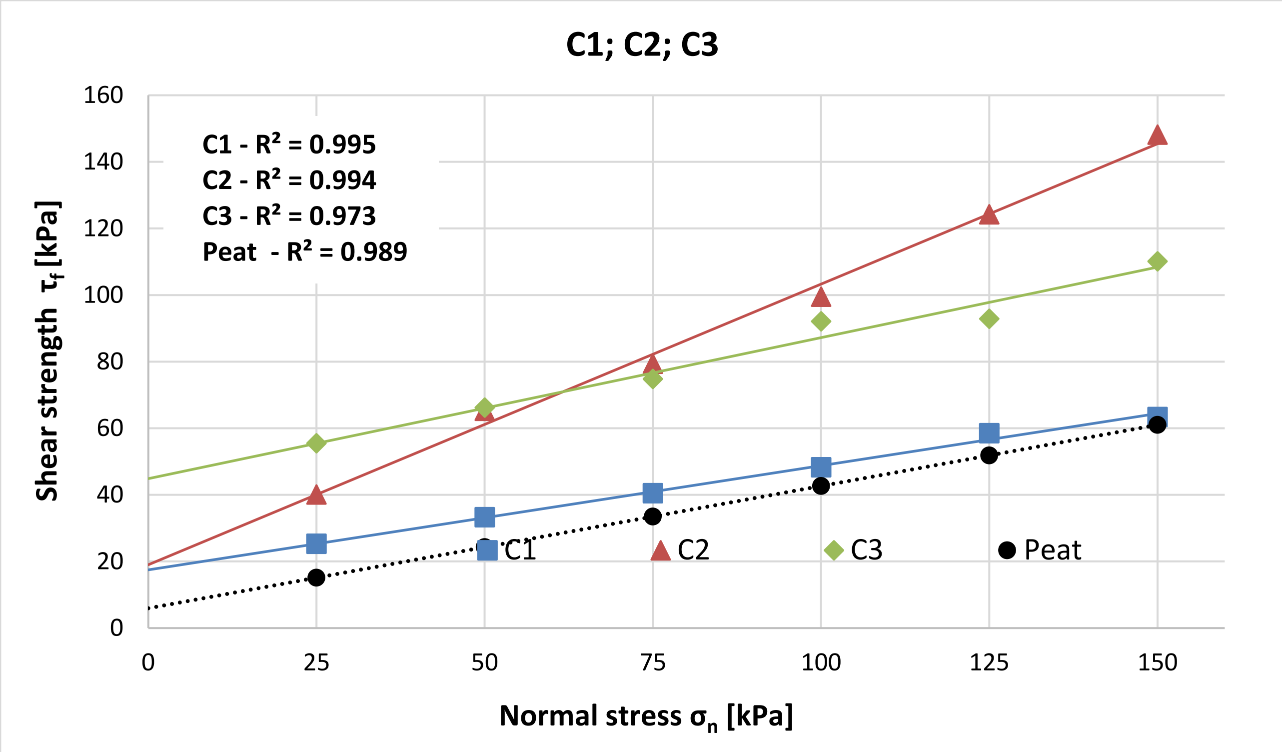



**Fig. 4.** Shear strength of C1, C2, and C3 composite materials and peat

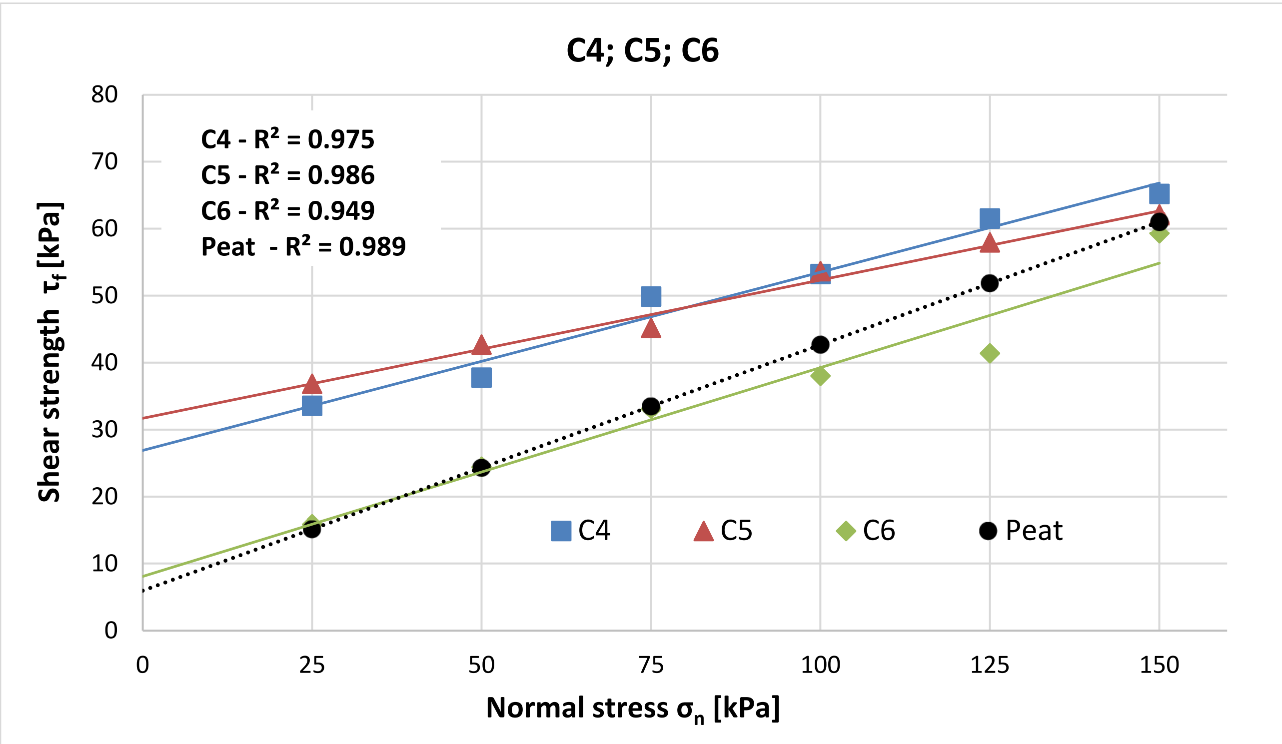



**Fig. 5.** Shear strength of C4, C5, and C6 composite materials and peat

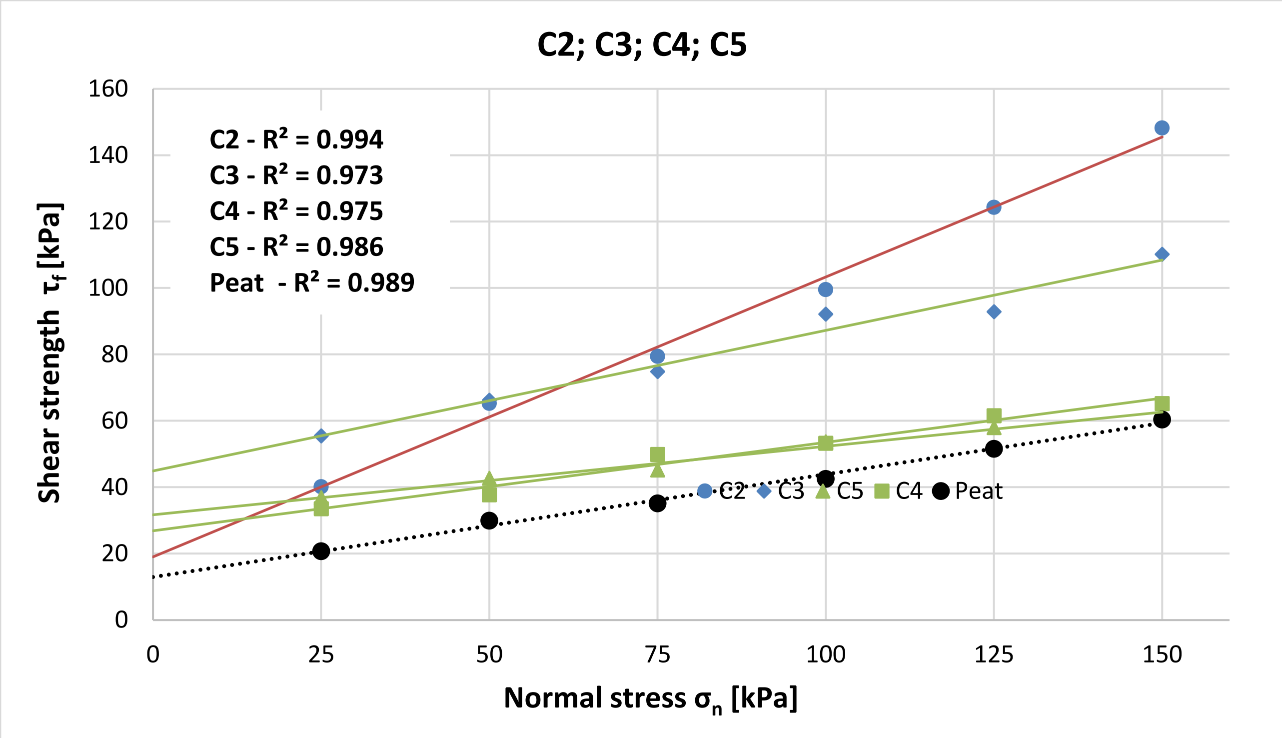
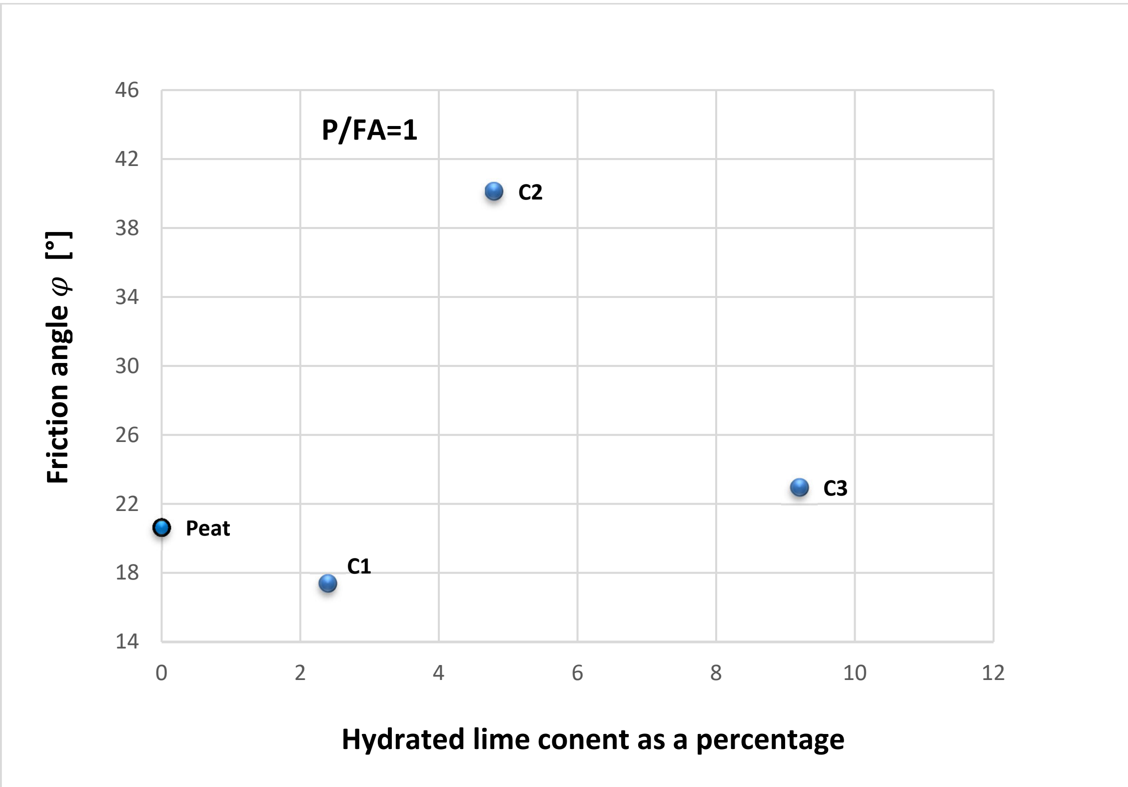
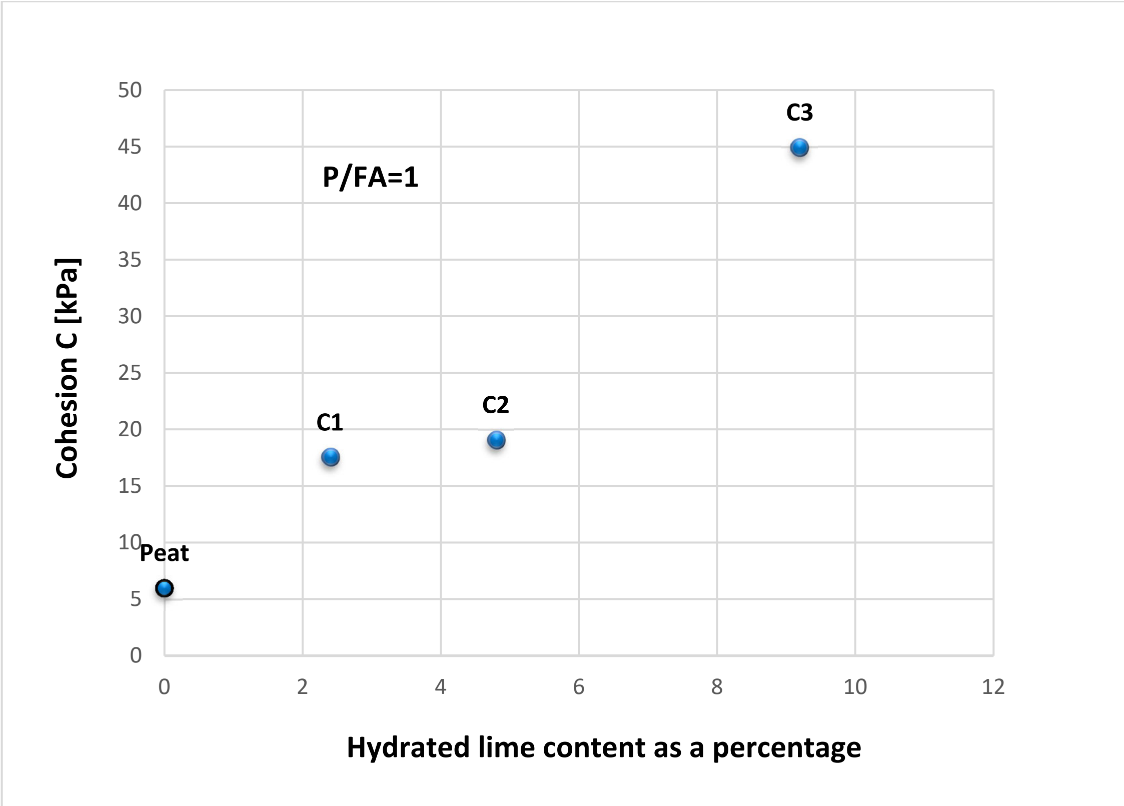



**Fig. 6.** Shear strength of C2, C3, C4, and C5 composite materials and peat



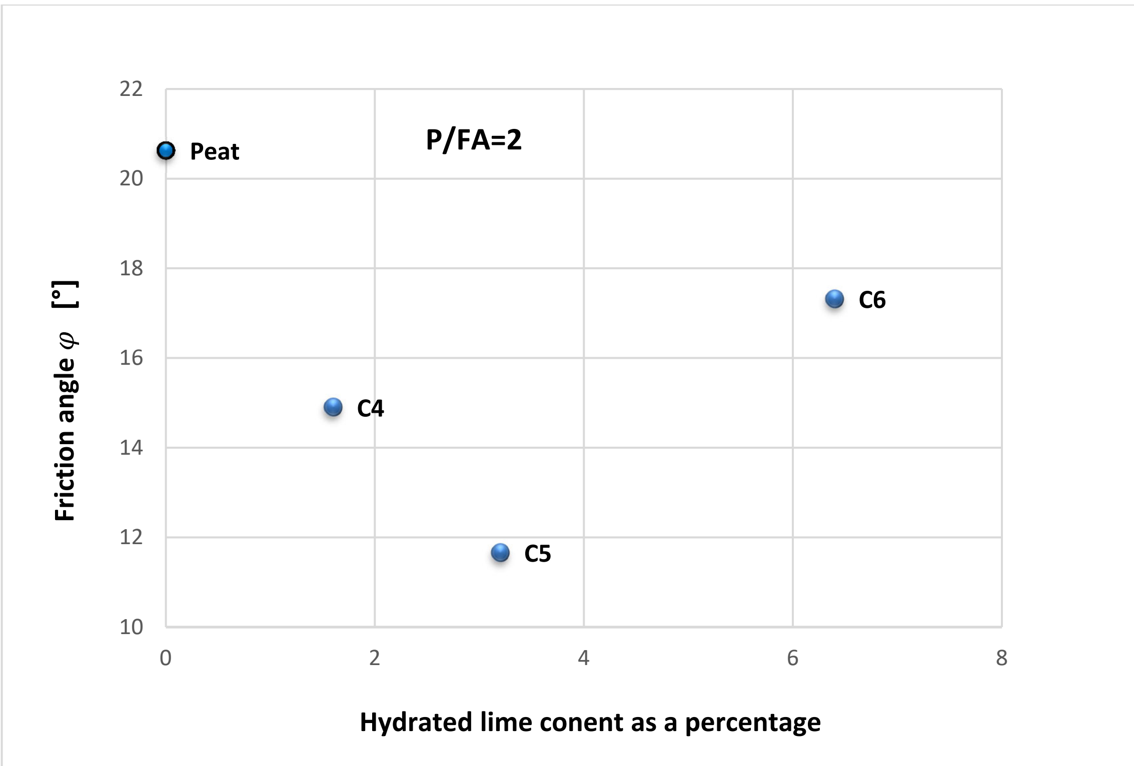

(P/FA – the ratio of peat to fly ash)

**Fig. 7.** Values of internal angle friction for the peat and the composite C1, C2, and C3 with various content of the hydrated lime



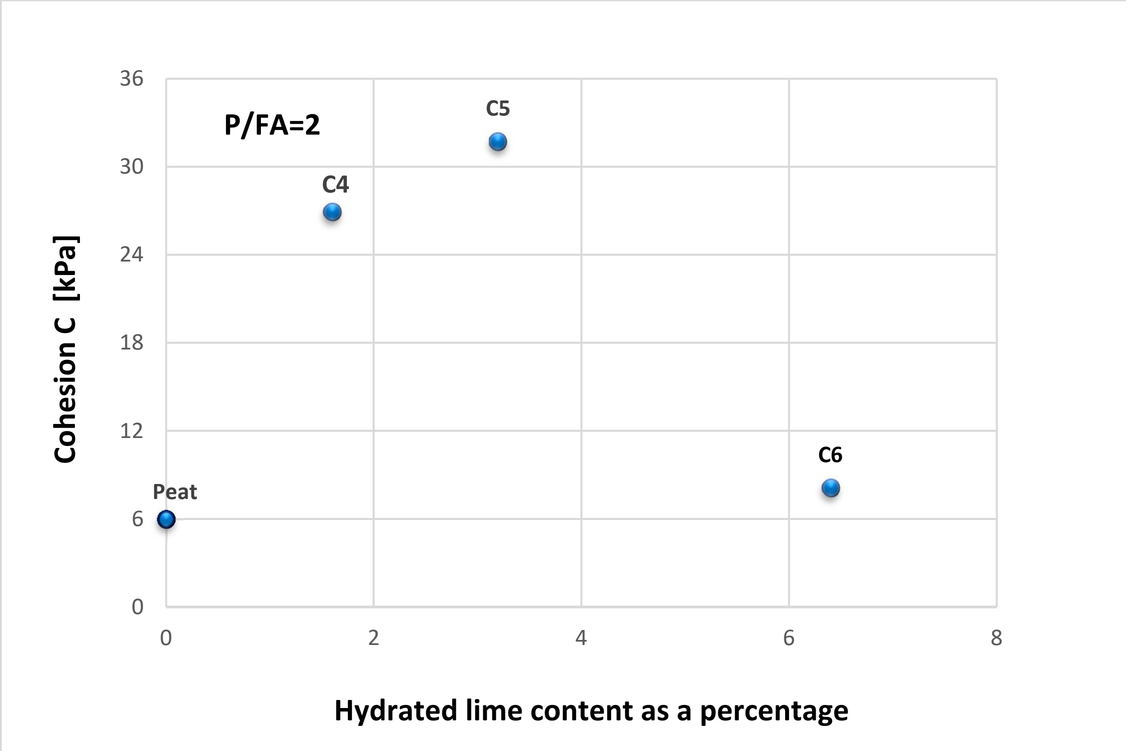

(P/FA – the ratio of peat to fly ash)

**Fig. 8.** Values of cohesion for the peat and the composite C1, C2, and C3 with various content of the hydrated lime




(P/FA – the ratio of peat to fly ash)

**Fig. 9.** Values of internal angle friction for the peat and the composite C4, C5, and C6 with various content of the hydrated lime




(P/FA – the ratio of peat to fly ash)

**Fig. 10.** Values of cohesion for the peat and the composite C4, C5, and C6 with various content of the hydrated lime

## 4. Analysis of Results

The shear strength of all composite materials of group 1 for the applied normal stress range of 25-150 kPa is higher than that of peat.

The shear strength of the composite material marked as C1 is comparable to the shear strength of peat (base material). Comparison of the shear strength of composite materials from group 1, i.e., C1, C2 and C3, in which the ratio P/FA = 1, shows that material marked as C1, which contains 2.4% of hydrated lime, is characterised by the lowest shear strength. This has a lower lime content than C2 and C3 materials. For normal stresses $\sigma_n <$ 60 kPa, the shear strength of the C2 composite is lower compared to C3. An inverse relationship is noticeable for $\sigma_n >$ 60 kPa for this pair of composites. The higher content of hydrated lime – HL in these materials increases the shear strength.

For composite materials of group 2, in which the ratio P/FA = 2, C6 composite material is characterised by the lowest shear strength, i.e., the one with the lowest content of hydrated lime, which is 6.4%. In this group of materials, the content of hydrated lime does not significantly increase the shear strength. The shear strengths of the C4 and C5 materials are comparable.

For further analysis, two composites from group 1 and group 2 were selected. Those were the composites with the highest shear strength of each group (C2, C3, C4, C5) and higher shear strength than that of peat.

Figures 7 to 10 show the relationships of changes in composite strength parameters depending on the content of added mineral materials.

In group 1, together with the increased content of hydrated lime, the internal friction angle value increases compared to peat for C2 and decreases for C3. Therefore, it can be considered that the content of hydrated lime in relation to the peat skeleton of about 5% gives the highest friction angle compared to materials with a lower and higher content of lime. The internal friction angle of the C3 composite (HL = 9.2%) is comparable to the internal friction angle of peat. The cohesion value of composite materials from group 1 rises alongside the increased content of hydrated lime. The largest increase in the cohesion value is observed in the C3 composite, whose cohesion value is more than seven times greater than that of peat. In the C2 composite, the value of cohesion is more than three times higher than that of peat. The cohesion values increase with the increase in the amount of hydrated lime in the composite compared to the cohesion of peat. For the C4, C5 and C6 composites, the cohesion values increased by 4.65, 5.32 and 1.35, respectively, in relation to the cohesion values of peat (base material). The hydrated lime content of about 6.4% can give a "grease" effect with a lower fly ash content than peat.

## 5. Conclusions

The analysis of the test results gives rise to the following conclusions:

1. Group 1 materials (P/FA = 1) are characterised by higher shear strength than those from group 2 (P/FA = 2), regardless of the hydrated lime content.
2. In group 1 composite materials (P/FA = 1), the increased value of the hydrated lime content in the composite significantly increases the cohesion value.
3. For group 1 (P/FA = 1), the internal friction angle increases at hydrated lime content of 4.8% and for content greater than 4.8%, the internal friction angle is reduced.
4. In group 1 (P/FA = 1), the cohesion value increases together with the content of hydrated lime. The cohesion values for each composite of group 2 are higher than for the peat.
5. For composite materials of group 2. (P/FA = 2) higher content of hydrated lime significantly reduces the value of the internal friction angle compared to the value of the peat angle.
6. Further studies should investigate the effects of composite materials' "seasoning" (material deposit time on construction site before modification begins) on the shear strength. The reason is that hydrated lime and ash have pozzolanic properties, which can increase the strength parameters during the operation of flood embankments.
7. Tests of resistance to environmental factors such as humidification, drying and cyclic freezing should determine the suitability of these composites.

## References

Aczel, A.(1996). Complete Business Statistics. 3rd Edition. Publisher :Richard D. Irwin. Inc. Illinois; Boston.

Ahnberg, H., Holm, G. (1999). Stabilisation of some Swedish organic soils with different types of binder. *Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization*, Rotterdam. https://doi.org/10.1201/9781315141466-14

Ahnberg, H., Holm, G. (2005). Stabilisation of some Swedish organic soils with different types of binder. *Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization,* Stokholm.

Axelsson, K., Johansson, S.E., Andersson, R. (2002). Stabilisation of Organic Soils by Cement and Puzzolanic Reactions – Feasibility Study. *Swedish Deep Stabilization Research Centre*, Linkoping.

Borys, M., Jędryka, E., Filipowicz, P., Generowicz, J., Kamińska, A., Kosmulski, J., Kowalski, M., Wolski, J., Barszczewska, I. (2002). *Ocena stanu technicznego wybranych odcinków wałów przeciwpowodziowych na terenie żuław elbląskich w basenie jeziora Druzno*. Instytut Melioracji i Użytków Zielonych, Falenty. (in Polish)

Borys, M. (1993). Niskie nasypy z miejscowych gruntów organicznych dla potrzeb budownictwa wodno-melioracyjnego. Falenty. Rozprawa habilitacyjna. Instytut Melioracji i Użytków Zielonych. (in Polish)

Borys, M., Rycharska, J. (2004). *Ocena stanu obwałowań przeciwpowodziowych wykonanych z namułów organicznych na przykładzie Żuław Elbląskich*. Woda Środowisko Obszary Wiejskie. Instytut Melioracji i Użytków Zielonych, Falenty. (in Polish)

Brzeziński, B. (2020). Gruntowe materiały kompozytowe torf – popiół lotny – wapno. Rozprawa Doktorska. Białystok. (in Polish)

Brzeziński, B. (2017). Badanie wytrzymałości na ściskanie gruntowych materiałów kompozytowych torf - popiół lotny - wapno. *Materiały Budowlane*, *1*(9), 142-144. (in Polish) https://doi.org/10.15199/33.2017.09.36

Brzeziński, B., Iskra-Świercz, D. (2016). Badanie ściśliwości materiałów kompozytowych torf - popiół lotny - wapno. Rozprawy Naukowe i Zawodowe Państwowej Wyższej Szkoły Zawodowej w Elblągu. ISSN: 1895-8117 (in Polish)

Brzeziński B, Iskra-Świercz D. (2021). Heavy Metals and Metalloids Leachability from Composite Ground Materials Peat – Fly Ash – Lime. *Rocznik Ochrona Środowiska*, *23*, 513-523. https://doi.org/10.54740/ros.2021.036

Brzeziński, B., Olchawa A., Wierzbicka M. (2023). Wybrane właściwości gruntowych materiałów kompozytowych jako materiału konstrukcyjnego do budowy niskich nasypów obwałowań przeciwpowodziowych. *Materiały Budowlane*, *6*, 32-36. (in Polish) https://doi.org/10.15199/33.2023.06.08

Cortellazzo, G., Cola, S. (1999). Geotechnical characteristics of two Italian peats stabilised with binders. *Dry Mix Methods for Deep Soil Stabilisation*, 93-100. https://doi.org/10.1201/9781315141466-13, https://www.taylorfrancis.com

Draper, N.R., Smith, H. (1973). Analiza regresji stosowana, Państwowe Wydawnictwo Naukowe, Warszawa.

Filipiak, J. (2006). *Badania skuteczności ulepszania niektórych organicznych przy użyciu różnych spoiw*. Rozprawa doktorska, Politechnika Koszalińska, Koszalin. (in Polish)

Filipiak, J. (2013). Popiół lotny w budownictwie. Badania wytrzymałościowe gruntów stabilizowanych mieszanką popiołowo-cementową. *Rocznik Ochrona Środowiska*, *13*, 1043-1054.

Hebib, S., Farrell, E.R. (2003). Some experiences on the stabilisation of Irish peats. *Canadian Geotechnical Journal*, *40*, 107-120. https://doi.org/10.1139/t02-091

Karta charakterystyki. Wapno budowlane EN 459-1CL 90-S. Wapno hydratyzowane. Trzuskawica S.A. (in Polish)

Lahtinen, P., Niutanen, V., Kontiala, P. (2005). Towards Sustainable Development Process with Mass and Deep Stabilisation – The Case of Vuosaari Seaport. *International Conference on Deep Mixing – Best Practice and Recent Advances,* Report 13, Vol 1. 19-47, Stockholm.

Liziński, T., Olchawa, A. (1997). Efekt ekonomiczny modernizacji nasypu przeciwpowodziowego wykonanej według technologii konsolidacji dynamicznej. *Wiadomości Melioracyjne*, *1*, 28-30. (in Polish)

Olchawa, A. (2003). Właściwości gruntowych kompozytów jako materiału do budowy obwałowań przeciwpowodziowych. *Woda Środowisko Obszary Wiejskie. Instytut Melioracji i Użytków Zielonych, Rozprawy naukowe i monografie,* Falenty. (in Polish)

Olchawa, A., Przewłócki, J. (2013). Stateczność czołowego obwałowania nasypu przeciwpowodziowego Jeziora Druzno. *Inżynieria Morska i Geotechnika*, *6*, 501-505. (in Polish)

Post, van L. (1922). Sveriges Geologiska Undersöknings torvinventering och några av dess hittills vunna resultat. *SvenskaMosskulturföreningensTidskrift*, 1-37, Jönköping.

Pousette, K.J., Macsik, J., Jacobsson, A. (1999). Peat soil samples stabilised in laboratory Experiences from manufacturing and testing. *Dry Mix Methods for Deep Soil Stabilisation.* Proceedings of the International Conference of Dry Mix Methods for Deep Soil Stabilization, 85-92, Rotterdam, https://doi.org/10.1201/9781315141466-12, https://www.taylorfrancis.com

PN-97/B-12095 Urządzenia wodno-melioracyjne. Nasypy. Wymagania i badania przy odbiorze. (in Polish)

PN-88/B-04481 Grunty budowlane. Badania próbek gruntu. (in Polish)

PN-EN/450-1:2012 Popiół lotny do betonu – Część 1: Definicje, specyfikacje i kryteria zgodności. (in Polish)

PN-81/B-03020 Grunty budowlane. Posadowienie bezpośrednie budowli. Obliczenia statyczne i projektowanie. (in Polish)

Quigley, P., O'Brien, J. (2010). A Feasibility Study of Dry Soil Mixing for a Blanket Bog. *Bridge and Infrastructure Research in Ireland and Concrete Research in Ireland*, 239-246, Cork.

Timoney, M.J., McCabe, B.A., Bell, A.L. (2012). Experiences of dry soil mixing in highly organic soils. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, *165*, 3-14. https://doi.org/10.1680/grim.2012.165.1.3

Whitlow, R. (2001). *Basic Soil Mechanics*. 4th Edition by Prentice Hall Life.