Humic matter as a challenge in deep soil mixing of soft organic soils

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1 Introduction

Soft organic soils such as peat pose significant challenges for geotechnical engineering due to their low undrained shear strength, high compressibility and pronounced time-dependent deformation behaviour [1–3]. Construction on these soils often requires extensive foundation or ground improvement measures, including soil replacement, deep foundations or in situ stabilisation techniques. Among these, deep soil mixing (DSM) has become an established and economically attractive method, as it allows in situ improvement of soil properties while limiting excavation, material transport and environmental disturbance [4–6].

In current engineering practice, ordinary Portland cement (OPC) is the most commonly used binder in DSM. However, the stabilisation of organic soils with OPC is frequently associated with delayed strength development, high scatter of mechanical properties and, in some cases, complete failure of stabilisation. A key reason for this behaviour is the interaction between cement hydration products and soil organic matter, particularly humic matter [7–9]. In addition, the high CO_2 footprint of OPC has intensified the search for alternative, more sustainable binders.

Alkali-activated binders (AABs) have gained increasing attention as a low-carbon alternative for soil stabilisation. They are based on aluminosilicate precursors activated by alkaline solutions and form a polymeric aluminosilicate network fundamentally different from the calcium silicate hydrate phases of OPC. This reaction mechanism is less dependent on calcium availability and may therefore be less susceptible to the retarding effects of humic matter. Recent studies show that AABs can deliver mechanical performance comparable to or even better than that of conventional methods in difficult soft soils, while reducing environmental impact [10–12]. Nevertheless, their interaction with organic soils and humic matter is not yet fully understood, particularly in comparison to conventional cement-based systems.

Despite the recognised importance of humic matter for stabilisation processes, organic soils are still commonly characterised using bulk parameters such as loss on ignition (LOI) or total organic carbon (TOC). These parameters do not account for the chemical heterogeneity of humic matter, which comprises fractions with distinct solubility and reactivity. This limitation hampers the interpretation of soil–binder interactions and the targeted selection of suitable binders. This contribution therefore examines humic matter as a governing factor in DSM of organic soils and highlights the relevance of its differentiated characterisation for sustainable ground improvement.

2 Humic matter in organic soils

Humic matter (HM) constitutes the most stable fraction of soil organic matter (SOM) and is formed during humification processes under conditions of limited oxygen availability (see Figure 1) [13]. In water-saturated environments such as bogs and fens, microbial decomposition is incomplete, favouring humification over mineralisation and leading to the accumulation of highly polymerised organic compounds [13–15]. Peat soils are therefore characterised by high contents of HM at various stages of humification, which strongly influence their physical, chemical and mechanical behaviour.

Due to its complex and heterogeneous nature, HM does not possess a fixed chemical structure. Instead, it is operationally classified according to its pH-dependent solubility into fulvic acids (FA), humic acids (HA) and humins [13,16]. Fulvic acids are soluble over the entire pH range and exhibit relatively low molecular weight, high oxygen content and a large number of functional groups. Humic acids dissolve only under alkaline conditions and are characterised by higher molecular weight, increased aromaticity and lower solubility. They are commonly subdivided into brown humic acids (BHA), which are less strongly humified, and grey humic acids (GHA), which represent a more advanced stage of humification with increased molecular complexity and density. Humins form the most strongly humified fraction and are practically insoluble [16–18].

The solubility behaviour and chemical reactivity of HM are governed by intermolecular interactions and ionic bonding mechanisms. Deprotonated functional groups, such as carboxyl and phenolic groups, readily form stable complexes with multivalent cations including Ca^{2+}, Mg^{2+}, Fe^{3+} and Al^{3+} [17,19]. In particular, GHA exhibit a strong affinity for metal ions and clay minerals, leading to the formation of stable clay–humus complexes that are difficult to dissolve or mobilise.

From a geotechnical perspective, these characteristics are highly relevant for DSM. In cement-stabilised organic soils, the alkaline environment created during hydration promotes the dissolution of HA, which subsequently react with calcium ions to form poorly soluble calcium–humate complexes. This reaction reduces the availability of calcium for the formation of cementitious phases and disrupts the development of a continuous soil–binder matrix. At the same time, the acidic nature of HM counteracts the alkaline conditions required for hydration reactions. GHA are particularly critical in this

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context due to their high degree of humification and strong metal–binding capacity [7,8]. Consequently, organic soils with similar total organic contents may exhibit markedly different stabilisation behaviour depending on the composition and humification state of their HM.

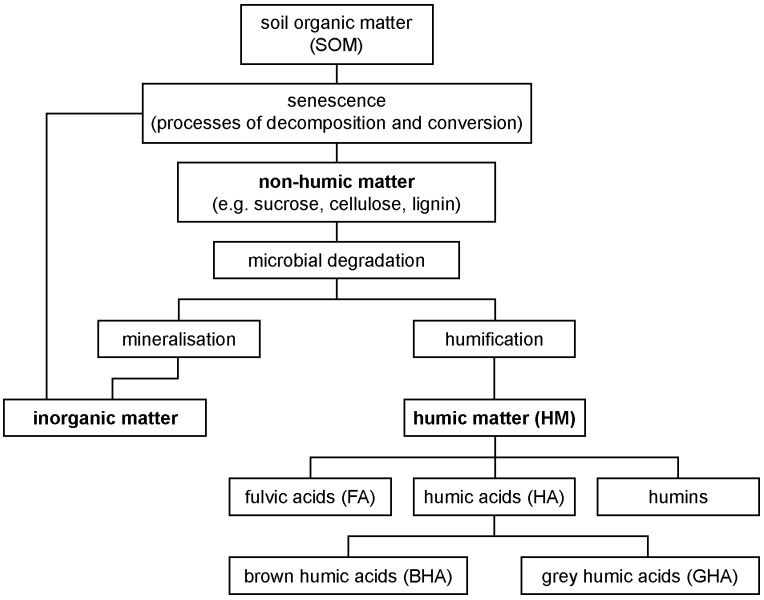

Figure 1. Schematic representation of the decomposition processes and transformation products of soil organic matter [20].

3 Soil characterisation and experimental framework

Peat soils from various locations in Germany were investigated, covering a wide range of degrees of decomposition, pH values and organic matter contents. Standard geotechnical and chemical parameters were determined to establish a baseline characterisation and to enable a systematic comparison of the soils (see Table 1).

Table 1. An overview of the examined peat, including its physical and chemical properties.

peat sample	origin	depths below ground level	von Post scale	acidity (pH)	water content	LOI	TOC
		[m]	[-]	[-]	[wt.%]	[wt.%]	[wt.%]
P1	Altshausen	0.5-2.0	H8-H10	7.0	109	40.8	21.1
P2	Freiburg	2.1-2.2	H6-H7	5.7	90	40.9	19.0
P3	Freiburg	2.2-2.3	H6-H7	5.7	65	36.0	17.4
P4	Freiburg	3.2-3.3	H7-H8	6.6	43	23.6	13.5
P5	Freiburg	3.3-3.4	H7-H8	7.3	63	22.6	9.4
P6	Frankfurt a.M.	4.2-4.5	H5-H6	5.8	103	26.3	21.8
P7	Berlin	n/a	H2-H3	4.3	207	50.3	25.9
P8	Hamburg	n/a	H6-H7	4.8	66	32.9	15.2
P9	Jungnau	n/a	H7-H8	5.7	546	90.6	40.5
P10	Lensahn	n/a	H6-H7	5.5	446	71.0	35.6
P11	Berlin	0.6-2.0	H3-H4	5.1	548	77.2	43.8
P12	Berlin	2.0-2.6	H5-H6	7.1	278	43.2	27.4
P13	Potsdam	n/a	H7-H8	5.7	27	75.0	39.1
P14	Tribsees	n/a	H8-H10	6.0	377	87.7	43.4

The chemical characterisation of HM was based on a multi-stage extraction approach, making use of the pH-dependent solubility of humic fractions. This procedure allows FA and HA to be distinguished and quantified and provides a differentiated description of organic matter composition beyond bulk parameters such as LOI or TOC.

FA were extracted using distilled water, reflecting their solubility over a wide pH range. HA were subsequently mobilised under alkaline conditions using 0.1 molar alkaline solutions. Two extraction variants were applied: a sodium hydroxide solution (NaOH) and a combined solution consisting of sodium hydroxide and sodium pyrophosphate (NaOH + $Na_4P_2O_7$) mixed in a 1:1 ratio. The addition of pyrophosphate promotes the release of strongly humified HA by weakening metal–mediated bonds within clay–humus complexes, thereby enhancing the extraction of GHA.

The extraction was performed in several stages to enable selective mobilisation of humic fractions and to reduce overlap between soluble and insoluble components. This approach allows soils with comparable total organic contents to

be distinguished based on differences in HM composition and degree of humification, which is particularly relevant for assessing their interaction with binders used in DSM.

Quantitative determination of the extracted humic fractions was carried out using ultraviolet–visible (UV/VIS) spectroscopy. UV/VIS spectroscopy is an optical analytical method that measures the absorption of electromagnetic radiation in the ultraviolet and visible wavelength range. The technique is well suited for HM, as their conjugated molecular structures exhibit characteristic absorption behaviour, enabling the determination and comparison of FA and HA contents in solution.

The characterisation of HM forms part of an integrated experimental framework addressing soil–binder interactions in DSM. Within this framework, chemical soil properties are related to mechanical and microstructural behaviour using unconfined compression tests, consolidation tests, ultrasonic measurements and microstructural analyses by SEM/EDX on stabilised soils with varying HM contents.

4 Results and implications for deep soil mixing

The results presented in this section focus on the chemical characterisation of HM in the investigated peat soils. Quantitative and qualitative outcomes of the extraction and UV/VIS analysis are summarised as a basis for interpreting soil–binder interactions in deep soil mixing. Mechanical and microstructural investigations form part of the same experimental framework but are not addressed in detail in this contribution.

The quantitative evaluation revealed pronounced differences in HM composition between the investigated peat soils. FA were present only in minor amounts (< 1 wt.%), while HA constituted the dominant fraction across all samples (see Figure 2). Despite similar total organic matter contents, as shown in Table 1, the extracted HA contents varied considerably (see Figure 2), indicating differences in the degree of humification and polymerisation.

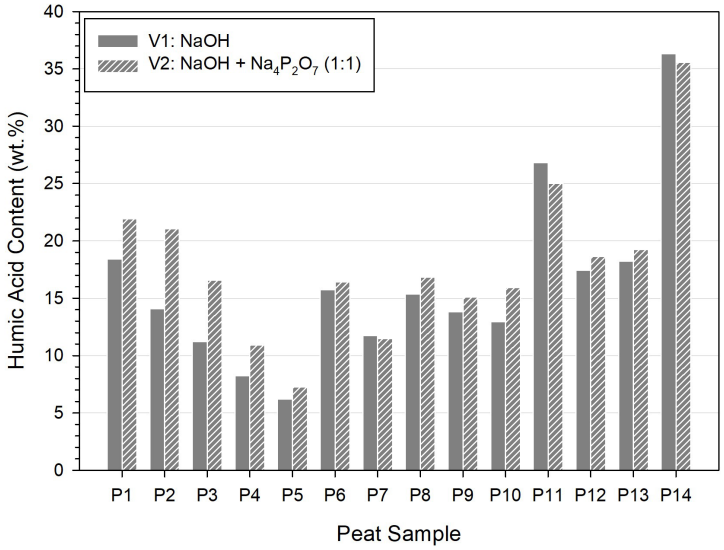

Figure 2. Humic acid content (wt.%) of peat samples after 24 h alkaline extraction (V1, V2), measured by UV/VIS at 225 nm.

For several soils, higher HA contents were obtained using the combined NaOH–$Na_4P_2O_7$ extraction compared to NaOH alone, indicating the presence of strongly humified humic fractions. This response highlights that soils with similar organic contents may differ substantially in their chemical reactivity due to differences in HM composition.

The qualitative assessment based on the colour development of alkaline extracts supported the quantitative results. Lighter colouration was associated with lower degrees of humification, whereas darker extracts indicated higher humic acid contents and the presence of strongly humified fractions. While colour–based evaluation does not provide quantitative resolution at higher concentrations, it proved suitable for differentiating soils with contrasting HM characteristics.

Overall, the results demonstrate that the combined quantitative and qualitative characterisation of HM enables a differentiated classification of organic soils, providing an essential chemical basis for interpreting soil–binder interactions in DSM.

5 Conclusions

HM is an important factor in the stabilisation of soft organic soils by DSM. This study shows that the quantity, composition and degree of humification of HM can vary considerably between peat soils, and that these factors need to be considered when evaluating soil-binder interactions.

The results show that general organic parameters such as LOI or TOC are not sufficient for meaningfully describing the chemical characteristics of organic soils. Quantitative differentiation of HM, supported by qualitative assessment of

humification, provides a more reliable basis for characterising organic soils. In particular, identifying HA-rich soils and strongly humified fractions is important for anticipating potential challenges in DSM applications.

In line with findings reported in the literature, soils with high HA content are generally incompatible with calcium-based binders such as OPC. AABs show promising potential as a more robust and sustainable alternative, as their reaction mechanisms are less dependent on calcium availability.

Ongoing and planned laboratory investigations aim to establish a direct link between HM composition and the mechanical and microstructural properties of stabilised soft organic soils. These studies will improve our understanding of the role of HM in DSM and support the development of bespoke binder formulations. Ultimately, combining quantitative HM characterisation with standardised methods could enhance our ability to predict ground improvement in soft organic soils.

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