

Evaluating the role of organic substrates and microbial activity on sand creep from 1D consolidation tests

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ABSTRACT: Organic-matter-rich sands in coastal and wetland environments often exhibit high compressibility and long-term creep, posing challenges for infrastructure stability. This study investigates whether fungal activity and organic substrates alter soil creep behavior in a controlled sand matrix. Silica sand samples (relative density 40%) were prepared with 1% sucrose or 7% starch, 0.3%–0.6% *Saccharomyces cerevisiae* biomass, and saturated with either water or glycerol. Water and glycerol were selected as contrasting low- and high-viscosity pore fluids to assess whether increased pore-fluid viscosity, representative of organic-rich solutions, modifies the creep response. One-dimensional consolidation tests were conducted at 0.15, 0.30, 0.60, and 1.20 MPa to examine creep behavior over a controlled one-order-of-magnitude stress interval. The secondary compression index, C_α , was evaluated from the settlements recorded over 48 hours at each load increment. This stress range, although higher than typical shallow stresses in coastal and wetland soils (generally < 50 kPa), was adopted to generate sufficiently large and measurable creep strains in an inert sand matrix, providing an upper-bound view of stress-controlled creep mechanisms that can guide subsequent low-stress investigations. Results show that C_α remains effectively constant across this stress range and is insensitive to organic amendments, microbial activity, or pore-fluid viscosity. A transiently high C_α in the glycerol-saturated sample at low stress relaxed into this range as tests progressed. These findings indicate that, for inert sands under moderate to high confinement, bulk stress conditions dominate creep behavior, rendering organic and biological effects negligible.

KEYWORDS: Creep behavior, Soil-fungi interactions, Soil consolidation, Bio-geotechnical engineering, Soil biomass effects

1 INTRODUCTION

Soil creep is the slow, imperceptible, and progressive downhill movement of soil material under the influence of gravity, typically occurring on gentle to moderate slopes (Osman, 2018; Culling, 1963). This time-dependent deformation contributes to long-term landscape evolution and can adversely affect both natural ecosystems (Oehm & Hallet, 2005) and built infrastructure (Farewell et al., 2012). Creep is often driven by the cumulative effects of minor disturbances – such as wetting-drying cycles, freeze-thaw events, and biological activity – that incrementally displace soil particles downslope. Although soil creep occurs naturally in various environmental settings, its rate and extent depend on a complex interplay of soil properties and external factors (Fedà, 1992).

This phenomenon is especially pronounced in soils with high organic matter (OM) content (Hameedi et al., 2020). Organic matter – comprising decomposed plant and animal residues, root exudates, microbial biomass, and humified substances – significantly alters the physical behavior of soils (Zhelezova et al., 2025). Soils rich in OM typically exhibit lower bulk density and higher compressibility, making them more vulnerable to long-term deformation under sustained loads (Abdi et al., 2018; Ritz & Young, 2004). Peat, which may contain over 75% organic material (Huat et al., 2011; Kazemian, 2018), exemplifies this behavior: its fibrous, water-retentive, and highly compressible structure leads to substantial and persistent creep when subjected to stress.

Despite numerous studies, the underlying mechanisms driving creep in organic-rich soils remain poorly understood (Peng et al., 2024).

While constitutive models and laboratory tests have attempted to simulate and predict time-dependent deformation – especially in fibrous and amorphous peats (Acharya et al., 2018) – many models lack the robustness needed to generalize findings to real-world, heterogeneous field conditions.

There remains considerable debate regarding which factors most strongly influence creep behavior, with candidate mechanisms including soil microstructure, biotic activity,

interparticle bonding, and fluid–solid interactions (Zhang & O’Kelly, 2013).

A critical but often underexplored dimension of this problem lies in recognizing that soil is not merely a mechanical mixture of particles and pore fluids; rather, it functions as a living, dynamic ecosystem (Zhelezova et al., 2025).

Soils host a vast array of microbial, fungal, and plant life that interacts continuously with mineral and organic components (Sokol et al., 2022).

These interactions can significantly influence soil’s physical, chemical, and biological properties, including those that govern deformation and creep. Understanding soil as a biologically active medium is therefore essential to unravelling the true complexity of long-term mechanical behavior.

In this study, we explore two interrelated hypotheses concerning the role of organic matter and fungi in soil creep:

- *substrate consumption hypothesis:* the degradation of organic substrates coating soil particles – particularly by fungi – may alter interparticle bonding and disrupt soil microstructure, promoting creep deformation.
- *viscosity hypothesis:* organic matter influences the viscosity and rheological behavior of pore fluids. In peat soils, elevated organic content may modify fluid viscosity, while in the rhizosphere, root exudates have been shown to impart viscoelastic behavior to the soil matrix.

To isolate these effects, we use sand, a relatively inert and mineral soil, as our baseline experimental matrix.

The simplicity of sandy soil provides a controlled environment for studying the influence of organic amendments and fungal activity on time-dependent deformation, particularly creep.

2 METHODOLOGY

2.1 Materials

2.1.1 Soil

The sand used in this study is a commercially available silica sand provided by Dansand, characterized by its poor grading and uniform mineral composition. It has a median grain size of 0.36 mm, a uniformity coefficient, U , of 2.10, and a curvature coefficient, C_r , below. A summary of its key physical and chemical properties is given in Table 1.

Table 1. Summary of physical and chemical properties of the tested sand 1 (Sorrentino & Franza, 2025a).

Parameter	Symbol	Value	Unit
<i>Shape Description</i>			
Sphericity		0.82	
Roundness		0.34	
<i>Particle Size Distribution</i>			
D_{10}		0.19	mm
D_{30}		0.27	mm
D_{50}		0.36	mm
D_{60}		0.41	mm
Uniformity Coefficient	U	2.10	
Curvature Coefficient	C_r	0.95	
<i>Chemical and Physical Properties</i>			
SiO ₂ content		99.08%	[-]
Grain Density		2.64	g/cm ³
Bulk Density		1460-1610	kg/m ³

Particle size analysis was performed using a QICPIC dynamic image analyzer at the National Research Facility for Infrastructure Sensing (NRFIS), University of Cambridge. The system analyzed over 27 500 particles, using the Equivalent Projected Circle (EQPC) diameter as the sizing metric. The resulting particle size distribution closely aligns with the supplier's data (Figure 1).

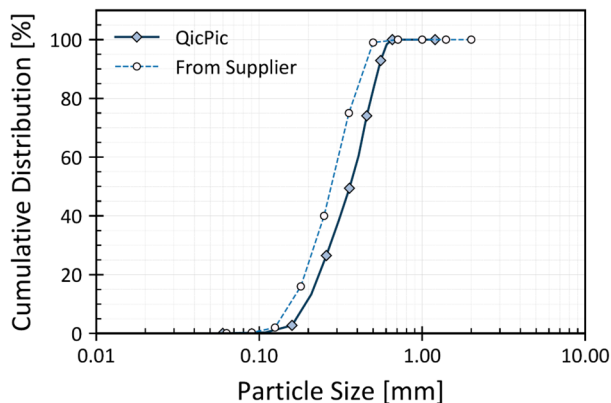


Figure 1. Particle size distributions obtained from supplier data and QICPIC image-based measurement (Sorrentino & Franza, 2025b).

2.1.2 Organic additives

To investigate the role of microbial activity in soil creep, we used *Saccharomyces cerevisiae*, a non-filamentous, single-celled fungal species commonly employed in microbiological

studies (Bester, 2005; Botha, 2006). This yeast was deliberately chosen over filamentous fungi (e.g., *Aspergillus*, *Penicillium*) to eliminate structural bridging effects from hyphal growth and isolate the impact of organic substrate consumption on soil behavior (Park et al., 2025; Zhang et al., 2023).

As a carbon-rich nutrient source, we initially applied a simple sugar solution to promote microbial activity. We later used Potato Dextrose Agar (PDA), a standard fungal growth medium composed of potato starch and glucose, offering both simple and complex carbohydrates (Atlas, 2004; Smith & Onions, 1983). PDA not only supports robust yeast growth under laboratory conditions but also serves as a proxy for natural organic matter, simulating biochemical inputs similar to those found in the rhizosphere or peat-rich soils.

This experimental setup allowed us to evaluate the effect of microbial degradation of organic matter on soil creep, independently of any mechanical reinforcement that might arise from fungal hyphae.

2.1.3 Viscous Fluid

To simulate the presence of organic-rich, viscous pore fluids in the soil matrix, we used glycerol (glycerine) - a biologically compatible, highly viscous trihydroxy alcohol known for its Newtonian behavior and well-characterized rheological properties.

Glycerol serves as a proxy for viscous fluids naturally found in soils, such as those produced by root exudates or the decomposition of organic matter (Naveed et al., 2017; Read & Gregory, 1997).

The rheological properties of glycerol were characterized using a RheolabQC rotational rheometer (Anton Paar) at NRFIS.

Measurements were conducted over a shear rate range of 0.01 to 100 s⁻¹, representing the low to moderate shear conditions relevant to soil creep processes.

This shear rate range was also employed in previous studies using the same rheometer to characterize viscous flow behavior in porous media (Sorrentino, 2022, Sorrentino & Biscontin, 2023).

The results confirmed Newtonian behavior within this range, with a constant viscosity of approximately 0.9 Pa·s at approximately 25 °C, in agreement with values reported in the literature (Sheely, 1932). For reference, the viscosity of deionized water at this temperature is approximately 0.001 Pa·s. Given the pore-fluid velocities and deformation rates expected during the experiments, this characterization provides a realistic approximation of in situ fluid conditions.

2.2 Experimental methods

2.2.1 Oedometer testing

Oedometer tests were performed using the standard oedometer frames available at Technical University of Denmark (DTU) Geo Lab, which are equipped with Linear Variable Differential Transformers (LVDTs) for precise displacement measurements.

Cylindrical samples were prepared with a diameter of 100 mm and a height of 20 mm. The samples were installed in the oedometer cell, and an initial seating load of 0.025 MPa was applied for 24 hours to ensure good contact between the porous disc and the sample surface, following the approach of (Yu et al., 2021).

Subsequent vertical stresses were applied incrementally according to a geometric loading sequence ($\sigma'_{v,n} = 2 \cdot \sigma'_{v,n-1}$) with each loading step maintained for 48 hours to allow for

detailed assessment of secondary consolidation. The coefficient of secondary compression, C_{α} , was calculated using:

$$C_{\alpha} = \frac{\Delta e}{\log t_2 - \log t_1} \quad (1)$$

where Δe is the change in sample void ratio between times t_1 and t_2 . To manage total test duration within practical limits (approximately one week per sample), four loading steps were selected: 0.15, 0.3, 0.6, and 1.2 MPa.

The two stress levels (0.15 MPa and 1.20 MPa) correspond to the lower and upper bounds of the applied loading sequence. The lower bound (0.15 MPa) is higher than typical effective stresses in the shallow coastal and wetland sands that motivated this study (generally < 50 kPa) but was selected to ensure measurable creep strains in the inert sand matrix. The upper bound (1.20 MPa) provides a high-confinement reference condition that allows the stress dependence of creep to be evaluated over one order of magnitude and isolates mechanically controlled behaviour from possible biological or organic effects.

2.2.2 Sample Preparation

All specimens were prepared using silica sand at a relative density of 40%, corresponding to lower–medium-dense state according to standard relative-density descriptions of granular soils (Lancellotta & others, 2012). Natural coastal and nearshore sandy deposits exhibit a broad range of in-situ relative densities (typically 20–60%, depending on the depositional history) (Brilli & Stark, 2024; Farrar, 1999), and a relative density of 40% was adopted as a conservative, relatively lower-medium-dense condition within this range. This state provides a deformable sand matrix relevant to coastal and wetland environments, while also maximizing pore space for added organic substrates and fungal biomass, thereby reducing the influence of particle–particle contact stiffness and enhancing the detectability of potential biologically induced creep effects.

Organic amendments were introduced by mixing either 1% sucrose (S) or 7% PDA (P) by dry mass, simulating labile and complex carbon sources, respectively. Fungal biomass (*Saccharomyces cerevisiae*) was added at two concentrations: 0.3% (F1) and 0.6% (F2).

For all specimens—including the clean sand benchmark and the glycerol-saturated sample—the same mass of sand was used, corresponding to a relative density of 40% for the clean sand. For the treated specimens, the organic substrates and fungal biomass were added to this sand and dry-mixed before saturation. The material was then saturated with water (W) or glycerol (G) and spooned into the oedometer cell under fluid using the same placement procedure for every test, to ensure full saturation, minimise air entrapment, and maintain consistent installation conditions.

Tests are labelled in terms that reflect the organic additive type and content, fungal concentration, and saturating fluid. Specifically, each sample name begins with a fixed prefix (SAND), followed by three components: (i) substrate type and concentration (e.g. S01 for 1% sugar, P07 for 7% PDA, or 00 for clean sand); (ii) fungal content (F0, F1, or F2 representing 0%, 0.3% and 0.6% of the total dry mass, respectively); (iii) saturation fluid type (W for water, G for glycerol).

3 RESULTS

Figure 2 highlights the time-dependent behavior and variation in secondary compression index (C_{α}) across different soil treatments under low (0.15 MPa) and high (1.20 MPa) vertical

stresses. Most samples exhibit a consistent creep response regardless of stress level, with C_{α} values falling within a similar range throughout the test duration. An exception is observed in sample SAND_00_00_G, which shows an initially elevated C_{α} under low confinement during the early phase of the second loading step. However, as the test progresses, this value gradually decreases and aligns with the trends seen in the other samples.

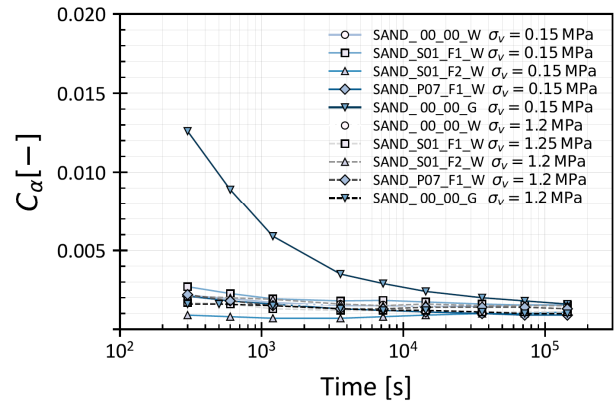


Figure 2. Evolution of the secondary compression index C_{α} over time for all tested samples under vertical stresses of 0.2 MPa and 1.5 MPa.

Figure 3 illustrates the influence of different organic additives, microbial activity, and pore fluid viscosity on the secondary compression index across the vertical stress levels applied in this experimental campaign. The data show no significant effect of either organic matter or pore fluid viscosity on C_{α} as calculated after 48 hours of sustained load.

This suggests that, for the pressure range investigated and using an inert granular matrix such as sand:

- for the stress range investigated, organic substrates and fungal biomass do not produce a measurable effect on the secondary compression index, even when C_{α} is evaluated over different time intervals;
- pore-fluid viscosity does influence creep at low stress and at early times: the glycerol-saturated sample shows an initially higher C_{α} under the lowest vertical stress, but this effect diminishes with time and C_{α} converges towards the values observed for the water-saturated tests;
- time-dependent deformation is dominated by the mineral skeleton, with the role of organic inputs being negligible compared to the overall soil framework stiffness at high stress.

4 CONCLUSIONS

One-dimensional consolidation tests on silica sand - amended with 1% sucrose or 7% PDA, 0.3%–0.6% *Saccharomyces cerevisiae* biomass, and glycerol - demonstrated that, over the stress range 0.15–1.20 MPa, the secondary compression index C_{α} after 48h remains essentially constant (0.001–0.002) regardless of applied stress, organic amendments, microbial activity, or pore-fluid viscosity.

Although the glycerol-saturated sample exhibited a transiently elevated C_{α} under 0.15 MPa, it converged to the common range as consolidation progressed.

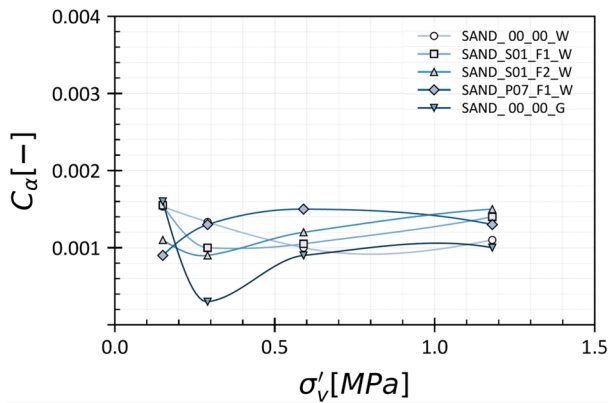


Figure 3. Variation of the secondary compression index (C_{α}) calculated at 48 hours as a function of vertical stress for all tested soil treatments.

These results suggest that, for inert granular media like sand under moderate to high confinement, bulk stress conditions dominate creep behavior and mask potential structural or biochemical influences of organic matter and microbes.

However, because our tests were limited to moderate–high effective stresses, they do not capture the behavior of shallow soils under lower confining pressures, where organic and microstructural factors might be more influential.

Additionally, the current oedometer setup cannot monitor microbial activity in real time, preventing direct linkage between biological respiration and creep evolution.

Future work should therefore use consolidation equipment capable of applying lower vertical stresses to better simulate shallow subsurface conditions and incorporate in-cell CO₂ or other gas sensors to track microbial metabolism during loading, enabling a more comprehensive understanding of bio-coupled soil deformation.

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