Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-992

The influence of soil organic content and water content on rheological behaviour of very soft clays

Meghna V S
Indian Institute of Technology, Palakkad, Kerala, India, meghnavs@gmail.com

Rakesh J. Pillai
Indian Institute of Technology, Palakkad, Kerala, India

ABSTRACT: Soil rheological behaviours include creep, stress relaxation, and strength reduction due to long-term load application. Creep behaviour in soil manifests in two forms: shear creep and volumetric creep. Shear creep is associated with events like landslides, debris flow, mudflow and glacial movements, whereas the long-term settlement of clayey soils associated with secondary consolidation corresponds to volumetric creep. Soft clays with high water content and organic content exhibit higher secondary consolidation characteristics. In this study, amplitude sweep test and one-dimensional consolidation test are employed to investigate the shear creep and volumetric creep responses of soft clays, respectively. An amplitude sweep test is conducted using a dynamic shear rheometer to evaluate the viscoelastic behaviour of organic and inorganic clays. From the above test, viscoelastic parameters like storage modulus (G′), loss modulus (G′′), linear viscoelastic range (LVE), deformation limit (γ_L), cross-over/flow point (γ_f) and loss factor (tan δ) can be obtained. The influence of soil organic content and water content on amplitude sweep test curve and obtained viscoelastic parameters are studied. The volumetric creep or secondary consolidation is particularly significant for soft clays along with primary consolidation characteristics. However, conventional constitutive models, such as the Mohr-Coulomb and Cam Clay models, are not capable of capturing the viscous secondary consolidation response of soft clays. In this study, the volumetric creep behaviour of soft clay is analysed through one-dimensional oedometer test, and the effect of water content and organic content on the secondary consolidation behaviour is monitored. To understand the influence of secondary consolidation characteristics on the settlement response of soft clays in the field, a 2D numerical analysis is performed for an embankment built on soft clay, considering the Soft Soil Creep model. From the study, it can be observed that soil organic content and water content significantly affect the rheological behaviour of very soft clays.

KEYWORDS: Soft Clays, Rheology, Secondary Consolidation, Creep, Soft Soil Creep model.

1 INTRODUCTION

In geotechnical engineering, understanding the time-dependent deformation of soils under sustained loading is important, as these rheological behaviours significantly influence the long-term stability and performance of structures. Soil rheological behaviour encompasses creep, the gradual deformation under constant stress; stress relaxation, where stress reduces over time at constant strain; and a reduction in strength due to prolonged load application. The term creep is often used synonymously with secondary consolidation of soil. However, secondary consolidation is only a type of creep. Soil creep is a critical phenomenon that manifests in two distinct forms: shear creep and volumetric creep. Shear creep, characterised by deformation under constant shear stress, is linked to catastrophic events such as landslides, debris flows, mudflows, and glacial movements. The time-dependent volume reduction that occurs under prolonged compressive stress, known as secondary consolidation, falls under the category of volumetric creep (Vyalov, 2013).

The suitability of using rheological measurements as a tool to study the soil structure on the micro-scale (Markgraf et al., 2012; Holthusen et al., 2020; Javaheri et al., 2021) and for stabilisation and transport of fine-grained sediments (Wang et al., 2022) has been reported in the literature. These studies focus on providing the framework for solving different natural and man-made phenomena occurring due to shear stress, like erosion, landslide, debris flow, etc. Amplitude sweep test with controlled shear deformations has been reported as an effective method to study the rheological properties of soils and sediments under shear deformations (Markgraf et al., 2006; 2012). The influence of organic matter and water content on the viscoelastic properties of soil has been studied by Markgraf et al. (2012) using rotational rheometry. Wang et al. (2022) have investigated the steady and dynamic rheological characteristics of fine-grained sediments at different water-solid ratios. The rheological properties of clay minerals such as kaolinite and montmorillonite, and other clayey soils were studied by Khaydapova et al. (2015). Holthusen et al. (2020) characterised the soil micro-mechanics through amplitude sweep test and reported that the viscoelastic parameters are mostly affected by soil organic content and strain, whereas the shear stress parameters are affected by soil organic content, normal stress and water content.

The post-construction settlement of soft clay poses challenges for the construction of structures over it, and the condition becomes worse when there is the presence of organic matter (Rasheed and Moghal, 2024). Peats and organic clays exhibit high secondary compression or volumetric creep (Reddy et al., 2014; Raheena and Robinson, 2020; Varghese et al., 2021). The secondary compression index (Cα), which is the slope of the e versus log t plot in the secondary compression range, is used to quantify the secondary compression settlement of soils. The Cα/Cc concept proposed by Mesri and Castro (1987) is another method to quantify the secondary compression characteristics of soils. The secondary compression characteristics of organic clay with varying organic content and water content were determined through 1D consolidation test by Reddy et al. (2014) and reported Cα/Cc value of 0.038 to 0.051 for the soils considered. The increase in secondary compression index (Cα) with increasing soil organic content was also observed by Varghese et al. (2021).

From the existing literature, it is evident that the organic content and water content have a significant influence on the shear and volumetric creep responses of clays. The present study investigates the influence of organic content and water content on the rheological behaviour of high-water content very soft clays. Two types of very soft clays have been studied here – an organic clay and an inorganic clay. Amplitude sweep test (AST) and one-dimensional oedometer test are employed to investigate the shear creep and volumetric creep responses of soft clays, respectively. The amplitude sweep tests were conducted at different consistency index values, and the response of both organic and inorganic clays was observed. One-dimensional oedometer tests were conducted for both the clays at their respective liquid limits, and the secondary consolidation characteristics were obtained. Further, a numerical analysis was performed to evaluate the settlement response of an embankment constructed on soft clay. The Soft Soil Creep model was used as the material model for soft clay, and the time - settlement response of the embankment was obtained considering organic content as the parameter.

2 MATERIALS AND METHODS

2.1 *Materials*

The materials used for the study are two types of high-water content, very soft clays with different organic content. The physical properties of the clays, such as Atterberg limits, natural water content, specific gravity, pH, organic content, and particle size distribution, were determined and are listed in Table 1. The clay with higher organic content (29%) is referred to as organic clay (O), while the clay with lower organic content (6%) is termed inorganic clay (I). The particle size distribution curve of the organic and inorganic clay is given in Figure 1.

Table 1. Physical properties of organic and inorganic clay.

Properties	Test Standard	Organic Clay (O)	Inorganic clay (I)
Natural water content (%)	ASTM D2216-19	282	99
Atterberg limits			
Liquid limit (%)	ASTM D4318-17	252	129
Plastic limit (%)	ASTM D4318-17	174	42
Shrinkage limit (%)	ASTM D427-04	52	17
Plasticity Index (%)	ASTM D4318-17	78	50
Specific Gravity	ASTM D854-23	2.05	2.62
pH	IS 2720(Part 26)-1987	2.56	7.66
Organic content (%)	ASTM D2974-20	29	6
Particle Size Distribution	ASTM D6913-21		
% Sand	ASTM D7928-21	6	26
% Silt		46	34
% clay		47	40
Soil Classification	ASTM D2487-17	OH	CH

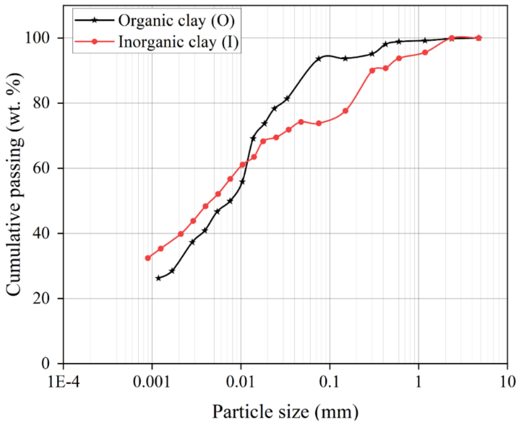

Figure 1. Particle size distribution curve of organic clay and inorganic clay.

2.2 *Methodology*

The influence of organic content and water content on the rheological behaviour of high-water content very soft clays was determined by conducting amplitude sweep test and one-dimensional oedometer test. Further, a numerical analysis was conducted for an embankment on soft clays, considering organic and inorganic clay.

2.2.1 *Shear Creep Behaviour*

The shear creep response of both the clays was measured by conducting the amplitude sweep test (AST) (strain sweep) using Anton Paar MCR 702e dynamic shear rheometer. The parallel plate system with 25mm plate diameter was used. All the tests were conducted at a plate distance of 2mm and a constant temperature of 28±0.1˚C. To obtain the complete viscoelastic behaviour of the clay, tests were conducted from a shear strain of 0.00001% up to 100%, with 6 data points per decade (total of 37 data points). The summary of test parameters used is given in Table 2. The influence of water content of clay on the shear creep behaviour of both organic and inorganic clay samples was measured by AST at consistency index (Ic) values of 0%, 50% and 100%. From the AST, variation of storage modulus (G') and loss modulus (G") with strain was obtained for both organic and inorganic clays. The influence of organic content and water content on the linear viscoelastic range (LVE) and deformation limit (γ_L), of the soft clays was also determined. Because of excessive noise at low deformations, the initial elastic modulus (G_0') and initial loss modulus (G_0'') values were estimated at the deformation closest to 0.0001%, and assumed that these moduli were constant throughout the deformation range of $0 < \gamma < 0.0001\%$. The deformation limit (γ_L) was identified as the deformation when G′ first deviated > 5% from G_0' and the flow point (γ_f) was identified as the deformation when G′ = G′′ (Javaheri et al., 2021).

Table 2. Amplitude sweep test setting parameters.

Parameter	
Plate diameter	25mm
Plate distance	2mm
Strain ramp	0.00001 to 100%
Frequency	0.5Hz

2.2.2 *Volumetric Creep Behaviour*

The volumetric creep behaviour of organic and inorganic clay was determined by conducting 1D oedometer test on reconstituted samples. A conventional oedometer with 60mm diameter and 20mm height was used. Soil samples at liquid limit were prepared by the slurry consolidation method suggested by Sahib and Robinson (2024). The time-settlement data was collected for the applied pressure of 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa and 800 kPa. Each pressure was maintained for a duration of 48 hours. The end of primary compression was determined using the logarithm of t method. The volumetric creep of the clays was expressed in terms of the secondary compression index.

A two-dimensional finite element analysis was conducted using PLAXIS 2D for an embankment constructed on very soft clay using the properties obtained from the oedometer test. The geometry considered for the study is similar to Suganya and Sivapullaiah (2012) and is given in Figure 2. The model consists of a 10m thick layer of very soft clay overlaying a 5m thick sand layer. A 3 m high embankment is constructed in two stages, with each lift having a height of 1.5m. The vertical boundaries were fixed for horizontal displacements and allowed vertical displacement. The bottom horizontal boundary was fixed for both horizontal and vertical displacements. The embankment and bottom sand layer were modelled as linear elastic perfectly plastic material with Mohr-Coulomb failure criteria. The soft clay layer was modelled using the Soft Soil Creep model, and the material properties used are given in Table 3. The material properties of the sand layer, embankment, and the remaining properties of the soft clay were adopted from Suganya and Sivapullaiah (2012). The analysis was conducted for both organic and inorganic clay, and the time – settlement plots were obtained.

Table 3. Soft Soil Creep model properties of organic and inorganic clay.

Material Properties	Organic clay	Inorganic clay
Modified compression index, λ^*	0.11	0.07
Modified swelling index, κ^*	0.011	0.007
Modified creep index, μ^*	0.04	0.02
Initial void ratio, e_0	4.5	2.02
Permeability (m/day)	5.16×10^{-5}	1.95×10^{-5}

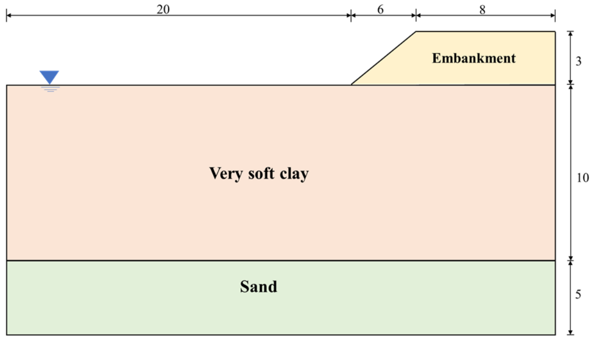

Figure 2. Geometry of the model embankment on very soft clay (all dimensions are in m).

3 RESULTS AND DISCUSSIONS

3.1 *Shear Creep Behaviour*

From the amplitude sweep test conducted on organic and inorganic clay samples at different Ic values, the parameters like storage modulus (G´), loss modulus (G´´), loss factor (tan δ), deformation limit (γ_L), cross-over/flow point (γ_f) and integral z (Iz) were obtained. The variation of G´ and G´´ with shear strain for organic clay is provided in Figures 3 (a) and (b), respectively. The initial values of storage modulus (G_0´) and loss modulus (G_0´´) differed for both clays. From Figure 3 (a), it can be observed that the G_0´is in the range of 10^5 Pa when Ic = 100% and it reduces to 10^4 Pa for Ic = 0%, for organic clay. In the case of inorganic clay, G_0´was in the range of 10^6 Pa for Ic = 100% and reduced to 10^4 Pa for Ic = 0% (Figure 3 (c)). The inorganic clay exhibited higher G_0´ and G_0´´ compared to the organic clay. This can be attributed to stronger interparticle interaction and dense microstructure in inorganic clay due to the absence of organic matter. The G_0´´ values were lower than G_0´for both organic and inorganic clay, and the values decreased as the consistency index reduced from 100% to 0% (Figure 3 (b) and (d)). As water content increases, G_0´ and G_0´´decrease in both clays. The exact values of G_0´and G_0´´ of both clays at different Ic values are given in Table 4. The linear viscoelastic range, defined by the deformation limit (γ_L), represents the strain range within which the soil exhibits purely elastic behaviour. In organic clay, γ_L increases as the consistency index decreases from 100% to 0%, whereas in inorganic clay, γ_L decreases with a reduction in consistency index (Table 4).

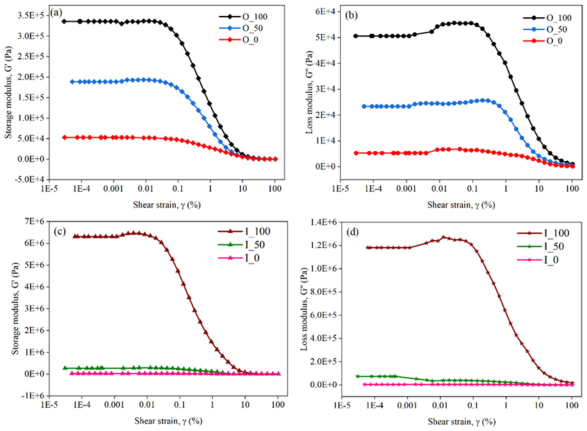

Figure 3. (a) Storage modulus and (b) loss modulus of organic clay at different consistency index values (c) Storage modulus and (d) loss modulus of inorganic clay at different consistency index values.

Both clays exhibited rigid microstructure with fully elastic characteristics for γ < 0.01% (linear viscoelastic range), as indicated by the variation of loss factor (tan δ) with shear deformation (Figure 4). Furthermore, an increase in tan δ was observed for γ ranging from 0.01 to 10% for organic clay and from 0.01 to 4% for inorganic clay, indicating the transition phase. The organic clay reached tan δ = 1 (flow point/cross-over point) at a strain range of 10 to 25% and around 5% strain for inorganic clay. The cross-over point (γ_f) of both clays at different Ic values are given in Table 4. The parameter integral z (Iz) provides a semi-quantitative description of stiffness degradation, making it the most useful indicator of microstructural stability (Markgraf et al., 2012; Javaheri et al., 2021). The calculated value of Iz for organic clay was in the range of 10 to 5, and for inorganic clay, it was below 5, for all the consistency index values considered in this study (Figure 5). The organic clay had consistently higher values of Iz and γ_f compared to the inorganic clay. This behaviour can be attributed to the presence of soil organic content, which acts as a strong binding agent and enhances the elasticity of clay. As a result, organic clays will undergo greater deformation before failure compared to inorganic clays (Markgraf et al., 2012; Javaheri et al., 2021). As Ic increases from 0% to 100%, γ_f and Iz decrease in organic clay, an opposite trend was observed in inorganic clay, where both parameters increase.

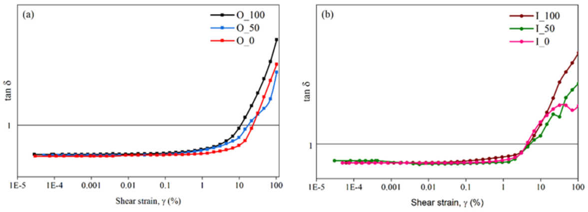

Figure 4. Loss factor variation of (a) organic clay and (b) inorganic clay with shear strain at different consistency index values.

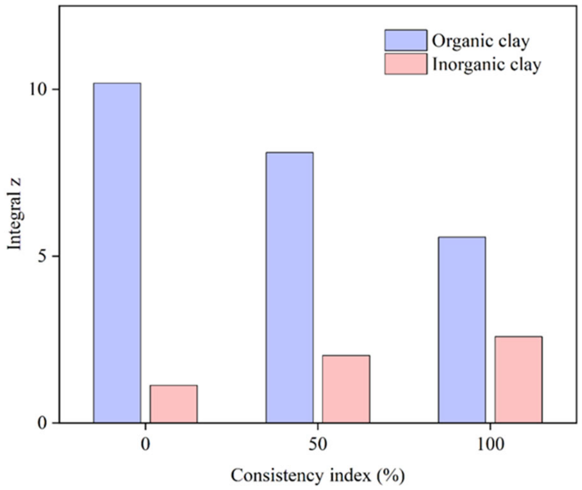

Figure 5. Variation of Integral z of organic and inorganic clay at different consistency index values.

The shear failure pattern of each clay sample was identified based on the shear stress vs shear strain plot as suggested by Holthusen et al. (2020). The stress-strain plots of organic clay samples (Figure 6 (a)) exhibited a peak stress value with a subsequent decrease in the stress, which can be interpreted as brittle failure (Holthusen et al., 2020). Whereas the inorganic clay samples exhibited peak value followed by a post-peak increase (Figure 6 (b) and (c)), which can be interpreted as brittle failure with re-stabilisation. A clear difference between the stress-strain plot and associated failure pattern could be observed for both clays. Organic clay samples exhibited a brittle failure, whereas the inorganic clay samples exhibited a brittle failure with re-stabilisation. The inorganic clay attained a higher peak stress compared to the organic clay. The influence of organic matter on attained peak stress and failure pattern was evident from the stress-strain plots. However, no significant change was observed in the stress–strain response or failure mode with varying Ic values.

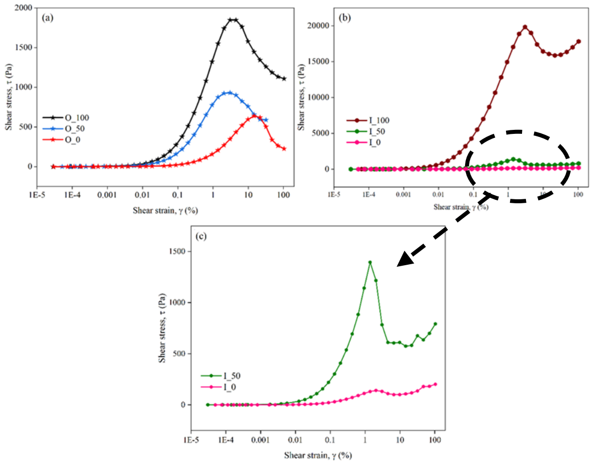

Figure 6. Shear stress vs shear strain plot of (a) organic clay and (b) inorganic clay at different consistency index values.

Table 4. Summarised results from amplitude sweep test.

Clay	Consistency Index (%)	Initial Storage modulus, G_0' (Pa)	Initial loss modulus, G_0'' (Pa)	Deformation limit, γ_L (%)	Cross-over point,γ_f (%)
Organic clay	100	3.4×10^5	5.1×10^4	0.06	11.86
	50	1.9×10^5	2.3×10^4	0.07	18.94
	0	5.3×10^4	5.3×10^3	0.04	25.59
Inorganic clay	100	6.3×10^6	1.2×10^6	0.03	5.07
	50	2.7×10^5	7.4×10^4	0.07	5.68
	0	2.6×10^4	4.6×10^3	0.08	4.39

3.2 *Volumetric Creep Behaviour*

The volumetric creep response of organic and inorganic clay was obtained from 1D consolidation test. The 1D consolidation test on clay samples was conducted under incremental loading of 25, 50, 100, 200, 400 and 800 kPa, with each load maintained for two days to obtain the secondary compression index. Soils with secondary compression index (Cα) greater than 0.064 are considered as having high secondary compression (Mesri, 1987; Rasheed and Moghal, 2024). From Figure 7, it can be observed that the Cα value of organic clay was obtained in the range of 0.06 to 0.1. The value of Cα was found to be increasing for organic clay as the consolidation pressure increases (Figure 7). This high value of Cα indicates that the organic clay falls under the category of soil with high secondary compression. In the case of inorganic clay, the Cα was in the range of 0.02 to 0.05 (Figure 7), indicating that the creep/ secondary compression is in the lower range. The higher secondary compression of organic clay can be attributed to the presence of high organic matter compared to inorganic clay (Reddy et al., 2014; Varghese et al., 2021). The influence of organic content on the volumetric creep response of clays was visible from the secondary compression index (Cα) values obtained. The presence of organic matter in the clays resulted in a higher Cα value, indicating that the clay will be subjected to higher secondary compression/creep settlement.

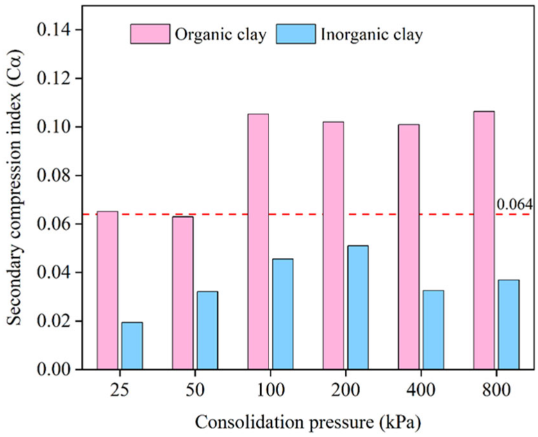

Figure 7. Secondary compression index (Cα) of organic and inorganic clay at different consolidation pressures.

To understand the significance of higher secondary compression index values obtained from the oedometer test of organic and inorganic soft clays, a 2D finite element analysis was conducted for an embankment constructed over soft clay. The obtained time-settlement plots for the embankment toe are given in Figure 8. From Figure 8, it can be observed that there is a distinct difference in both magnitude and time-dependent (volumetric creep) deformation of both clays. Organic clay reached a settlement value of around 2.8 m, whereas inorganic clay reached only 1.5m. Both the clays exhibit rapid settlement in the initial days due to primary consolidation (Figure 8). Further, the settlement rate decreases significantly. However, the organic clay continues to experience substantial deformation, even after the excess pore water pressure is completely dissipated. This sustained long-term deformation can be attributed to volumetric creep or secondary compression, which is more pronounced in organic clay due to its high natural water content, high void ratio, and significant organic matter content (Reddy et al., 2014; Sahib and Robinson, 2024). In comparison, the inorganic clay shows a relatively flatter settlement curve beyond the primary compression phase, indicating lower volumetric creep. Based on the finite element analysis, it is evident that, when embankments are constructed over soft organic clays, long-term settlement due to creep must be accounted for in the design to avoid post-construction deformations and associated serviceability issues.

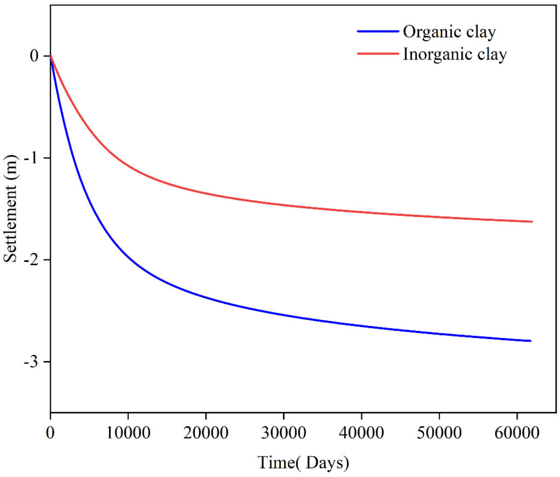

Figure 8. Time-settlement plot obtained for the node at the embankment toe.

4 CONCLUSIONS

This paper studies the rheological behaviour of very soft clays with different organic content and water content. The influence of organic content and water content on shear creep behaviour of soft clays was obtained from the amplitude weep test conducted on organic and inorganic clay at different consistency index values. Further, the volumetric creep/secondary consolidation behaviour of these clays was obtained from 1D oedometer test. The specific conclusions obtained from the study are as follows:

- Organic content is found to have a significant influence on both shear and volumetric creep behaviour. The initial storage modulus (G_0') and loss modulus (G_0'') of organic clay were approximately ten times lower than those of inorganic clay, while the deformation limit (γ_L) and integral z (Iz) were higher. The higher organic content allows the soil to undergo greater deformation before failure when subjected to shear deformations. Based on stress-strain response, the organic clay exhibited brittle failure with no post-peak increase, whereas the inorganic clay exhibited post-peak increase.
- The influence of water content on shear creep parameters of organic and inorganic clays was different. G_0' and G_0'' values of both clays decrease as water content increases. In organic clay, the deformation limit, integral z, and cross-over point increase with rising water content, whereas these parameters decrease in inorganic clay. There was no change in the stress–strain response or failure mode with varying water content, for both organic and inorganic clay.
- The effect of organic content on volumetric creep behaviour of soft clays was evident from the observed values of secondary compression index ($C\alpha$). The organic clay exhibited higher $C\alpha$ values ranging from 0.06 to 0.1, whereas the inorganic clay had a lower range of 0.02 to 0.05. This indicates that the organic clay will be subjected to higher time-dependent deformation/ volumetric creep compared to inorganic clay. This behaviour was further confirmed through finite element analysis of an embankment constructed over these clays. The results showed that the organic clay underwent approximately 1.8 times higher settlement than the inorganic clay, emphasising the long-term deformation potential associated with organic clays.
- It can be concluded that organic content and water content have significant influence on the rheological behaviour of soft clays. Organic content positively affects the shear creep behaviour, by causing large deformations before failure. But the presence of organic content results in higher secondary compression settlements in soft clays. The influence of water content on shear creep parameters was different for organic and inorganic clays. However, the soft clay with higher water content exhibited higher volumetric creep.

5 REFERENCES

Holthusen, D., Batistão, A.C. and Reichert, J.M., 2020. Amplitude sweep tests to comprehensively characterize soil micromechanics: brittle and elastic interparticle bonds and their interference with major soil aggregation factors organic matter and water content. *Rheologica Acta*, [online] 59(8), pp.545–563.

Javaheri, F., Esfandiarpour-boroujeni, I., Kourki, H., Farpoor, M.H. and Stewart, R.D., 2021. Rheological evaluation of soil aggregate microstructure and stability across a forested catena. *Geoderma*,[403(April), p.115196.

Khaydapova, D., Milanovskiy, E. and Shein, E., 2015. Rheological properties of different minerals and clay soils. *Eurasian Journal of Soil Science*, *4*(3), pp.198-202.

Markgraf, W., Horn, R. and Peth, S., 2006. An approach to rheometry in soil mechanics-Structural changes in bentonite, clayey and silty soils. *Soil and Tillage Research*, 91(1–2), pp.1–14.

Markgraf, W., Watts, C.W., Whalley, W.R., Hrkac, T. and Horn, R., 2012. Influence of organic matter on rheological properties of soil. *Applied Clay Science*, [online] 64, pp.25–33.

Mesri, G. and Castro, A., 1987. C α/C c concept and K 0 during secondary compression. *Journal of geotechnical*

Raheena, M. and Robinson, R.G., 2020. Determination of Coefficient of Secondary Compression in Accelerated Incremental Loading Consolidation Test. *Lecture Notes in Civil Engineering*, 85(1986), pp.1113–1125.

Rasheed, R.M. and Moghal, A.A.B., 2024. Compressibility and Durability Characteristics of Protein-Based Biopolymer-Amended Organic Soil. *Journal of Materials in Civil Engineering*, 36(7), pp.1–15.

Reddy, B.K., Sahu, R.B. and Ghosh, S., 2014. Consolidation Behavior of Organic Soil in Normal Kolkata Deposit. *Indian Geotechnical Journal*, 44(3), pp.341–350.

Sahib, A.A. and Robinson, R.G., 2024. End-of-secondary compression for some Indian soils. *International Journal of Geotechnical Engineering*, [online] 18(5), pp.481–488.

Suganya, K. and Sivapullaiah, P.V., 2012, May. Parametric study of embankments founded on soft organic clay using numerical simulations. In *ISSMGE—TC 211 international symposium on ground improvement IS-GI Brussels* (Vol. 31).

Varghese, R., Chandrakaran, S. and Rangaswamy, K., 2021. Influence of type of organic substances on the strength and consolidation behaviour of inorganic clay soil. *International Journal of Geotechnical Engineering*, 15(9), pp.1165–1176.

Vyalov, S.S., 2013. Rheological fundamentals of soil mechanics (Vol. 36). Elsevier.

Wang, H., Zentar, R. and Wang, D., 2022. Rheological Characterization of Fine-Grained Sediments under Steady and Dynamic Conditions. *International Journal of Geomechanics*, 22(1), pp.1–10.