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Experimental investigation of influence of soil plasticity on compression characteristics and creep behaviour of clayey soils

Étude expérimentale de l'influence de la plasticité du sol sur les caractéristiques de compression et le comportement au fluage des sols argileux

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ABSTRACT: Comprehending the creep mechanisms and determining the factors influencing compression and creep characteristics is indispensable for accurate long-term settlement predictions, a critical determinant of structural stability and safety of structures. Also, both natural and artificial slopes, as well as embankments, manifest varying rates of creep movements. Recent experimental investigations have highlighted the significant role played by the influence of soil composition, fabric structure, over-consolidation ratio (OCR), and plasticity in the time-dependent behaviour and compression characteristics of clays. However, a comprehensive description and correlation of these factors have yet to be proposed. To address this gap, an extensive experimental study was conducted under well-defined conditions. Reconstituted samples, including low-plasticity clay (kaolinite), high-plasticity clay (bentonite), and their mixtures, underwent standard and creep oedometric tests. We show that samples with lower plasticity exhibit reduced volume changes during compression and swelling and lower values of the creep coefficient (C_α). The stress dependency of C_α is more pronounced in mixtures containing bentonite compared to pure kaolinite. Also, strong OCR-dependency of C_α has been observed.

RÉSUMÉ: Comprendre les mécanismes de fluage et déterminer les facteurs influençant les caractéristiques de compression et de fluage est indispensable pour des prévisions précises de tassement à long terme, un déterminant essentiel de la stabilité structurelle et de la sécurité des structures. En outre, les pentes naturelles et artificielles, ainsi que les remblais, présentent des taux de fluage variables. Des recherches expérimentales récentes ont mis en évidence le rôle important joué par l'influence de la composition du sol, de la structure du tissu, du taux de surconsolidation (OCR) et de la plasticité dans le comportement dépendant du temps et les caractéristiques de compression des argiles. Cependant, une description complète et une corrélation de ces facteurs doivent encore être proposées. Pour combler cette lacune, une étude expérimentale approfondie a été menée dans des conditions bien définies. Les échantillons reconstitués, comprenant des argiles à faible plasticité (kaolinite), des argiles à haute plasticité (bentonite) et leurs mélanges, ont été soumis à des tests œdométriques standards et de fluage. Nous montrons que les échantillons ayant une plasticité plus faible présentent des changements de volume réduits lors de la compression et du gonflement et des valeurs plus faibles du coefficient de fluage (C_α). La dépendance du C_α à la contrainte est plus prononcée dans les mélanges contenant de la bentonite que dans la kaolinite pure. En outre, une forte dépendance de $C\alpha$ à l'OCR a été observée.

Keywords: Soil plasticity; compression characteristics; creep behaviour; over-consolidation ratio; coefficient of secondary compression.

1 INTRODUCTION

Soil plasticity and composition have been shown to affect the mechanical response of clays, as has been presented by Olek (2022) in the context of creep behaviour. Soil creep characteristics are commonly described using a parameter known as the "coefficient of secondary compression - C_α" (Mesri, 1973). This parameter holds significance in engineering applications and constitutive modelling, particularly when estimating creep settlements. The time-dependent behaviour is traditionally characterised by linearly determining C_α through the relationship between the void ratio and the logarithmic function of time. Yin (1999) illustrated that the creep coefficient exhibits variation with the void ratio and the limitations associated with the logarithmic function used for linear performance. Nevertheless, for this paper, the linear formulation, as employed by Olek

(2022), is adopted to ascertain the parameter C_α. As for the stress dependency of C_α, there exist two conflicting perspectives. Barden and Laing (1969) assert that C_α is nearly independent of stress level, contrary to the findings of other researchers such as Lei et al. (2016).

Soil plasticity is the property governing deformation in soil without the occurrence of cracking or fracturing, making it a crucial aspect for analyzing long-term deformation, commonly known as creep deformation. The observed impact of clay plasticity on clay creep has been shown by Anagnostopoulos and Grammatikopoulos (2011), who conducted oedometer creep tests on thirteen types of natural clays in the broader Thessaloniki area, Greece. The findings suggest that the creep coefficient relies on both plasticity and water content. Additionally, Karstunnen and Yin (2010) established that the creep coefficient exhibits dependence on the process of destructuration specifically within intact natural clays. Despite these insights, there has been limited exploration into the influence of clay structure, including plasticity and its OCR on creep properties and soil responses, particularly when studying reconstituted samples of clays.

Varatharajan and Sivarajan (2011) observed that bentonite, a highly plastic clay, demonstrates more significant creep deformation compared to kaolin, a clay with lower plasticity. Nevertheless, the effect of long-term creep behaviour was not explored, leaving a gap in our understanding of this aspect. A comprehensive exploration of clay plasticity's influence on clay compression behaviour is lacking, highlighting a notable gap in our foundational understanding of time-dependent clay behaviour. To enhance our understanding of how soil plasticity influences the creep behaviour of clay soils, we have initiated a comprehensive experimental program involving the preparation of artificial mixtures of kaolin (K) and bentonite (B) and their mixtures.

2 METHODOLOGY AND MATERIAL

2.1 Methodology

The main goal of this contribution is to gather comprehensive experimental data on how plasticity influences compression (via standard oedometric tests) and creep behaviour (creep oedometric tests) of clays. Soil samples were prepared as mixtures with different proportion rates of kaolinite (K – low plasticity clay) and bentonite (B – high plasticity clay). Individual samples (further denoted as „mixtures“) are denoted such as 100K, 75K-25B, 50K-50B, 25K-75B, and 100B, showing the proportion of individual clays (such as 100K – 100% of kaolinite and 0% of bentonite clay). Plastic and liquid limits were determined for each mixture. Specifically, the plastic limit for each mixture was determined through interpolation using referenced values from (Sivapullaiah et al., 1985) and (Duque et al., 2022). For the determination of liquid limit (LL), the cone penetration method was employed. This method relies on the soil's shear strength, offering improved accuracy and preventing potential overestimation of the liquid limit, particularly in soils with LL exceeding 100% (e.g., bentonite) (Orhan et al., 2006).

Table 1 presents PL, LL, and plasticity index (PI) values. As anticipated, mixtures with a higher bentonite proportion demonstrate elevated PI values.

Table 1. PL, LL and PI of all mixtures.

Mixtures	PL(%)	LL(%)	PI
K	40	64.55	24.55
75K-25B	42.42	124.80	82.37
50K-50B	44.85	229.07	184.22
25K-75B	47.27	287.70	240.42
B	49.7	315.37	265.67

For oedometer tests, an analysis of soil compression, characterized by the critical state line slope (λ^*) in the e-ln(p) space, and swelling, represented by the unloading-reloading line slope (κ^*) in the same space, was performed. Parameters λ^* and κ^* are based on the definitions from the hypoplastic model for clays proposed by Masin (2005) and are equivalent to C_c and C_r. The creep oedometer tests undergo a minimum 7-day creep period after T_{eop}. This timeframe is deemed adequate, as indicated by prior research on reconstituted samples, where T_{eop} is typically achieved within 24 hours (Olek, 2022), (Lei et al., 2016). T_{eop} was determined for each creep stage by Casagrande‘s method (Taylor, 1948). The impact of soil plasticity on long-term settlement was explored by assessing the secondary compression coefficient (C_α):

$$C_\propto = \frac{\Delta e}{\Delta \log t} \qquad (1)$$

The current OCR was determined for every stress increment to address the influence of the OCR on determined soil characteristics. The OCR is defined as σ'_p / σ'_z, where σ'_p is the pre-consolidation stress and σ'_z is the applied experimental stress. In standard oedometer tests (refer to Table 2 for the applied stress levels), the kaolinite sample was subjected to a maximum of 1600 kPa, while the remaining samples were loaded to a maximum of 800 kPa due to the excessive deformation. In the case of creep oedometer tests, bentonite is exposed to a maximum 200 kPa creep stage, while the other samples undergo a maximum of 400 kPa.

Table 2. Experimental plan, note the steps in brackets were performed only for mixtures and kaolinite.

Test	Creep Stress (kPa)/ Stress Increments (kPa)
Creep test	25-50-100-200(-400)
Standard oed. test	0-25-50-100-200-400-800(-1600-800)-400-200-100-50-25-0

2.2 Material

In preparing the investigated materials, specimens comprised dry kaolin and bentonite powder blended with distilled water. Prescribed guidelines dictate initial water content: W_i = 1.4-2.2LL for pure kaolinite tests, W_i = 1.2-1.6LL for pure bentonite tests, and equivalent water contents of 1.4-2.0LL for mixtures. Varied initial water content aims to assess its impact on compression characteristics and determine the content required for normal consolidation across diverse stress levels (e.g., 25, 50, 100 kPa), especially at low stresses. This procedure has been implemented to avoid comparing the mechanical behaviour of normally consolidated samples with over-consolidated ones.

3 RESULTS

3.1 Influence of initial water content on kaolinite compression characteristics

For kaolinite, we analysed compression curves and as expected, we found out that their shape is dependent on the initial water content, even after joining NCL as shown in Figure 1. The NCL is notably influenced by W_i, with a downward shift at lower W_i levels, converging after 200 kPa. This indicates over-consolidation at low stresses (~<200 kPa) for lower W_i. Utilizing the data, we establish a relationship between OCR and W_i, defining the highest NCL (W_i = 148.2%) as the benchmark for OCR = 1.0.

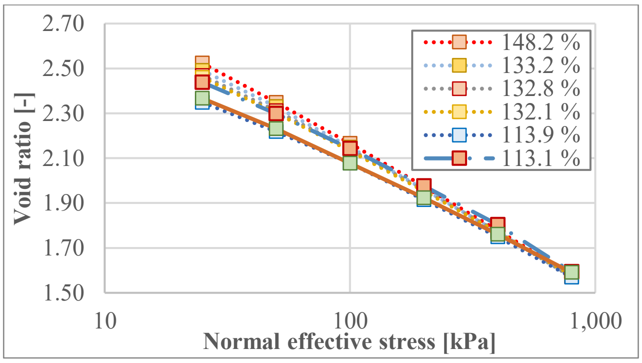

Figure 1. Influence of initial water content (W_i, in per cent) of reconstituted samples of kaolinite on NCL.

The OCR is referenced to the test with the highest initial water content, W_i = 148.2% (and thus the highest positioned NCL). Figure 2 depicts the relationship between OCR and W_i, revealing an inverse proportionality at low-stress levels. Around W_i = 130%, the OCR decreases to ~1.0 establishing this value as a limit. Beyond this limit, OCR remains stable. Thus, precise regulation of W_i is crucial to establishing an accurate NCL for the entire experimental scope. Figure 2 validates using W_i approximately twice the liquid limit for kaolinite, ensuring a normal consolidation state across all stress levels (25, 50, 100, 200, etc.)

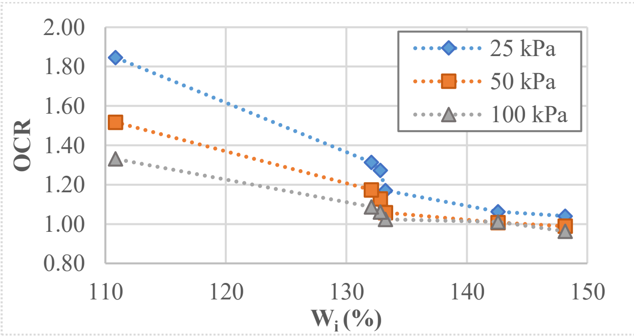

Figure 2. Correlation between initial water content and OCR of kaolinite at low-stress levels.

3.2 Influence of plasticity on soil compression characteristics

To examine the impact of plasticity on compression characteristics, Figure 3 illustrates the variation in λ^* and κ^* across all tested mixtures (represented by PI). The sample with lower plasticity (and lower proportion of bentonite) demonstrates reduced values of λ^* and κ^*, corresponding to lesser volume change during compression and swelling.

The primary consolidation duration (T_{eop}) is influenced by soil composition, as shown in Figure 4. Samples with higher bentonite percentages exhibit prolonged primary consolidation. Notably, for mixtures with bentonite (from 25K-75B to B), T_{eop}

reaches its maximum at 50 kPa, gradually decreasing until 200 kPa. In contrast, for kaolinite, T_{eop} is around 12 minutes at 25 kPa and remains relatively around 18 minutes during subsequent compression.

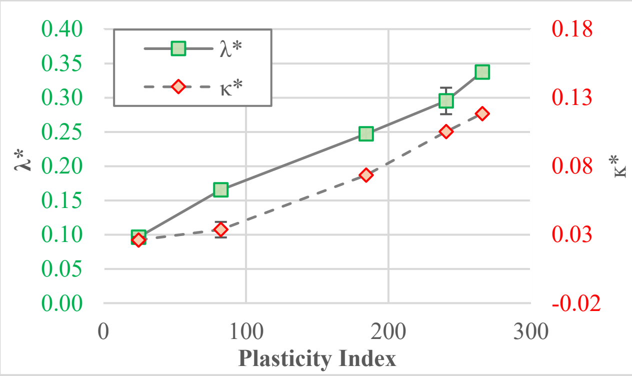

Figure 3. Evolution of compression indices (λ, κ*) with plasticity for different mixtures.*

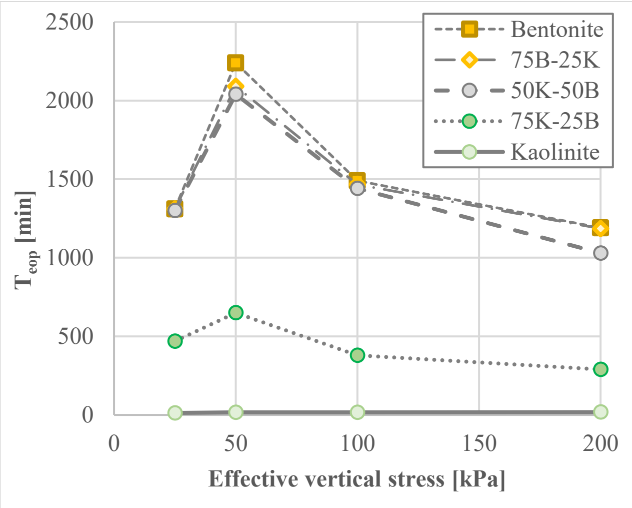

Figure 4. Influence of stress levels and soil plasticity on T_{eop}.

3.3 Influence of plasticity on creep behaviour

C_α is plotted against various soil compositions, represented by different Plasticity Index (PI) values at three stress levels (50, 100, 200 kPa), as depicted in Figure 5. Mixtures with higher plasticity manifest elevated C_α values, exhibiting significant changes among different stress levels. Conversely, the lower plasticity sample exhibits a contrasting trend; for instance, the C_α values for kaolinite remain nearly constant across all applied stress levels.

Figure 6 reveals another intriguing aspect: a trendline resembling the correlation between C_α and the stress level. Notably, the C_α values peak at 50 kPa across all mixtures containing bentonite. In the case of kaolinite, C_α for kaolinite shows only a statistically insignificant increase with applied stress across all applied stress levels. In the figures, we also present the values of OCR at all stress levels.

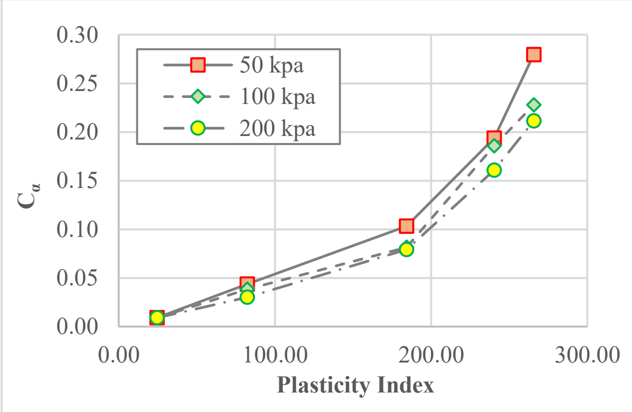

Figure 5. Correlation between C_α and soil plasticity.

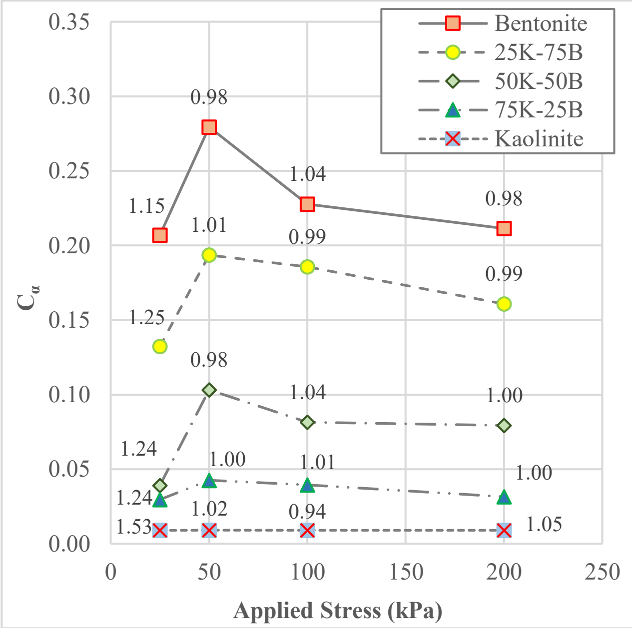

Figure 6. Influence of soil compositions on C_α at different stress levels. OCR at the current stress level is shown for all experiments.

All soil samples display over-consolidation in the 25 kPa stress range, with OCR values ranging from 1.1 to 1.53, and sample over-consolidation being the most likely factor in the low C_α at 25 kPa. Starting from 50 kPa, OCR values stabilize around 1. Capturing a definitive trend even for lower stresses requires additional experiments with high initial water content (W_i).

4 CONCLUSIONS

In this contribution, we presented an extensive experimental study consisting of 18 standard and 20 creep oedometric tests performed on low-plasticity clay (kaolinite), high-plasticity clay (bentonite), and their mixtures.

- Initial water content (W_i) plays a pivotal role in governing the OCR, especially at low stress levels. Elevated W_i corresponds to a lower OCR value. Relatively low W_i (<130% for kaolinite) translates to samples being tested in overconsolidated state, which makes comparison of soil characteristics at low and high stresses impossible. It also induces a downward shift in the shape of NCL, evident at lower W_i levels and converging after reaching 200 kPa.

- Samples with lower plasticity exhibit reduced volume changes during compression and swelling, as evidenced by smaller values of λ* and κ*.
- Soils with higher plasticity display increased creep deformation, as indicated by higher values of the creep coefficient (C_α). The stress dependency of C_α is more pronounced in mixtures containing bentonite, as evidenced by a significant change in C_α, in contrast to the marginal change observed in kaolinite. Nevertheless, C_α attains its peak value at 50 kPa in all mixtures. A similar trend is also observed in T_{eop}. To accurately delineate the trend of C_α and T_{eop} with increasing stress levels, additional tests at higher W_i are essential. This precaution is necessary to prevent the manifestation of sample over-consolidation at 25 kPa, a probable cause for the lower C_α and T_{eop} at this stress level.
- Limitation of creep analysis arises from the limited amount of data, especially in case of bentonite and mixtures. That causes the shortcoming in investigating the influence of W_i on OCR at individual stress levels, correlation between OCR and C_α and statistical analysis of data.
- Primary objective is to correlate compression characteristics, creep coefficient, OCR, and soil plasticity. This requires thorough verification and determination of plasticity index values through an alternative experimental method for liquid limit, such as Cassagrande percussion cup method. Hence, more tests are essential to acquire a comprehensive dataset for subsequent statistical analysis.

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REFERENCES

Olek, B.S., 2022. An experimental investigation of the influence of plasticity on creep degradation rate. Acta Geotechnica, 17(3), pp.803-817. https://doi.org/10.1007/s11440-021-01272-z.

Mesri, G., 1973. Coefficient of secondary compression. Journal of the soil mechanics and foundations division, 99(1), pp.123-137. https://doi.org/10.1061/JSFEAQ.0001840.

Yin, J.H., 1999. Non-linear creep of soils in oedometer tests. Geotechnique, 49(5), pp.699- 707. https://doi.org/10.1680/geot.1999.49.5.699.

Barden, L., 1969. Time dependent deformation of normally consolidated clays and peats. Journal of the Soil Mechanics and Foundations Division, 95(1), pp.1-31. https://doi.org/10.1061/JSFEAQ.0001214.

Lei, H., Wang, X., Chen, L., Huang, M. and Han, J., 2016. Compression characteristics of ultra-soft clays subjected to simulated staged preloading. KSCE Journal of Civil Engineering, 20, pp.718- 728. https://doi.org/10.1007/s12205-015-0343-y.

Anagnostopoulos, C.A. and Grammatikopoulos, I.N., 2011. A new model for the prediction of secondary compression index of soft compressible soils. Bulletin of Engineering Geology and the Environment, 70, pp.423-427. https://doi.org/10.1007/s10064-010-0323-x.

Karstunen, M. and Yin, Z.Y., 2010. Modelling time-dependent behaviour of Murro test embankment. Géotechnique, 60(10), pp.735-749. https://doi.org/10.1680/geot.8.P.027.

Varatharajan S. 1D comperssion creep behavior of kaolinite and bentonite clay. department of civil engineering Calgary, Phd Thesis, Alberta. 2011 Jul.

Sivapullaiah, P.V. and Sridharan, A., 1985. Liquid limit of soil mixtures. ASTM International. https://doi.org/10.1520/GTJ10521J.

J. Duque, J. Roháč, D. Mašín &, Experimental investigation on Malaysian kaolin under monotonic and cyclic loading: inspection of undrained Miner's rule and drained cyclic preloading – 2022. https://doi.org/10.1007/s11440-022-01643-0.

Taylor, D.W., 1948. Fundamentals of soil mechanics (Vol. 66, No. 2,9. 161). LWW.

Orhan, M., Özer, M. and Işik, N., 2006. Comparison of Casagrande and cone penetration tests for the determination of the liquid limit of natural soils. Journal of the Faculty of Engineering and Architecture of Gazi University, 21(4).

Mašín, D., 2005. A hypoplastic constitutive model for clays. International Journal for numerical and analytical methods in Geomechanics, 29(4), pp.311-336. https://doi.org/10.1002/nag.416.