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VARIATION OF CONSOLIDATION COEFFICIENT OF EXPANSIVE CLAYS AT HIGH INITIAL WATER CONTENT

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Abstract

The coefficient of consolidation is a fundamental parameter for estimating the rate of settlement of structures found on saturated clayey layers. In this study, twelve series of one-dimensional consolidometer tests were performed on both undisturbed and remoulded/reconstituted samples of an expansive clay from Western Australia. The aim of this study is to investigate the variation in coefficient of consolidation at high initial water contents. The consolidometer tests start at very low consolidation stress (3 kPa) and increase to the relatively high-stress level of 1600 kPa to consider the effect of stress level on the results. The results show that the initial water content, stress level, and clay mineralogy have a great impact on the coefficient of consolidation. Moreover, the physicochemical factor governs the compression behaviour of remoulded samples prepared at initial water contents less than the liquid limit, and reconstituted samples at initial water contents higher than the liquid limit at medium to high-stress levels. Therefore, the coefficient of consolidation decreases with increasing consolidation stress for such samples. On the other hand, the mechanical factor mainly controls the compression behaviour of reconstituted samples at low-stress levels, and there is an increasing trend of the coefficient of consolidation with consolidation stress. In addition, the results also show that sample disturbance has a great influence on the coefficient of consolidation by decreasing the value by approximately four times.

Keywords: Coefficient of consolidation, Expansive clay, Initial water contents, Mineralogy, Reconstituted, Remoulded, Undisturbed sample.

1. Introduction

The settlement in a granular soil occurs shortly after an excess load is applied, whereas that in a saturated clayey soil occurs over a longer period. In fact, this the settlement, which is referred to as 'consolidation settlement', can be completed over months, years, or even decades for clayey soils as a result of the low permeability of such soils. In the other words, the rate of water expulsion from a clayey soil controls the rate of settlement, and this rate is affected mainly by the hydraulic conductivity of the soil. Therefore, the coefficient of consolidation (C_v), which expresses the rate of consolidation in saturated clays, can be defined in terms of hydraulic conductivity (k), unit weight of water (γ_w), and coefficient of volume change (m_v), as follows [1]:

$$C_v = \frac{k}{m_v \, \gamma_w} \quad (1)$$

Terzaghi and Peck [2] expected C_v to remain constant with increasing the consolidation stress in an oedometer test. In their opinion, both k and m_v decrease with increasing effective consolidation stress (σ_v') at a virtually identical rate that maintains C_v at an almost constant value [2]. Robinson and Allam [3] criticised this idea by reviewing various published data of C_v- σ_v' variations in the literature and conducting laboratory tests on different clay minerals. Based on their findings, the variation in C_v and σ_v' for clayey soils is not constant; it is dependent on the vertical consolidation stress and clay mineralogy [3].

However, the effect of index properties and clay mineralogy on the compressibility properties of clayey soils have been investigated by several researchers [4-8] but the effect of the initial conditions (such as initial water content) and level of sample disturbance on the coefficient of consolidation have received less attention. Moreover, there is a lack of experimental data regarding an investigation of the effect of high initial water content on the mechanism of compressibility and the coefficient of consolidation of expansive clays. As a result, the following questions are investigated in this study:

- What is the effect of initial water content on the coefficient of consolidation of expansive clays?
- What is the trend of the coefficient of consolidation with vertical consolidation stress when the initial water content is high?
- What is the main factor controlling the compressibility and rate of consolidation for expansive clays?
- How does the value of consolidation stress affect the coefficient of consolidation of expansive clays?
- What is the effect of sample disturbance on the value of consolidation coefficient of expansive clays?

Based on these questions, the impact of initial water content on the coefficient of consolidation is investigated for highly expansive clays. To consider the effect of stress level, the consolidation pressure initiates at a low stress of 3 kPa (low-stress level) that increases to 1600 kPa (high-stress level) in the consolidometer tests. The stress level is adapted to cover the range of stresses normally being applied to the clay during construction. Moreover, consolidometer tests were performed on both undisturbed and remoulded samples (prepared with the same water content as that in-situ) to study the effect of sample disturbance on the coefficient of consolidation.

2. Coefficient of Consolidation (C_v)

Compression curves of clayey soils can be divided into three phases for analytical purposes: initial compression, primary consolidation, and secondary compression [1]. The initial compression phase occurs almost instantly with the application of the first load increment in the consolidometer test. The primary consolidation phase, which is the most important part of the compression curve, is time-related and completed when the excess pore water pressure dissipates [2].

Terzaghi and Peck [2] one-dimensional theory of consolidation is thus far the most broadly employed framework to estimate the rate of consolidation. The only parameter required to compute the degree of consolidation of a clay layer is the coefficient of consolidation (C_v). By knowing the amount of C_v, it is possible to assess the percentage of consolidation and the amount of stress transferred to the skeleton at any stage of the consolidation process. However, the consolidation process is really a three-dimensional phenomenon, but for the most practical applications, the result of the one-dimensional analysis is sufficiently accurate, especially for such a laterally confined clayey soil deposit bounded between two porous layers as the drainage patterns are so similar to one-dimensional theory [1].

The coefficient of consolidation is a fundamental parameter for estimating the rate of settlement of structures built on saturated clayey layers. However, several methods, including empirical and computational relationships, have been proposed over the past six to seven decades to determine C_v. Two standard methods, namely log-time and square-root-time, remain the most practical and reliable methods to estimate the rate of consolidation [9, 10]. In this paper, the log-time technique has been used to compute the coefficient of consolidation of the studied clay in light of the high acceptance between geotechnical engineers and the recommendations in the standard (ASTM D2435-04) [11].

3. Materials, Methods and Tests

Twelve series of consolidometer tests (on both undisturbed and remoulded/reconstituted samples) were performed on expansive clay with various initial water contents to investigate the variation of coefficient of consolidation. The studied clay, referred to in this study as 'black clay', was collected from Baldivis, 46 km south of Perth, the capital city of Western Australia (Fig. 1). The geotechnical parameters, sample preparation and test procedure are explained in this section.

Fig. 1. Sampling site for the studied clay (Google maps 2016)[12].

3.1. Geotechnical properties

Table 1 illustrates the initial water content as well as soil properties of the studied soil [4]. All soil classification tests were carried out according to ASTM standards [11]. Based on the results of the X-ray Diffraction (XRD) tests conducted at Curtin University's Microscopy and Microanalysis Facility, the predominant clay mineral of the black clay is smectite [4]. The physical properties of the black clay are tabulated in Table 1.

Table 1. Physical properties of black clay.

Geotechnical property	Value
Liquid limit % (w_L)	82
Plastic limit % (w_P)	35
Plasticity index % (I_P)	47
Specific gravity (G_s)	2.6
Sand (%)	20
Silt (%)	12
Clay (%)	68
Unified soil classification system	CH
Swell pressure (kPa)	83[13]

3.2. Sample preparation and test procedure

Three different soil sample preparation methods were chosen in this study: undisturbed, remoulded and reconstituted samples. Two undisturbed samples were collected from the Baldivis site from a 0.5-m deep of a test pit. Undisturbed samples were collected by pushing a large 250-mm tube into the soil.

Samples were extruded in the laboratory, wrapped in multiple cling foils, and sealed to keep the initial moisture before the one-dimensional consolidometer tests. The in-situ moisture content of the undisturbed samples measured soon after collection from the site was approximately 40%. Disks were cut from the undisturbed sample and trimmed carefully for placement in the oedometer ring.

To decrease the disturbance effect of the tube walls at the outer part of the sample during pushing of the sample into the soil, only one sample was trimmed from each soil disk.

To investigate the influence of disturbance on the consolidation characteristics of the studied soil, remoulded samples were prepared by adding the desired amount of water to the soil to correct the water content of the specimen. Unit weight of in-situ samples was measured to be 16.7 kN/m3. Moreover, remoulded samples were compacted using a metal tamper to achieve the same unit weight.

Reconstituted samples were prepared by mixing oven-dried ground clay with a predefined amount of water, following Burland's procedure of preparing reconstituted samples [14]. When the initial water content of the sample was more than the liquid limit (i.e., reconstituted samples), the prepared soil was carefully spooned into the consolidation rim to avoid trapping any air bubbles in the sample. As the samples were too soft, just a vibrating metal rod was used to exhaust air bubbles.

All remoulded and reconstituted samples were sealed in three successive airtight plastic bags for 24 hr to mature. The inner face of the consolidation ring was covered by a thin layer of silicon grease prior to sample preparation to reduce the friction between the soil and the ring. Consolidometer tests were conducted on various samples (total of 12 samples) with different degrees of disturbance (i.e., remoulded/reconstituted and undisturbed samples) and several different initial water contents in an automatic one-dimensional consolidation apparatus. The soil samples were 25.4 mm high and 64 mm in diameter. Table 2 illustrates the sample number, initial water content, sample condition, and vertical stress increments of the consolidometer tests.

Table 2. Consolidometer test procedure.

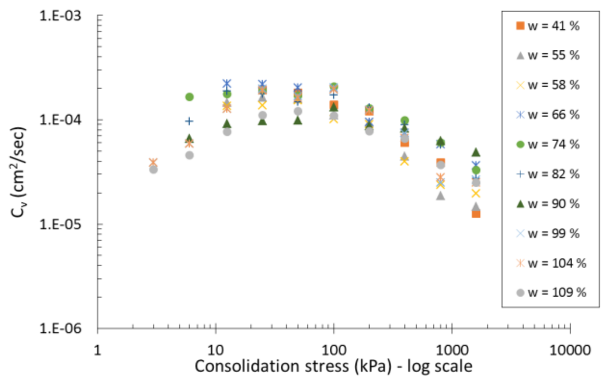
Sample no.	Sample type	W (%)	Vertical consolidation stress (kPa)
*BC-R*1	Remoulded	41	25, 50, 100, 200, 400, 800, 1600
*BC-R*2	Remoulded	55	12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*3	Remoulded	58	12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*4	Remoulded	66	12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*5	Reconstituted	74	6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*6	Reconstituted	82	6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*7	Reconstituted	90	6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*8	Reconstituted	99	3, 6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*9	Reconstituted	104	3, 6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-R*10	Reconstituted	109	3, 6, 12.5, 25, 50, 100, 200, 400, 800, 1600
*BC-U*1	Undisturbed	40	100, 200, 400, 800, 1600
*BC-U*2	Undisturbed	43	200, 400, 800, 1600

4. Discussion and Results

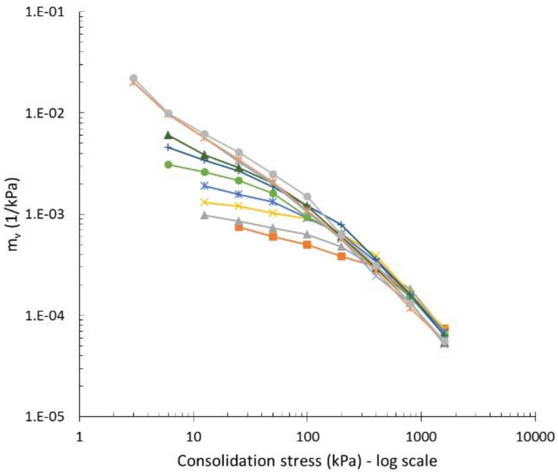
4.1. Vertical stress effect

Figure 2 shows the variation in consolidation parameters (i.e., C_v, k and m_v) with vertical consolidation stress for the remoulded and reconstituted samples. As shown in Figs. 2(b) and (c), k and m_v decrease with increasing vertical consolidation stress, which is in agreement with past researches [2, 3]. However, there is a decreasing trend in both consolidation parameters (i.e., k and m_v), although they decrease at different rates. This difference in rates results in C_v varying with the change in consolidation stress. For instance, m_v decreases from 3.1x10^{-3} 1/kPa at σ_v'=6 kPa to 6.4x10^{-5} 1/kPa at σ_v'=1600 kPa (w=74%) while k decreases from 1.84x10^{-5} cm/hr to 7.43x10^{-7} cm/hr for the same range of consolidation stress. This shows the ratio of the rate of decrease of k is almost half of m_v's rate for the same consolidation stress range.

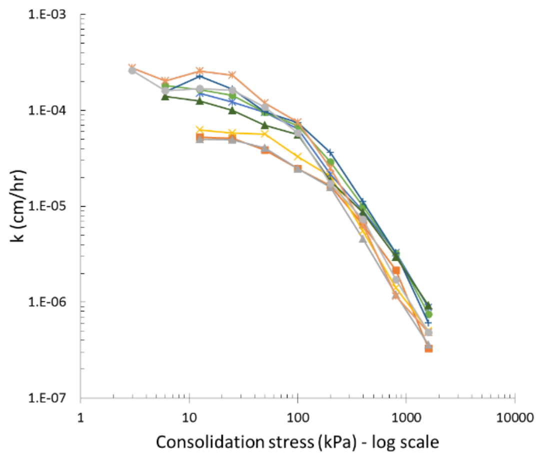
In addition, the results show that the variation of C_v is dependent on the level of stress and the initial water content. The $C_v - \sigma_v'$ graphs are plotted in Fig. 3 for two ranges of initial water content: Initial water content less than the liquid limit (i.e., w=41%, 58%, 66%, and 74%) and initial water content equal to or greater than the liquid limit (i.e., w=82%, 90%, 99%, 104%, and 109%). For initial water contents less than the liquid limit, C_v decreases continuously with increasing consolidation stress in Fig. 3(a). For instance, C_v decreases from 1.65×10^{-8} m^2/s at σ_v' =6 kPa to 3.31×10^{-9} m^2/s at σ_v' =1600 kPa (w=74%). The trend differs for reconstituted samples prepared at initial water contents greater than the liquid limit in Fig. 3(b). For the studied clay, the C_v of the reconstituted samples with high initial water contents (i.e., samples BC-R6 to BC-R10) increases for consolidation stresses less than 100 kPa, whereas it decreases for consolidation stresses greater than 100 kPa as shown in Fig. 3(b). For instance, C_v increases continuously from 3.89×10^{-9} m^2/s at σ_v' =3 kPa to 1.96×10^{-8} m^2/s at σ_v' =100 kPa, then it decreases to 2.48×10^{-9} m^2/s at σ_v' =1600 kPa (w=104%). These different trends for the variation of coefficient of consolidation in reconstituted clays can be explained by the mechanism governing the compression behaviour of clayey soils.



(a) C_v variation with consolidation stress.

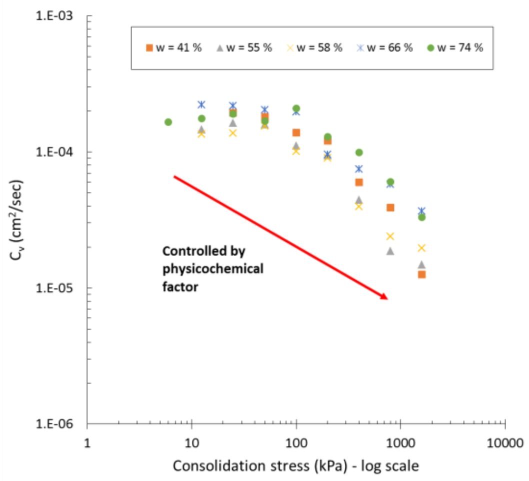


(b) m_v variation with consolidation stress.

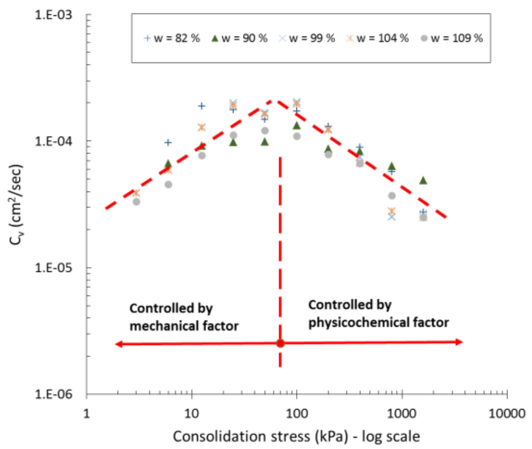


(c) *k* variation with consolidation stress.

Fig. 2. Variation of consolidation parameters with consolidation stress.



(a) w<wL.



(b) w≥ *wL.*

Fig. 3. Variation of C_v with consolidation stress.

Robinson and Allam [3] proposed that the coefficient of consolidation depends on clay mineralogy. According to their research, C_v of clays with montmorillonite (smectite) as the main mineral decreases with increasing consolidation stress; whereas those with main minerals of illite and kaolinite minerals exhibit an increasing trend. The present study confirms this finding for the remoulded samples prepared at initial water contents less than the liquid limit. Similarly, C_v decreases with increasing consolidation stress for the reconstituted samples for medium to high-stress levels. On the contrary, C_v increases with the increasing consolidation stress for low-stress levels of reconstituted samples prepared at initial water contents greater than the liquid limit. Furthermore, it seems that the C_v trend depends not only on the clay mineralogy but also on the stress level of such clayey soils.

The trend with consolidation stress can be explained by the mechanism controlling the compression behaviour. Two main factors govern the compression behaviour of clays, namely mechanical and physicochemical factors [15]. The mechanical factor is employed for short-range inter-particle forces governed only by the physical characteristics of soil particles, such as strength, flexibility, and surface friction [3]. In this case, the physical properties of the minerals and the lubricating influence of water are the two factors controlling the compression behaviour. On the other hand, physicochemical effects specify almost long-range inter-particle forces particularly in diffuse double layers [3].

The results of this study show that the variation of C_v with consolidation stress depends on different factors such as clay mineralogy, initial water content, and stress level. For reconstituted samples at high initial water contents, the variation of consolidation coefficient is controlled mainly by the mechanical factor rather than the physicochemical factor, even for clays predominantly composed of smectite (montmorillonite). It seems that the high initial water content in montmorillonite clays suppresses the diffuse double layer formation; thus, the compression behaviour of such clays is influenced mainly by mechanical factors.

Nevertheless, for initial water contents less than the liquid limit, there is a decreasing trend of C_v with consolidation stress and the governing mechanism of compression behaviour is physicochemical. Similarly, when the consolidation stress is high at high initial water contents, the mechanism controlling the compression behaviour is mainly physicochemical and there is a decreasing C_v trend.

4.2. Initial water content effect

Figure 2(b) presents the $m_v - \sigma_v'$ curves of the remoulded and reconstituted samples. The results show that the $\mathrm{m_v}$ values of the remoulded samples are generally lower than those of the reconstituted samples at the same consolidation stress. Moreover, the m_v value mostly decreases with increasing consolidation stress.

The test results further illustrate that there is a general increasing trend of C_v for the reconstituted samples Fig. 2(a) with decreasing initial water content Fig. 2(a). For example, the C_v value for w= 90% (4.88×10^{-9} m^2/s) is almost 1.5 and 3.9 times that for w=74% and 41% (3.31×10^{-9} m^2/s and 1.26×10^{-9} m^2/s), respectively at the same consolidation stress of 1600 kPa.

4.3. Sample disturbance effect

Figure 4 presents the variation of C_v for two levels of sample disturbance (i.e., undisturbed sample and remoulded sample). The results show that the values of C_v for the two undisturbed samples are greater that of the remoulded sample. For instance, the C_v value of BC-U1 is $5.15\text{x}10^{-9}$ m^2/s at a consolidation stress of 1600 kPa, while at the same stress and for the remoulded sample (BC-R1) the C_v is $1.26\text{x}10^{-9}$ m^2/s. So it is almost four times more than that of the remoulded soil.

Figure 4 further illustrates that the C_v values of both undisturbed samples decrease with increasing consolidation stress. It is expected that the physicochemical mechanism controls the compression behaviour of the undisturbed samples as the in-situ water contents of the undisturbed samples are lower than the liquid limit of the black clay.

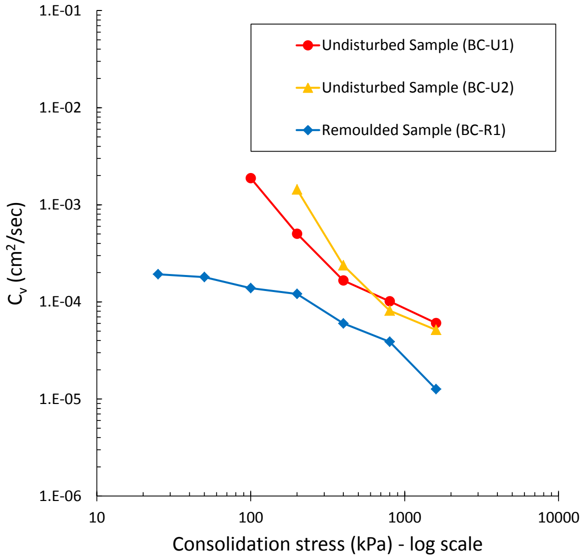


Fig. 4. Variation of C_v with consolidation stress for an undisturbed and remoulded sample.

5. Conclusions

Twelve series of consolidometer tests were performed on both undisturbed and remoulded/reconstituted samples with various initial water contents to investigate the effect of the initial water content and sample disturbance on the coefficient of consolidation. Based on the results of the consolidometer tests, the following is concluded:

- The C_v of expansive clays varies with increasing consolidation stress and is dependent on clay mineralogy, stress level, and initial water content.
- The variation of C_v with consolidation stress depends on the initial water content of the studied clay with the predominant clay of smectite. For an initial water content less than its liquid limit, the compression behaviour is governed mainly by the physicochemical mechanism. Moreover, the same trend for C_v is expected at medium to high-stress levels, even for those samples with initial water contents greater than their liquid limit. On the other hand, C_v increases with increasing consolidation stress when the stress level is low and initial water content is high. Further experimental tests will be carried out on the reconstituted samples, especially at low-stress levels, to investigate the governing mechanism of the compression behaviour.
- There is a general decreasing trend of C_v with increasing initial water content for the remoulded and reconstituted samples.
- Sample disturbance reduces the C_v of expansive clays; C_v of undisturbed samples were almost four times that of the remoulded ones at the same water content.

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Nomenclatures

C_v	Coefficient of consolidation, cm^2/s
G_s	Specific gravity
I_p	Plasticity index, %
k	Hydraulic conductivity, cm/hr
m_v	Coefficient of volume change, 1/kPa
p	Consolidation stress, kN/m^2
w	Initial water content, %
w_L	Liquid limit, %
w_p	Plastic limit, %

Greek Symbols

σ'_v	Effective vertical stress, kPa
γ_w	Unit weight of water, kN/m^3

Abbreviations

ASTM	American Society for Testing and Materials
XRD	X-Ray Diffraction

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