Compression Rates of Untreated and Stabilized Peat Soils

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ABSTRACT

Characterized by high initial void ratio, organic content and water holding capacity, fibrous peat exhibits high compressibility and low shear strength. Consequently, formation of deep fibrous peat layer often poses difficulties in construction. In practice, compressibility of deep fibrous peat layer can be reduced by deep soil stabilization technique. The technique is developed in such a way that dry binders are mixed with in situ peat soil to form columnar reinforcement in the deep peat ground prior to preloading. Preloading simulations of both untreated and stabilized peats were carried out in laboratory by loading of both soils using standard oedometer consolidation apparatus. Ordinary Portland cement, ground granulated blast furnace slag and siliceous sand were used to stabilize the soil. Analysis on the time-compression curves from the tests revealed that coefficients of vertical consolidation (c_v) of both soils were best predicted using square root of $t_{52.6}$ method when compared to those evaluated using conventional curve fitting methods. Main reason for this is the experimental time-compression curves for the method best fit its theoretical curve. In addition, the method predicts c_v of soil at 52.6% average degree of consolidation, which is less likely to be affected by secondary compression that usually occurs concurrently at the later stage of soil primary consolidation.

KEYWORDS: Fibrous peat, deep soil stabilization, preloading, oedometer, coefficient of vertical consolidation.

INTRODUCTION

Apart from shear strength and permeability, compressibility is one of the most important mechanical properties of soil. Soil compressibility evaluation is in fact an essential monitoring aspect in any ground improvement project. Hence, accurate evaluation of soil compressibility characteristics from consolidation tests is of great importance. In geotechnical engineering practice, Terzaghi's one dimensional consolidation theory is still widely used to evaluate soil compressibility due to its simplicity in spite of the evolution of many sophisticated consolidation theories, which take into account factors not considered by Terzaghi (1943).

One of the most important consolidation parameter in soil compressibility is coefficient of vertical consolidation (c_v), which is used to predict the rate of soil primary settlement. In laboratory consolidation tests, prediction of c_v is normally based on curve fitting methods. Considering Terzaghi's one dimensional consolidation theory which states that the average degree of soil consolidation is a function of time, two conventional curve fitting methods were developed. They are logarithm of time and square root of time methods. By comparing experimental time-compression curve with the theoretical one, c_v can be predicted using both methods. However, accuracy of c_v prediction is very much dependent on the resemblance of experimental time-compression curve to that of the theoretical curve. In addition, according to Robinson (2003), secondary compression of soil normally occurs concurrently at the later stage of primary consolidation. Thus, c_v is more accurately predicted at middle stage of primary consolidation as it is less likely to be affected by secondary compression when compared to that evaluated at the later stage of primary consolidation.

For fibrous peat, the soil consolidation behavior is different from the conventional one of clay. According to Edil (2003), fibrous peat is a typical highly organic and fiber content soil with low degree of humification, that does not exhibit the basic tenets of the conventional clay compression behavior because of its highly different solid phase properties and microstructure. Thus, analysis of compression of such soil presents certain difficulties when the conventional methods are applied because the curves obtained from the conventional oedometer tests and the behavior exhibits by them differ from that of clay. Furthermore, while such soil is more prone to decomposition during oedometer testing, gas content and additional gas generation may complicate the interpretation of oedometer tests (Edil, 2003). With the soil successfully stabilized with binders like lime and cement, its compressibility behavior is likely to differ from that of untreated fibrous peat. It is evident from research findings that experimental time-compression curves of untreated and stabilized fibrous peats best fit the square root of time theoretical curve and prediction of c_v based on the point of deflection from linearity at 52.6% average degree of consolidation of the curve is reasonably acceptable since it is less likely to be influenced by secondary compression. A mixture of Ordinary Portland Cement, ground granulated blast furnace slag and siliceous sand was used as a binder to stabilize the soil. The paper aims to justify the viability of using square root of $t_{52.6}$ method in comparison to the conventional curve fitting methods to evaluate the soils' c_v, and to analyze and compare the rates of secondary and tertiary compression of both soils.

DESCRIPTION OF FIBROUS PEAT SOIL SAMPLES

For the purpose of evaluating the compressibility of peat, block samplers of 300 mm diameter x 300 mm height were used to collect undisturbed fibrous peat soil samples below ground water table at 1 m depth from the ground surface at a site in Sri Nadi village, Klang, Selangor, Malaysia (Figure 1). For the soil sampling purpose, trial pits were excavated to a depth of 1 meter and the groundwater table was found to be about 0.3 m from the ground surface. This shows that the peat has a very high water holding capacity. Visual observation on the peat indicated that the soil was dark brown in color. When the soil was extruded on squeezing (passing between fingers), it could be observed that the soil was somewhat pasty with muddy water squeezed out, and the plant structure was not easily identified. Based on the visual observation, the soil can be classified as H_4 according to von Post System based on its degree of humification. Some basic properties of the soil are shown in Table 1.

Figure 1: Fibrous peat soil at Sri Nadi village, Klang, Selangor, Malaysia

Table 1: Basic properties of Klang peat

Basic soil property	Average
Natural Moisture Content (%)	668
Specific Gravity	1.40
Fiber Content (%)	90
Organic Content (%)	96
Ash Content (%)	4
pH of peat	3.51
Peat soil classification	Fibrous

THEORETICAL CONSIDERATION

One-dimensional Consolidation Theory

When a load is applied on a fully saturated soil, the soil undergoes a time-dependent deformation that occurs concurrently with the dissipation of excess pore water pressure from the soil as a result of gradual transition of applied load from the pore water to the soil particles. Such process is known as primary consolidation. Based on the definition, Terzaghi (1943) presented a one-dimensional consolidation theory to evaluate soil primary consolidation. Among the notable assumptions in the theory are compression (deformation) and flow of pore water is one-dimensional that is in the vertical direction only, coefficients of volume compressibility, vertical permeability and vertical consolidation (m_v, k_v and c_v) remain constant throughout the consolidation process, and there is a unique relationship, independent of time, between void ratio, e and effective stress, σ'_v.

According to Terzaghi (1943), there is an absolute linkage between soil primary consolidation and dissipation of excess pore water pressure and thus, equation relates the excess pore water pressure, *u* at depth, *z* and time, *t* can be expressed as

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \tag{1}$$

where c_v = coefficient of vertical consolidation. The theory also assumes that c_v is a function of permeability and compressibility and hence, c_v can also defined as in Equation 2.

$$c_v = k_v / m_v\gamma_w \tag{2}$$

where k_v = coefficient of permeability for vertical flow, m_v = coefficient of volume compressibility, and γ_w = unit weight of water. As direct measurement of k_v is not done in standard oedometer consolidation tests, c_v is determined by fitting the experimental time-compression curves with the theoretical curve in which the relationship between theoretical time factor, T_v and average degree of consolidation, U_v are obtained by solving Equations (3) and (4) (Bardet, 1997).

$$U_v = 1 - \frac{8}{\pi^2} \sum_{\substack{m=1 \\ odd}}^{+\infty} \frac{e^{-m^2\pi T_v/4}}{m^2} \tag{3}$$

$$T_v = c_v t / H^2 \tag{4}$$

where t = time and H = length of drainage path for one-way vertical drainage (For two-way vertical drainage, length of drainage path = H/2). Values of U_v as a function of T_v are plotted as shown in Figure 2. Determination of T_v to predict c_v is dependent on the type of curve fitting method used. Three types of curve fitting methods, namely logarithm of time, square root of time, and square root of $t_{52.6}$ methods were used to determine and compare c_v of both untreated and stabilized fibrous peats.

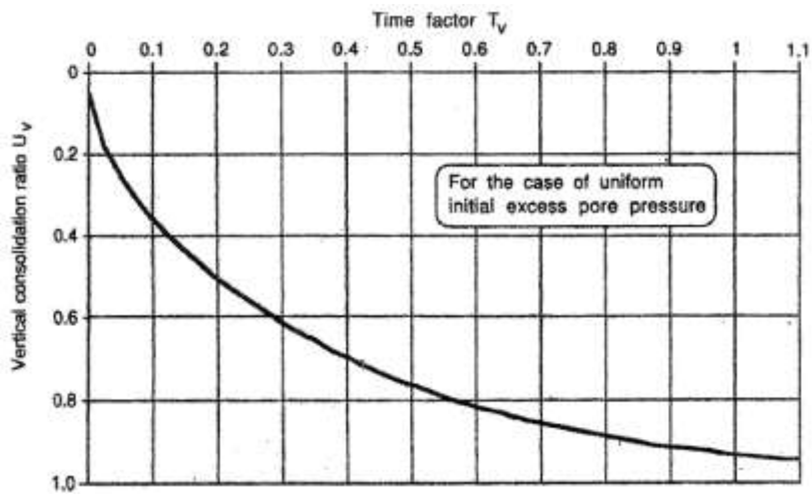


Figure 2: Average degree of consolidation due to vertical drainage, U_v (= percent vertical consolidation) as a function of time factor, T_v (Hausmann, 1990)

Logarithm of Time Method

In logarithm of time method (Casagrande and Fadum, 1940), compression of soil is plotted against logarithm of time for a typical consolidation pressure as shown in Figure 3. By defining the 0% primary consolidation from the early portion of the experimental time-compression curve, the end of primary consolidation (100% primary consolidation) can be determined by drawing a horizontal line that intersects the curve from the point of intersection between the primary consolidation and the secondary compression tangent segments. Based on the 50% primary consolidation from the curve, time to reach 50% primary consolidation (t_{50}) can be determined. With equal strain loading condition, the theoretical time factor for 50% primary consolidation for one-dimensional vertical consolidation with one-way drainage is 0.197. As such c_v of soil is defined by Equation 5, whereas the soil's coefficient of secondary compression (c_α) is defined as in Equation 6.

$$c_v = \frac{T_{50}\,H^2}{t_{50}} = \frac{0.197\,H^2}{t_{50}} \qquad (5)$$

where t_{50} = time to reach 50% average degree of consolidation based on the experimental time-compression curve, and T_{50} = Theoretical time factor at 50% average degree of consolidation.

$$c_\alpha = \frac{\Delta H_s / H_o}{\log(t_2/t_1)} \qquad (6)$$

where H_o = Initial soil layer thickness, and ΔH_s = Change in height of soil layer due to secondary compression from time, t_1 to time, t_2.

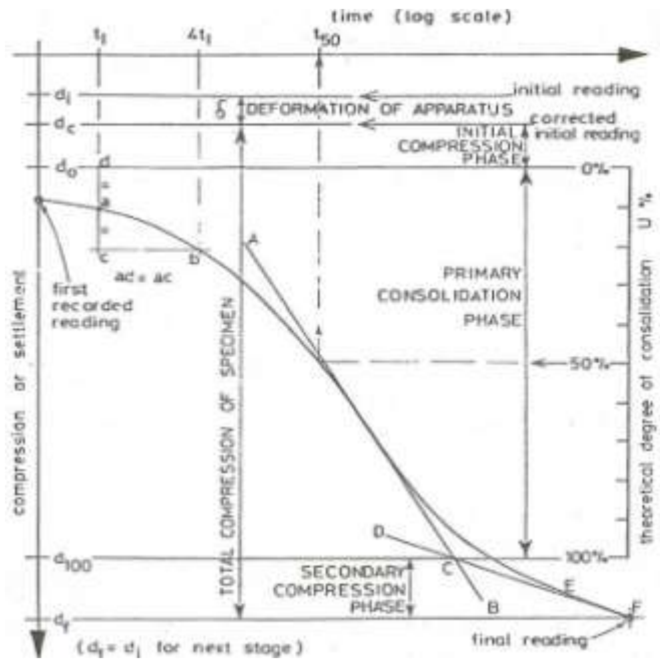


Figure 3: A typical experimental log time-compression curve (Head, 1982)

Square root of time method

Taylor (1948) developed the square root of time method based on the assumption that the hydrodynamic process dominates up to 90% consolidation. In the method, a plot of soil compression versus the square root of time is drawn for a typical consolidation pressure as shown in Figure 4. Then, the best linear line through the initial part of the curve intersecting the ordinate at O, which marks the beginning of primary consolidation, is drawn. From ordinate O, the second linear line is drawn such that its horizontal distance is 1.15 greater than that of the first linear line. The intersection of the second linear line with the curve gives the compression and the time to reach 90% primary consolidation (t_{90}). It should be noted that the value read off the abscissa is $\sqrt{t_{90}}$ and as such, when the average degree of consolidation, U_v is equal to 90%, the T_v for one-dimensional vertical consolidation with one-way drainage under equal strain loading condition is 0.848. Thus, c_v for the soil is defined as in Equation 7.

$$c_v = \frac{T_{90} H^2}{t_{90}} = \frac{0.848 H^2}{t_{90}} \qquad (7)$$

where t_{90} = time to reach 90% average degree of consolidation based on the experimental time-compression curve, and T_{90} = theoretical time factor at 90% average degree of consolidation.

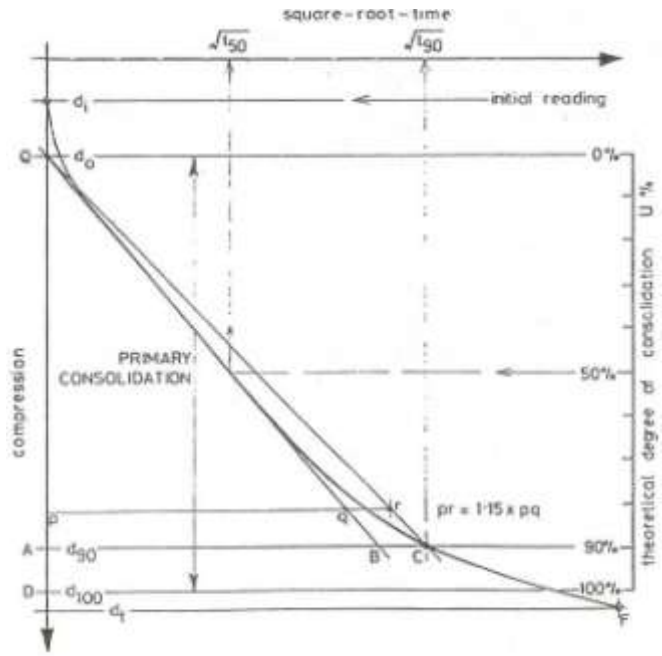


Figure 4: A typical experimental square root of time-compression curve (Head, 1982)

Square root of $t_{52.6}$ method

Square root of $t_{52.6}$ method is actually a curve fitting method simplified from square root of time method. Based on the square root of time theoretical curve, the T_v is determined from the point that starts to deviate from linearity in the square root of time-compression relationship. The T_v was found to deviate from linearity at 0.217 corresponding to 52.6% average degree of consolidation as shown in Figure 5. Hence, taking T_v = 0.217, c_v can be predicted when $t_{52.6}$ is obtained from the experimental time-compression curve using the formula in Equation 8. However, applicability of such method is still very much dependent on the similarity of the experimental time-compression curve with the theoretical one.

$$c_v = \frac{T_{52.6}\,H^2}{t_{52.6}} = \frac{0.217\,H^2}{t_{52.6}} \qquad (8)$$

where $t_{52.6}$ = time to reach 52.6% average degree of consolidation based on the experimental time-compression curve, and $T_{52.6}$ = theoretical time factor at 52.6% average degree of consolidation.

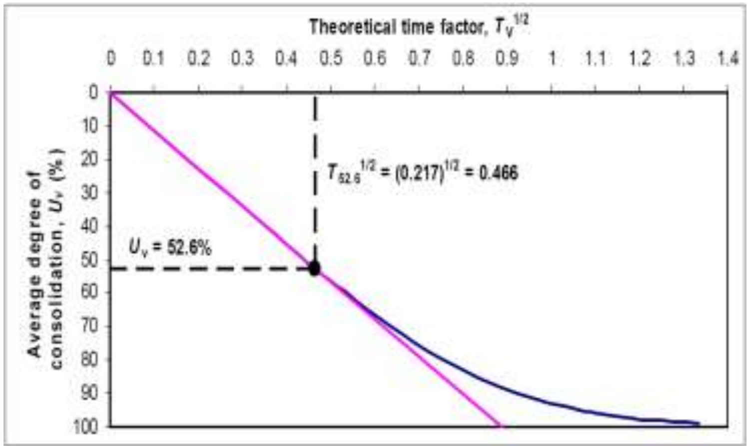


Figure 5: Square root of $t_{52.6}$ theoretical time-compression curve

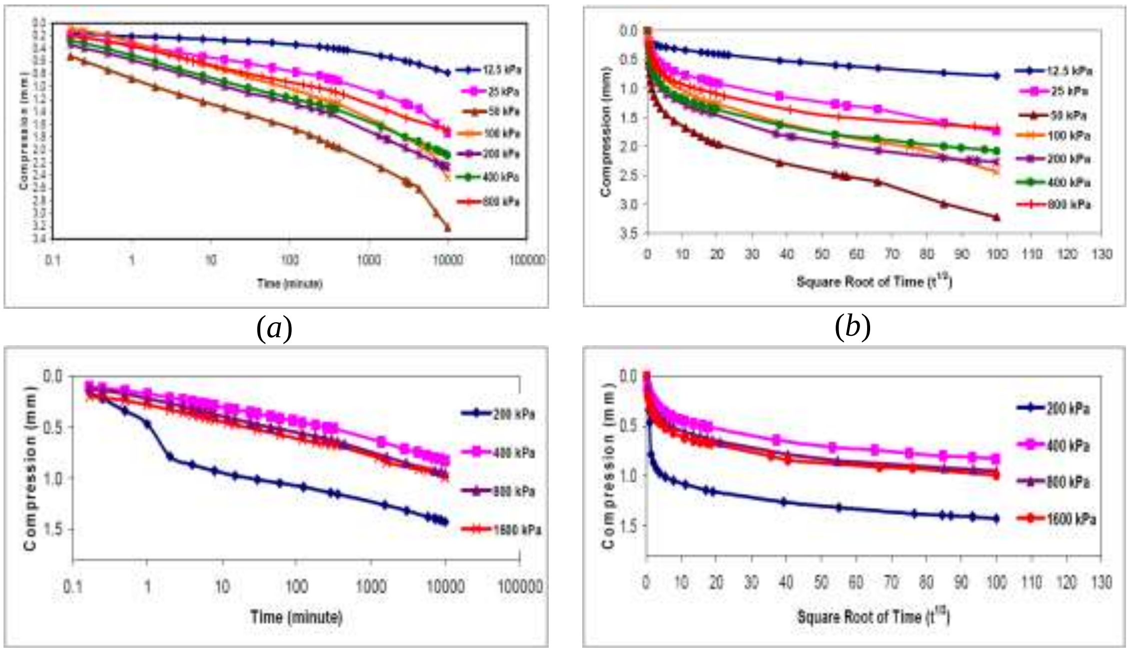
TEST RESULTS AND ANALYSIS

Experimental time-compression curves

Standard oedometer consolidation tests in accordance to BS 1377 (1990) were carried out on specimens of undisturbed and stabilized Klang peats. While each soil specimen was subjected to one-dimensional vertical consolidation allowing for two-way vertical drainage, loading of the soil specimen was done with a load increment ratio of 2 and load increment time of 7 days in order to observe the soil long term compression behavior. Loads were applied incrementally on Klang peat specimen in the range of 12.5 to 800 kPa whereas for stabilized Klang peat, the applied loads were in the range of 200 to 1600 kPa. The stabilized peat specimen was prepared at 300 kg/m^3 binder and 950 kg/m^3 of siliceous sand by weight of wet peat at 668% natural moisture content and cured for 14 days before testing for its compressibility.

Typical experimental time-compression curves for the soils are plotted using two conventional methods, namely logarithm of time and square root of time methods as shown in Figure 6. While Figure 6(a) for Klang peat and 6(c) for stabilized Klang peat show the time-compression curves plotted using logarithm of time method, Figure 6(b) for Klang peat and 6(d) for stabilized Klang peat indicate the time-compression curves plotted using square root of time method. Comparison between the two methods showed that the time-compression curves for both soils best fit the square root of time theoretical curve. As such c_v for both soils are more precisely predicted using the square root of time method in comparison to logarithm of time method.

However, the setback of the method is that it predicts c_v at a later stage of soil primary consolidation that is at 90% average degree of consolidation. Secondary compression of peat may occur as early as 59% average degree of consolidation when the soil is subjected to a consolidation pressure (Robinson, 2003). The secondary compression may render prediction of c_v in the method less accurate. Thus, it may be a viable solution to predict c_v by comparing the point at which the best linear line drawn in the experimental time-compression curve starts to deviate from linearity, with that of the theoretical curve because graphical evidence in Figure 5 has proven that the theoretical curve starts to deviate from linearity at 52.6% average degree of consolidation.



(*a*) (*b*)

(*c*) (*d*)

Figure 6: Typical experimental time-compression curves for (*a*) Klang peat plotted using logarithm of time method (*b*) Klang peat plotted using square root of time method (*c*) Stabilized Klang peat plotted using logarithm of time method (*d*) Stabilized Klang peat plotted using square root of time method

Typical analysis of experimental time-compression curve

To further justify the viability of using the square root of $t_{52.6}$ method for fibrous peat consolidation analysis, detailed analysis of experimental time-compression curve of Klang peat under a consolidation pressure of 12.5 kPa using different curve fitting methods are graphically illustrated in Figures 7, 8 and 9. When the soil compression is plotted against logarithm of time as shown in Figure 7, the curve is slightly concaved upward from the start and the point of deflection that marks the end of primary consolidation cannot be easily identified due to small difference between the slope gradients of primary consolidation and secondary compression. The time to reach the end of primary consolidation and secondary compression were 1.10 and 213.33 minutes respectively, which were relatively short. A significant compression characteristic that can be observed from the curve is the soil large tertiary compression which continues indefinitely after the end of secondary compression. The experimental time-compression curve clearly differs from the conventional one of clay and thus, accuracy of c_v prediction using such method is highly questionable.

On the other hand, a better curve fitting is obtained when the soil compression is plotted against square root of time as shown in Figure 8. Although, the experimental time-compression curve fits its theoretical curve, prediction of c_v based on 90% average degree of consolidation at a point that deflects from linearity clearly shows that the c_v prediction is affected by secondary compression which occurs concurrently at the later stage of primary consolidation. Furthermore, evaluation of time to reach the end of primary consolidation using such method is not very satisfactory because the t_{90} point is defined by a line and a curve which intersect at a very small angle, and so the exact position is not easy to identify (Head, 1982).

A better prediction of c_v can be obtained from the similar curve if it is to be based on the point at which the curve starts to deviate from linearity as such prediction of c_v is based on the middle stage of primary consolidation (52.6% average degree of consolidation) (Figure 9). With regard to this, the c_v prediction is less likely to be affected by secondary compression. This justifies that $t_{52.6}$ = 0.207 minute from the square root of $t_{52.6}$ method is reasonable for predicting c_v of the soil under the consolidation pressure.

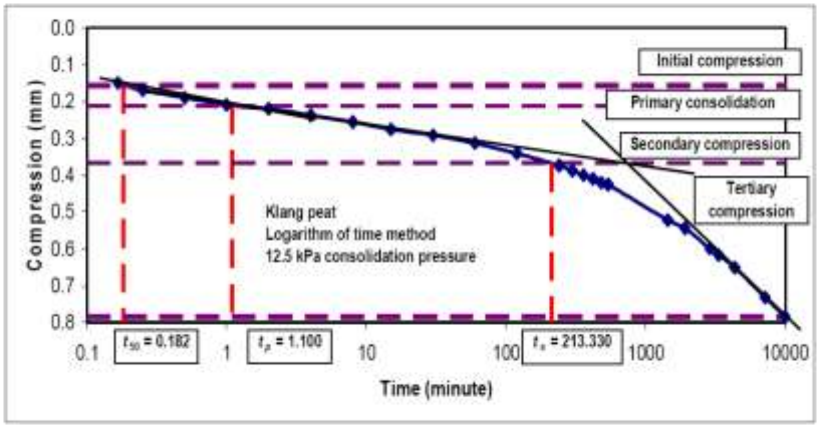


Figure 7: Typical analysis of Klang peat compressibility using logarithm of time method

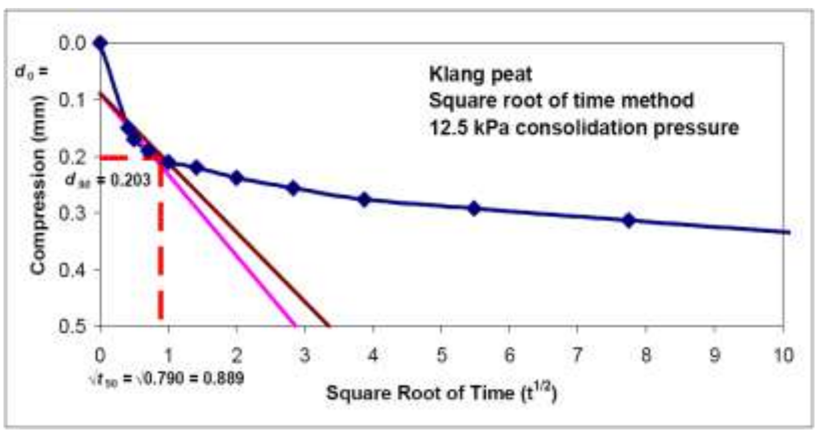


Figure 8: Typical analysis of Klang peat compressibility using square root of time method

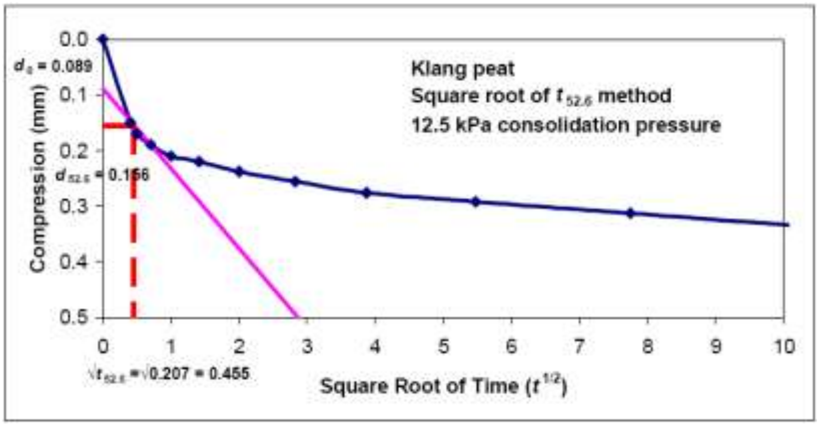


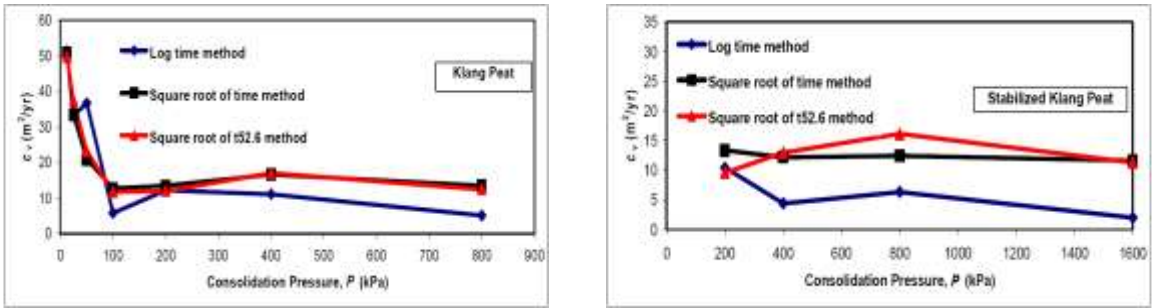
Figure 9: Typical analysis of Klang peat compressibility using square root of $t_{52.6}$ method

Effect of consolidation pressure on the trend of the soils coefficient of vertical consolidation (c_v) and coefficients of secondary and tertiary compression ($c_{\alpha 1}$ and $c_{\alpha 2}$)

The trend of c_v with consolidation pressure for both untreated and stabilized Klang peats evaluated using the three curve fitting methods outlined earlier is graphically depicted in Figure 10. Using the square root of $t_{52.6}$ method, for a range of consolidation pressure from 12.5 to 800 kPa, c_v for untreated Klang peat varied between 11.8 to 49.8 m^2/year as indicated in Figure 10(a). Using the same method, c_v for stabilized Klang peat ranged from 9.6 to 16.1 m^2/year for a range of consolidation pressure of 200 to 1600 kPa as shown in Figure 10(b). This shows that the rate of primary consolidation of stabilized Klang peat was lower if compared to that of untreated one. Figure 10(a) indicates that while there was a general trend of reduction in the rate of primary consolidation with increasing consolidation pressure of untreated Klang peat, trend of lower c_v of smaller range of variation with consolidation pressure was observed in stabilized Klang peat as illustrated in Figure 10(b).

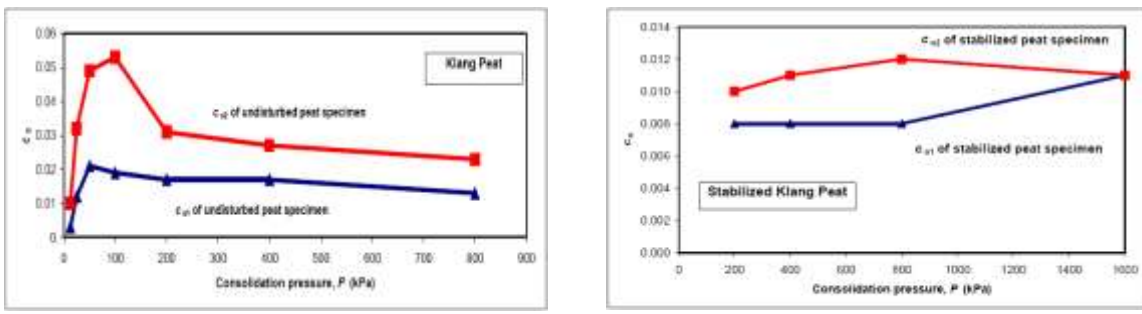
While coefficient of secondary compression of soil, $c_{\alpha 1}$ is normally predicted based on the linear relationship of log time-compression curve after the end of primary consolidation, its coefficient of tertiary compression, $c_{\alpha 2}$ is determined from the linear portion of the log time-compression curve after the end of secondary compression. The trend of coefficients of secondary and tertiary compression ($c_{\alpha 1}$ and $c_{\alpha 2}$) of untreated Klang peat can be observed in Figure 11(a). Analysis on the graph in the figure indicated that over a range of consolidation pressures from 12.5 to 800 kPa, the coefficient of secondary compression of untreated Klang peat ranged from 0.003 to 0.021, whereas, the range of its coefficient of tertiary compression was 0.010 to 0.053. At a range of consolidation pressure from 200 to 1600 kPa, the coefficient of secondary compression of stabilized Klang peat ranged from 0.008 to 0.011 while its coefficient of tertiary compression varied between 0.010 to 0.012 (Figure 11(b)).

It is evident from the results that the rates of secondary and tertiary compressions were significantly reduced in stabilized peat specimen in comparison to those of untreated peat specimen. The trend also provides a clear indication that with increasing consolidation pressure, the rate of tertiary compression approaches the rate of secondary compression, which eventually results in the tertiary component of compression merges with secondary compression at high consolidation pressures. Interestingly, the small ranges of coefficients of secondary and tertiary compressions in the stabilized peat specimen indicate that their rates of secondary and tertiary compressions were almost constant with consolidation pressure.



(a) (b)

Figure 10: Trend of c_v under various consolidation pressures in oedometer consolidation tests for (a) Klang peat (b) Stabilized Klang peat



(a) (b)

Figure 11: Trend of $c_{\alpha1}$ and $c_{\alpha2}$ under various consolidation pressures in oedometer consolidation tests for (a) Klang peat (b) Stabilized Klang peat

CONCLUSIONS

Based on the rate of compressibility analysis on both untreated and stabilized peats, the following conclusions are made.

- The experimental time-compression curves for both untreated and stabilized Klang peats best fit the square root of time theoretical curve. However, prediction of c_v should be based on the point which starts to deviate from linearity from the curve as it is less likely to be affected by secondary compression when compared to that predicted at 90% average degree of consolidation.
- A general trend of decrease of c_v of untreated Klang peat predicted using square root of $t_{52.6}$ method with increasing consolidation pressure, and a trend of lower c_v of smaller variation with consolidation pressure of stabilized Klang peat predicted using the same method imply that the

rate of primary consolidation of the soil was significantly reduced after stabilization as compared to that before stabilization.

- As the consolidation pressure increased, the rate of tertiary compression for both untreated and stabilized Klang peats approached its rate of secondary compression, indicating that the tertiary component of the soils merged with its secondary component at high consolidation pressure.

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