

Secondary Consolidation Characteristics of Organic Soil Modified by Biological Enzymes Based on Gibson Model

Yixin Zhang (✉ 1223343337@qq.com)

Central South University of Forestry and Technology Changsha Campus: Central South University of Forestry and Technology <https://orcid.org/0000-0001-9879-9823>

Changping Wen

Central South University of Forestry and Technology Changsha Campus: Central South University of Forestry and Technology

Research Article

Keywords: Subgrade engineering, Enzyme improvement of organic soil, Gibson rheological model, Secondary consolidation test

Posted Date: October 29th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1024673/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Secondary consolidation characteristics of organic soil modified by biological enzymes based on Gibson model

Yixin Zhang^a, Changping Wen^b

(College of Civil Engineering, Central South University of Forestry and Technology, Changsha, Hunan 410018, China; Hunan

Engineering Laboratory of Modern Wood Structure Engineering Materials Manufacturing and Application Technology, Central South

University of Forestry and Technology, Changsha 410018, China)

Abstract: In order to study the secondary consolidation characteristics of organic soil modified by enzyme, the secondary consolidation tests of organic soil modified by enzyme were carried out. Firstly, the consolidation coefficient C_v , secondary consolidation coefficient C_a and compression index C_c of modified organic soil under different levels of loads and different enzyme contents were obtained according to the analysis of experimental data. Then, the parameters of Gibson rheological model were fitted respectively according to the experimental results. Finally, the relationship between rheological model parameters, C_a/C_c , secondary consolidation coefficient C_a and loading was analyzed under different enzyme contents. The results show that: (1) The rheological model parameters of organic soil modified by enzyme are negatively correlated with the enzyme content, and positively correlated with

Yixin Zhang^a, Changping Wen^b

^a Master Student of Civil Engineering, Central South University of Forestry and Technology, Changsha 410018, China (E-mail: 1223343337@qq.com)

^b Professor of Civil Engineering Department, Central South University of Forestry and Technology, Changsha 410018, China (E-mail: wcp13739071598@163.com)

CORRESPONDENCE Yi-xin Zhang 1223343337@qq.com Department of Civil Engineering, Central South University of Forestry and Technology, Changsha 410018, China

the load value. When the enzyme content is 0.01%, some parameters reach the maximum value; (2) The secondary consolidation coefficient is related to the load. The secondary consolidation coefficient of samples with different enzyme contents shows a certain rule under all levels of load. With the increasing of load, the final secondary consolidation coefficient C_a approaches a stable value; (3) The C_a/C_c values of the samples of the modified organic soil with different enzyme contents are between 0.042 and 0.1 under different loads. The results show that the model is suitable for describing the secondary consolidation creep characteristics of organic soil, and can be used to guide the long-term deformation prediction of organic soil foundation.

Keywords: Subgrade engineering, Enzyme improvement of organic soil, Gibson rheological model, Secondary consolidation test

1 Introduction

Organic soil consists mainly of decaying plant matter and weathered rock matter (Saride et al. 2013). Organic matter in soil (the sum of various animal and plant residues and microorganisms in the soil and the materials produced by their life activities) can enter the interlayer void of soil structure, leading to soil expansion and reducing the shear strength and permeability of soil (Zhu et al. 2019). The organic matter in soil is mainly composed of C and N organic compounds, including monosaccharides and polysaccharides with single chemical structure and humus substances with complex structure. The main component of organic matter is generally humus, and the main component of humus is humic acid. It has a porous spongy structure and is more hydrophilic and adsorbent than clay minerals. Organic matter is widely distributed in natural soil. If organic matter is divided according to the content of organic matter in soil, soil can be divided into: peat, peat soil, inorganic soil, organic soil. The organic content of organic soil is about 5%-10%.

Many experiments have been carried out to study the effect of organic matter on soil. The

content of organic matter in soil can significantly affect the engineering properties of soil (Canakci et al. 2015). The presence of organic matter reduces soil compactness and peak strength values (Malkawi et al. 1999). The physico-chemical characteristics of organic matter (humic acid) are not conducive to the strength development of soil (Guo et al. 2008). There is a critical value for the influence of the mass fraction of organic matter (humic acid) on the unconfined compressive strength and failure strain of soil, and the plasticity of soil increases with the increase of the mass fraction of humic acid (Zhu et al. 2008). According to the theory of heat flow difference, the restraining mechanism of organic matter on soil strength growth is revealed (Harvey et al. 2010). The influence of 13 kinds of organic matter on the shear strength of soil is analyzed, indicating that the existence of organic matter seriously affects the strength of soil (Tremblay et al. 2002).

Organic soils are known for their poor engineering properties, including very high compressibility and low shear strength (Saride et al. 2013). At the same time, it has the characteristics of low pH value, large porosity, high natural water content, high plasticity and low bearing capacity. Therefore, it is necessary to deal with the foundation and subgrade with higher organic matter content in the project. The traditional treatment methods commonly used are overloaded preloading method, dynamic compaction method, replacement and filling treatment method, drainage consolidation method and so on. Although the above methods have formed corresponding norms and standards, there is a large noise, high cost, low environmental protection, low efficiency and other characteristics. Based on the traditional treatment methods, scholars began to explore the traditional improvers to treat organic soil. In order to improve the poor engineering performance of organic soil, the use of modified calcium-based stabilizers such as lime, cement and fly ash to improve organic soil can effectively improve the strength of organic soil (Saride et al.

2013). Using modified magnesium thioxide cement as an improvers can effectively improve organic soil (Zhu et al. 2019). The use of composite modifier (C-PG-CAC) to improve organic soil can effectively improve soil strength, and compared with ordinary Portland cement, this composite modifier has better improvement effect (Liu 2017). Many foreign scholars have also found better traditional amendments to improve organic soil.

However, the above traditional methods have high CO₂ emissions, which are not only environmentally friendly, but also have high engineering cost (Qian et al. 2015). The use of traditional modifiers such as cement and lime leads to higher environmental pollution and greenhouse gas emissions (Ramdas et al. 2020). Therefore, it is urgent to find a new improvement method. Biological methods improve the strength properties of soil by increasing its shear strength and compressibility (Ramdas et al. 2020). Enzymes are effective in improving and maintaining soil strength and hydraulic properties (Pooni et al. 2019). Enzyme is a reasonable way to improve traditional soil stabilization methods (Ramdas et al. 2020). The biological enzyme soil curing agent (hereinafter referred to as enzyme) is a new soil amelioration agent extracted from plant fermentation, which can effectively reduce the swelling and shrinkage of soil. To a certain extent, it can replace the traditional inorganic material based improves and meet the requirements of engineering standards. It has the characteristics of high temperature resistance, non-toxic, non-corrosive and environmental protection (Chen et al. 2019; Wen and Wang 2018). Scholars have carried out relevant studies on soil improvement by water dilution biological enzymes (Shankar et al. 2009). Biological enzymes can significantly improve the mechanical properties of soil, and the greater the amount of biological enzymes, the stronger the compressive and shear resistance of soil (Chen et al. 2019; Chen et al. 2019; Wen 2018). Two kinds of biological enzymes were used to

improve the soil, and the shear strength of the improved soil increased a lot compared with that of the undisturbed soil (Dong 2020). The technology of soil improvement with biological enzymes has been preliminately applied in foreign countries (Shankar et al. 2009). Although the research on soil improvement with biological enzymes in China is ongoing, it is still not mature enough.

Rheology includes: creep, stress relaxation, long-term strength, elastic aftereffect and hysteresis effect (viscous effect) (Sun 2007). Creep is defined as follows: the relationship between soil deformation and time under the condition of constant effective stress. The definitions of primary and secondary consolidation are as follows: primary consolidation refers to soil compression caused by the extrusion of water and gas in pores, while secondary consolidation refers to the creep compression of soil skeleton and the rearrangement of soil particles caused by the discharge of bound water (Hu et al. 2016). The above causes two general problems: the relationship between consolidation and creep; Relationship between secondary consolidation and creep. Some scholars are inclined to the second view, that is, the secondary consolidation is creep (Zhu and Feng 2009), and the authors is inclined to this view. However, some scholars believe that it is difficult to distinguish the deformation amount of creep, the important reason is that it is difficult to distinguish the time threshold of primary and secondary consolidation (Feng and Zhu 2009). The authors adopted the $e\text{-}lgt$ relationship curve proposed by Bjerrum to determine the time threshold of primary and secondary consolidation (Bjerrum 1967).

In recent years, research on rheological constitutive model of soil is still a hot topic at home and abroad, and the construction of rheological constitutive model of soil is developing rapidly (Zhu et al. 2010; Jiang et al. 2008). Using the correlated flow rule and Von Mises yield criterion, a rheological model was established by introducing the damage variable (Yahya et al. 2000). The

rheological mechanical properties of soil were studied through rheological tests, and the hehai model was proposed (Xu et al. 2006). However, the traditional rheological constitutive equation of soil is still widely used. Traditional methods include: experience method, element method, etc. Among them, element method is the most commonly used method for rheological constitutive model construction because of its few parameters, clear physical meaning and simple form. In series, the nonlinear viscoplastic body and the viscoelastic shear rheological model of 5 elements were connected, and the rheological model of 7 elements was established, and the rationality of the model was verified by experiments (Xu and Yang 2005). The viscoelastic-plastic rheological model of four elements is obtained by using the software element and spring element in series and combining the viscoplastic body, and the constitutive equation of the model is described (Song et al. 2012).

The coefficient of secondary consolidation is considered to be a constant in traditional soil mechanics, including the technical code for design and Construction of embankment in soft soil foundation of highway (JTJ017-96). However, with the continuous study of scholars, it is found that this is not the case. With the increase of time, the secondary consolidation coefficient decreases (Bouchard et al. 1985), and there is a correlation between the secondary consolidation coefficient and the consolidation pressure (Nash et al. 1992; Ge et al. 2015; Miao et al. 2007; Zhang et al. 2003). With the increase of consolidation pressure, the behavior of secondary consolidation coefficient is not the same (Feng and Zhu 2009; Zhou and Chen 2006). Therefore, the relationship between secondary consolidation coefficient and consolidation pressure is the focus of future research. In addition, the non-uniform settlement and post-construction settlement deformation of buildings are related to the secondary consolidation characteristics of soil (Castro et al. 1981). Therefore, in summary, the creep test of secondary consolidation of organic soil modified by biological enzymes

was carried out in laboratory. The research shows that the one-dimensional secondary consolidation process of organic soil conforms to the rheological model law of Gibson three elements, so the parameters of the rheological model of Gibson three elements are fitted. The rheological model parameters E_0 (elastic modulus of Hook body), E_I (Kelvin bulk modulus of elasticity) and η (Kelvin volume viscosity coefficient) are roughly negatively correlated with the enzyme content, and E_I and η reach their maximum value when the enzyme content is 0.01%. E_0 , E_I and η increase with the increase of load. At the same time, the study shows that the secondary consolidation coefficient is related to the load, and the secondary consolidation coefficient of the samples with different the secondary consolidation coefficient of the samples with different enzyme contents show a certain rule under different levels of load. shows a certain rule under different levels of load. The C_d/C_c value is between 0.042 and 0.1, which is consistent with the conclusion of Mesri (Mesri 1977). The predicted values of the model is in good agreement with the experimental values. The results show that the model is suitable for describing the secondary consolidation creep characteristics of organic soil, and can be used to guide the long-term deformation prediction of organic soil foundation.

2 Experiment

2.1 Test Material

2.1.1 Source of Test Soil

The soil tested in this paper is taken from Tianxin District, Changsha city, with a depth of 1-1.5m. The soil is brown-yellow and yellow-brown, and the soil is uniform. The surface of the soil is wet, and the particles are mainly fine particles, Hands can be squeezed into a ball, the pores are small and many, After water loss, the soil grain structure will shrink correspondingly. The main physical and mechanical indexes are shown in Table 1. According to the highway subgrade design

code (JTG D30-2015), the soil is determined to be clay.

Table 1 Basic physical and mechanical indexes of test soil samples

density / (g/cm ³)	moisture content/%	liquid limit /%	plastic limit /%	plasticity index /%
2.067	26.4%	36.2	20.9	15.3

2.1.2 Bioenzyme Reagents

The biological enzyme soil curing agent (hereinafter referred to as enzyme) used in this experiment is Terra-Zyme (Wen and Wang 2018), which is developed by Nature Plus Co., LTD., and imported from The United States through Terra Lucong Technology Co., LTD.. This enzyme is a brown viscous liquid product, non-toxic and pollut-free, soluble in water, and has special smell. The plant enzyme content is more than 60%. The pH value is between 4.3 and 5.3, and the water stability is good, as shown in Fig. 1.



Fig. 1. Enzymes

2.1.3 Preparation of Soil Sample

Because it is difficult to measure the organic matter content in the soil, it is necessary to manually reshape the soil with different percentage of organic matter. Scholars used different methods to configure the soil organic matter, with efficient stabilizer CSCN gelled material, the

humic acid (HAP) powder mixed with the original soil preparation of organic clay (Ma et al. 2018), using sodium humate as plus organic matter, reshape the different organic matter content of soil organic matter (Chu et al. 2006), or fulvic acid is used to make different organic matter content of soil organic matter (Xu et al. 2007). The authors uses the air-dried plant residues as the additional organic materials, and the ratio of the enzyme content to the dry mass of soil to prepare organic soil samples with the enzyme content of 0.00%, 0.01%, 0.02%, 0.03% and 0.04%, respectively. The sample preparation method is in strict accordance with the highway geotechnical test regulations (JTG E40-2007).

2.2 Test Method

The consolidation instrument used in the test is WG single lever consolidation instrument, as shown in Fig. 2. The specimen is 2cm high, with a cross-sectional area of 30cm², and drainage on both sides. In the experiment, the only variable was the enzyme content. All of them adopt hierarchical loading, according to the loading ratio of 1, the primary load is 25kpa, the maximum load is 800kpa, and the loading duration of each level is 7 days. The total duration of this test is 42 days. The standard for consolidation stability of each stage load is that the deformation in the last 24h is no more than 0.005mm, and the next stage load can be added. The test data is recorded by manual reading.



Fig. 2. WG single lever consolidation instrument

2.3 Test Results and Analysis

2.3.1 Coefficient of Consolidation C_v

According to the highway geotechnical test specification JTG E40-2007, the consolidation coefficient C_v was obtained by using the square root of time method. Taking the percentage table reading d as the ordinate and the square root of time t as the abscissa, the $d - \sqrt{t}$ relation curve was made, and the straight line at the beginning of the $d - \sqrt{t}$ curve was extended to obtain the theoretical zero point, Another line passes this point whose abscissa is 1.15 times the abscissa of the previous line. In this case, The abscissa squared of the intersection of the another line with the $d - \sqrt{t}$ curve is the time t_{90} required for 90% consolidation. According to Eq. (1), the consolidation coefficient under different enzyme contents and different load grade is calculated, as shown in Fig.

3.

$$C_v = \frac{0.848H^2}{t_{90}} \quad (1)$$

Where, H is half of the average value of the initial and final height of the sample under a certain load; t_{90} is the time required for the consolidation degree of the sample to reach 90%.

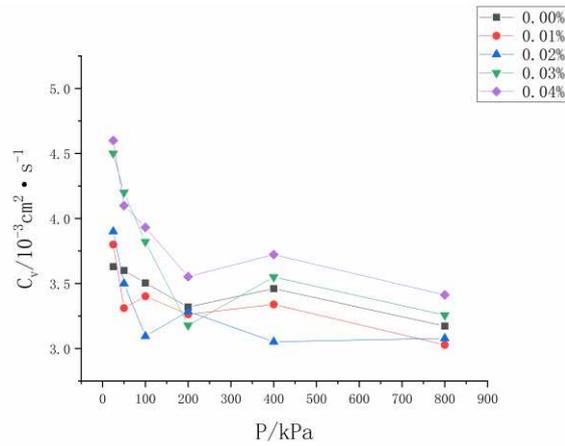


Fig. 3. Relation curve between C_v and P

Based on the study of Fig. 3, the relationship between the load and the consolidation coefficient of organic soil modified by enzyme under different enzyme contents shows the following relationship:

(1) The consolidation coefficient decreases with the increase of the load under different enzyme contents. When the load is less than 200kPa, the consolidation coefficient changes significantly with the load. When the load is greater than 200kPa, the consolidation coefficient gradually tends to be stable.

(2) Under the same load, the consolidation coefficient decreases first and then increases with the increase of enzyme content.

2.3.2 Coefficient of Secondary Consolidation C_a

The e - $\lg t$ relationship curve of one-dimensional secondary consolidation test of organic soil improved by enzyme with different contents is shown in Fig. 4. The e - $\lg t$ relationship curve in Fig. 4 is studied. With the increase of enzyme content, the completion time of main consolidation is faster. Taking the enzyme content of 0.02% as an example, The abscissa of the intersection of tangent line of the curve part of the e - $\lg t$ relation curve of soil sample under different loads and the extension line of the straight segment is about 1380min. For different loads, the main consolidation

completion time is different, but the difference is not significant. In order to facilitate the sorting and calculation of test data, the authors takes 1380min as the main consolidation completion time.

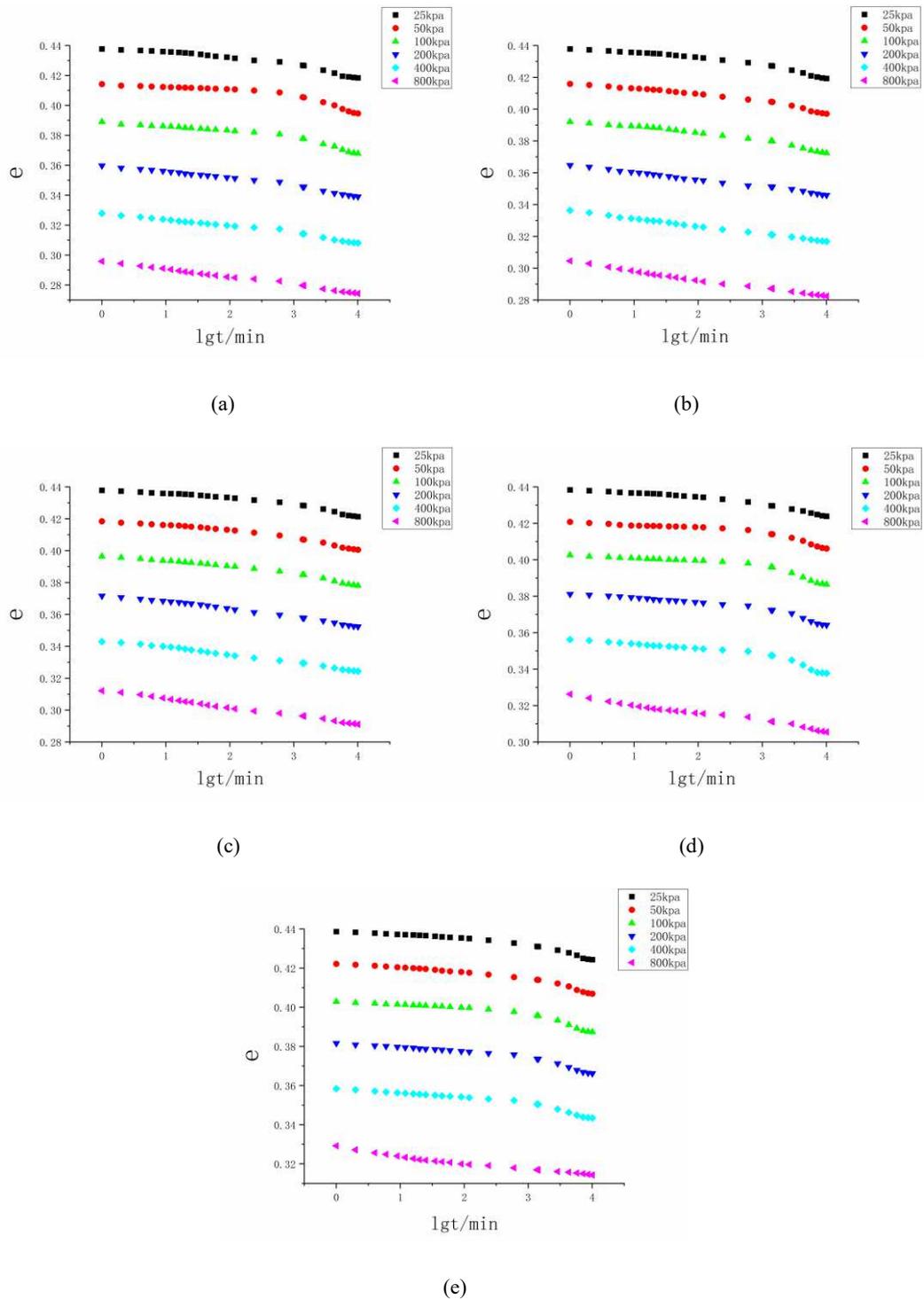


Fig. 4. e - $\lg t$ relation curve: (a) Enzyme content 0.00%, (b) Enzyme content 0.01%, (c) Enzyme content 0.02%, (d)

Enzyme content 0.03%, (e) Enzyme content 0.04%.

The method proposed by Buisman to determine the secondary consolidation coefficient from the e - $\lg t$ relation curve is as follows: $C_a = -\Delta e / (\lg t_2 - \lg t_1)$, has been widely used. From this equation, it can be concluded that the secondary consolidation coefficient is independent of pressure (Shi et al. 2003), that is, after the completion of primary consolidation, the e - $\lg t$ relation curve of soil sample deformation tends to a straight line, and the slope of the straight line is the secondary consolidation coefficient. Due to space limitation, the authors took the sample with 0.02% enzyme content as an example, and the calculation results of Secondary consolidation coefficient were shown in Table 2.

Table 2 Calculation results of sample secondary consolidation coefficient with 0.02% enzyme content

Load /kPa	e_1	e_2	t_1/min	t_2/min	C_a
25	0.43338	0.42128	1380	10080	0.00591
50	0.41314	0.40054	1380	10080	0.00622
100	0.39046	0.37815	1380	10080	0.00607
200	0.36382	0.35238	1380	10080	0.00556
400	0.33481	0.32444	1380	10080	0.00503
800	0.30154	0.2911	1380	10080	0.00509

The secondary consolidation coefficient of different levels of loads under different enzyme contents is shown in Fig. 5. A study of Fig. 5 shows that the secondary consolidation coefficient is related to the load, and the secondary consolidation coefficient of samples with different enzyme contents show a certain rule under all levels of load. At about 100kPa, the secondary consolidation coefficient of samples with different enzyme contents reach the peak; When less than 200kPa, the secondary consolidation coefficient changes obviously with the increase of load. When the load is greater than 200kPa, with the increase of the load, the variation trend tends to be gentle and eventually approaches to a constant. When less than 100kPa, the secondary consolidation coefficient C_a increases with the increase of load. The reason is that the structure of organic soil is damaged by loads, which strengthens the creep of the bound water film, so C_a increases. When the load is greater

than 100kPa, the secondary consolidation coefficient C_a decreases with the increase of the load. The reason is that as the organic soil becomes more and more compacted, the cementation capacity of adsorbing water film on the surface of soil skeleton becomes larger, which prevents the secondary consolidation deformation, and the creep capacity of organic soil becomes weaker, so C_a decreases. With the increasing load, the structure of organic soil is damaged, and the final secondary consolidation coefficient C_a approaches a stable value. This conclusion is consistent with the research results of Zhou and Yu (Zhou and Chen 2006; Yu et al. 2007).

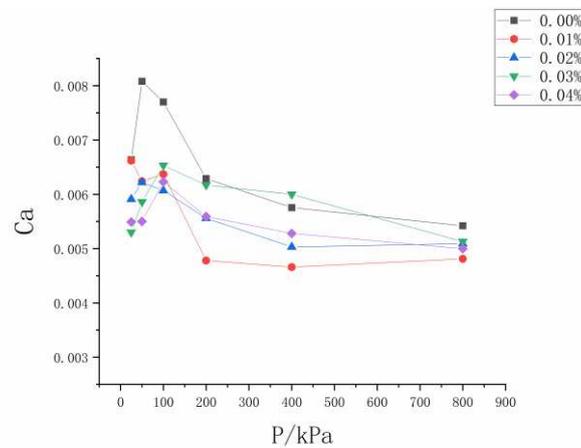


Fig. 5. The relation curve between the secondary consolidation coefficient C_a and load P with different enzyme contents

2.3.3 Compression Index C_c

According to the highway geotechnical test specification JTG E40-2007, the compression index is calculated by the following method: $C_c = \Delta e / (\lg P_2 - \lg P_1)$. The compression index of different levels of loads with different enzyme contents is shown in Fig. 6. According to Fig. 6, with the same enzyme content, the compression index C_c increases with the increase of load P . Under the same load, the compression index C_c decreases with the increase of enzyme content.

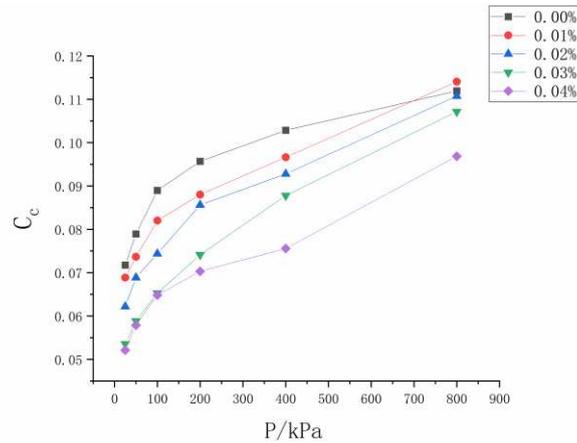


Fig. 6. Relation curve of compression index C_c and load P with different enzyme contents

Wang et al. showed that the C_a/C_c ratio of different clays mainly varied from 0.02 to 0.05 (Wang et al. 2015), Walker found that C_a/C_c is about 0.025 (Walker 1969). Mesri summarized the secondary consolidation tests of 22 kinds of soils and concluded that C_a/C_c of the same soil is a certain value, ranging from 0.025 to 0.1 (Mesri 1977). This conclusion has been recognized by most scholars (Rafat and Rowshon 2018; Miao et al. 2007; Zhang et al. 2003). Mesri further pointed out that $C_a/C_c=0.04\pm 0.01$ for most inorganic clays and $C_a/C_c=0.05\pm 0.01$ for organic clays (Mesri 1973). Due to space limitation, the authors took the sample with 0.02% enzyme content as an example. The values of C_a and C_c roughly meet the linear relationship (as shown in Fig. 7), the slope of which is 0.02469 (Deng et al. 2012), and the absolute value of the correlation coefficient R of linear fitting is 0.86825. The relation curve of C_a/C_c and load P was shown in Fig. 8. The C_a/C_c values of samples of organic soil modified by different enzyme contents under different levels of loads are 0.042~0.1, which is consistent with the conclusion of Mesri (Mesri 1977). Therefore, C_a/C_c values can be used to roughly estimate the C_a values of organic soil in some areas of Changsha.

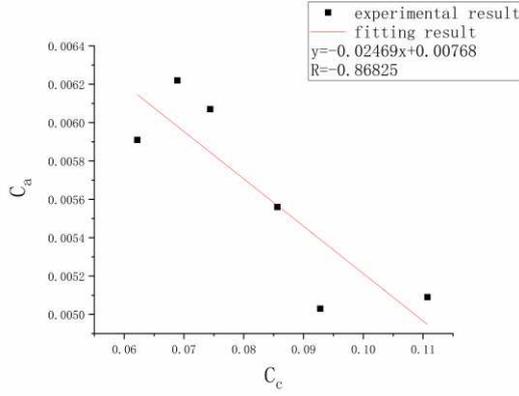


Fig. 7. Relationship curve between C_a and C_c

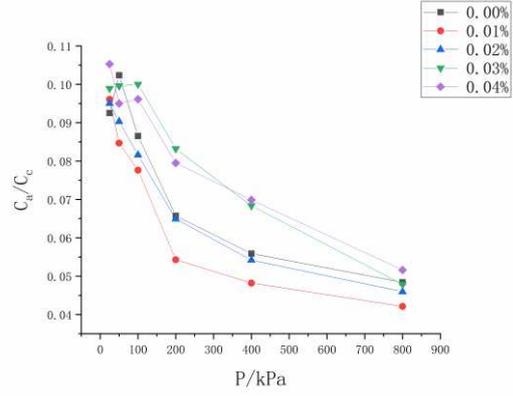


Fig. 8. Relation curve between C_a/C_c and load P

3 Determine The Rheological Model Parameters

3.1 Gibson Rheological Model

Although the construction methods of rock and soil rheological constitutive models have made great progress, the traditional construction methods of rock and soil rheological constitutive equations are still widely used, and the element method, as the most commonly used traditional method, is particularly prominent in the numerical analysis and theoretical calculation of geotechnical engineering. In this paper, a method to determine the parameters of the rheological model proposed by Gibson in 1962 is introduced. Gibson uses the three-element rheological model (namely Merchant model, which is composed of a Hook body and a Kelvin body in series) to describe the stress-strain relationship of soil as follows:

$$\varepsilon = \frac{\sigma'}{E_0} + \int_0^t \frac{\sigma'}{\eta} e^{-\frac{E_1}{\eta}(t-\tau)} d\tau \quad (2)$$

After the pore pressure disappears:

$$\varepsilon = \frac{\sigma'}{E_0} + \frac{\sigma'}{E_1} \left(1 - e^{-\frac{E_1}{\eta}t} \right) \quad t \geq t_0 \quad (3)$$

In the formula, t_0 is the dissipation time of pore pressure, namely the completion time of main consolidation; The elastic modulus E_0 of Hook body is obtained from the final settlement S_f under a certain load; σ' is the incremental load.

The elastic modulus E_1 and viscosity coefficient η of Kelvin can be determined by fitting the

curves of strain $S(t)$ and time t under load:

$$y = -\ln \frac{S_v - s(t)}{H\sigma'} = \frac{E_1}{\eta}t + \ln E_1 \quad (4)$$

3.2 Fitting of Rheological Model Parameters of Organic Soil Modified by Enzyme

The secondary consolidation test of organic soil modified by enzyme found that the main consolidation of samples with different enzyme contents was basically completed after 1380min of different levels of loading. According to Gibson method for data processing, The $y-t$ relationship curves of samples with different enzyme contents under different loads were obtained from the strain time curve. The study found that at the late stage of secondary consolidation, the $y-t$ curve linear correlation is better. Therefore, linear fitting is carried out for the sub-consolidation part of $y-t$ relation curve. according to the Eq. (4) for processing, The fitting results of $y-t$ curve of samples with different enzyme contents are shown in Table 3-7. It can be seen from Table 3-7 that the fitting effect is good under all levels of load loading, and the correlation coefficient is above 0.88.

Table 3 Rheological model fitting results and parameters of the samples when the enzyme content was 0.00%

Load/kPa	Fitted equation	The correlation coefficient	E_0 /MPa	E_1 /MPa	η /(MPa·s)
25	$y=0.0000625t+0.96$	0.88857	1.5	2.6117	4.18E+04
50	$y=0.0001493t+1.83286$	0.89105	3.15	6.2517	4.19E+04
100	$y=0.0002264t+3.00429$	0.90074	5.01	20.1719	8.91E+04
200	$y=0.0002743t+4.57857$	0.89453	7.01	97.375	3.55E+05
400	$y=0.0003199t+6.33143$	0.88718	9.16	561.96	1.76E+06
800	$y=0.0003581t+8.33143$	0.88322	11.5	4152.35	1.16E+07

Table 4 Rheological model fitting results and parameters of the samples when the enzyme content was 0.01%

Load/kPa	Fitted equation	The correlation coefficient	E_0 /MPa	E_1 /MPa	η /(MPa·s)
25	$y=0.00006151t+0.89571$	0.88831	1.44	2.4491	3.98E+04
50	$y=0.0001203t+1.91286$	0.89485	2.98	6.7724	5.63E+04
100	$y=0.0001778t+3.11714$	0.89283	4.7	22.5817	1.27E+05
200	$y=0.0002195t+4.57714$	0.90196	6.54	97.2359	4.43E+05
400	$y=0.0002522t+6.30429$	0.9025	8.56	546.913	2.17E+06
800	$y=0.0002872t+8.37571$	0.89986	10.95	4340.35	1.51E+07

Table 5 Rheological model fitting results and parameters of the samples when the enzyme content was 0.02%

Load/kPa	Fitted equation	The correlation coefficient	E_0 /MPa	E_I /MPa	η /(MPa·s)
25	$y=0.00005531t+0.81$	0.89359	1.3	2.2479	4.06E+04
50	$y=0.000106t+1.80143$	0.89122	2.74	6.0583	5.72E+04
100	$y=0.0001585t+2.89286$	0.89292	4.3	18.045	1.14E+05
200	$y=0.0002006t+4.30857$	0.89363	6.09	74.334	3.71E+05
400	$y=0.0002386t+5.91429$	0.89037	8.03	370.29	1.55E+06
800	$y=0.0002788t+7.87143$	0.89014	10.35	2621.3	9.4E+06

Table 6 Rheological model fitting results and parameters of the samples when the enzyme content was 0.03%

Load/kPa	Fitted equation	The correlation coefficient	E_0 /MPa	E_I /MPa	η /(MPa·s)
25	$y=0.00004489t+0.71$	0.94256	1.12	2.034	4.53E+04
50	$y=0.0001096t+1.35286$	0.94574	2.35	3.8685	3.53E+04
100	$y=0.0001843t+2.06571$	0.92484	3.72	7.8909	4.28E+04
200	$y=0.0002532t+3.01$	0.91945	5.27	20.287	8.01E+04
400	$y=0.0003343t+4.14714$	0.91106	7.11	63.253	1.89E+05
800	$y=0.0003812t+5.96286$	0.9145	9.35	388.72	1.02E+06

Table 7 Rheological model fitting results and parameters of the samples when the enzyme content was 0.04%

Load/kPa	Fitted equation	The correlation coefficient	E_0 /MPa	E_I /MPa	η /(MPa·s)
25	$y=0.00005506t+0.59714$	0.93453	1.09	1.8169	3.3E+04
50	$y=0.0001133t+1.28286$	0.93447	2.3	3.6069	3.18E+04
100	$y=0.0001808t+2.04714$	0.92336	3.66	7.7457	4.28E+04
200	$y=0.0002401t+2.99857$	0.91535	5.13	20.057	8.35E+04
400	$y=0.0002946t+4.10429$	0.90759	6.71	60.6	2.06E+05
800	$y=0.0003142t+5.94143$	0.91376	8.74	380.48	1.21E+06

3.3 The Relationship between Rheological Model Parameters and Loads

Rheological model parameters of samples with different enzyme contents under different loads are shown in Fig. 9. According to Fig. 9, the rheological model parameters E_0 , E_I and η of the three components of organic soil modified by enzymes are roughly negatively correlated with the enzyme content. When the enzyme content is 0.01%, E_I and η reach the maximum, and the parameters E_0 , E_I and η increase with the increase of load.

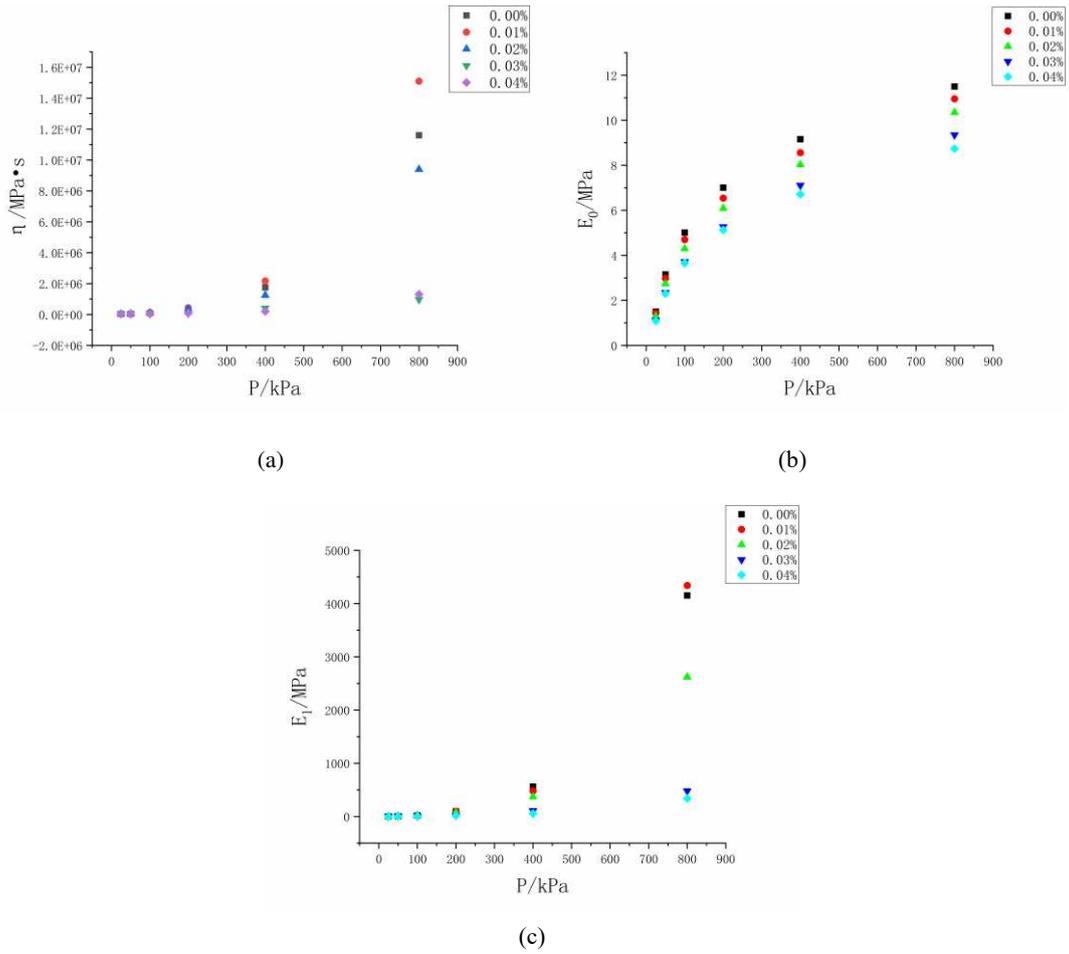


Fig. 9. Relation curve between rheological model parameters and load P under different enzyme contents: (a)

The relationship between modulus η and load P , (b) The relationship between modulus E_0 and load P , (c) The relationship between modulus E_1 and load P .

3.4 Establishment of Rheological Model with Different Enzyme Contents

The empirical relationship between enzyme content and Gibson model parameters was established. The empirical relationship between model parameters and load under different enzyme contents were shown in Eqs (5)-(10) (Z is enzyme content; P is the load value), and the rheological model of organic soil considering the influence of enzyme content was established.

$$0.00\%: \begin{cases} E_0 = 11.868 - 11.55e^{-\frac{P}{232.1}} \\ E_1 = 11.853e^{\frac{P}{136.5}} - 11.625 \\ \eta = 41800 + 0.16616P^{2.727} \end{cases} \quad (5)$$

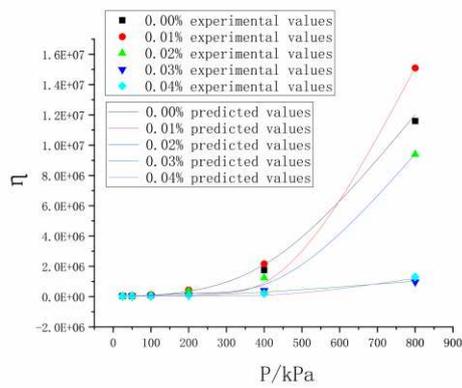
$$0.01\%: \begin{cases} E_0 = 11.348 - 10.99e^{-\frac{P}{241.1}} \\ E_1 = 14.643e^{\frac{P}{140.5}} - 15.047 \\ \eta = 59748.4e^{\frac{P}{144.55}} - 31229.25 \end{cases} \quad (6)$$

$$0.02\%: \begin{cases} E_0 = 10.75 - 10.465e^{-\frac{P}{245.03}} \\ E_1 = 15.564e^{\frac{P}{155.9}} - 16.024 \\ \eta = 76520.3e^{\frac{P}{166.11}} - 48348.5 \end{cases} \quad (7)$$

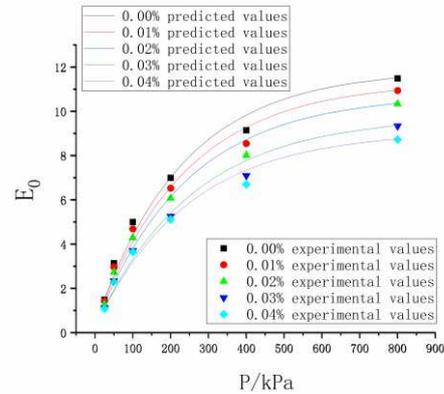
$$0.03\%: \begin{cases} E_0 = 9.784 - 9.542e^{-\frac{P}{258.84}} \\ E_1 = 13.104e^{\frac{P}{233.8}} - 12.55 \\ \eta = 18137.7e^{\frac{P}{199.75}} + 24744.1 \end{cases} \quad (8)$$

$$0.04\%: \begin{cases} E_0 = 9.098 - 8.85e^{-\frac{P}{249.43}} \\ E_1 = 12.696e^{\frac{P}{233.1}} - 12.316 \\ \eta = 4252.56e^{\frac{P}{142.2}} + 27929.8 \end{cases} \quad (9)$$

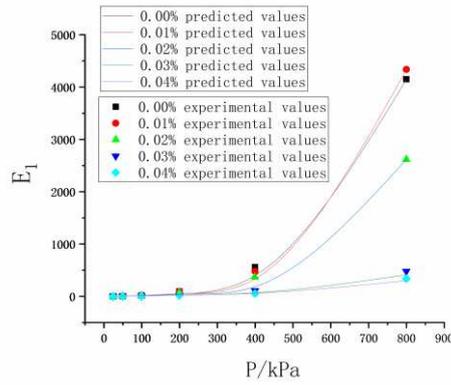
The experimental values of rheological model parameters in Table (3)~(7) and the predicted values of rheological model parameters in Eqs. (5)~(9) are shown in Fig. 10. As can be seen from Fig. 10, the experimental values of the rheological model parameters are in high agreement with the predicted values, so Eqs. (5)~(9) can well predict the parameter values of the rheological model.



(a)



(b)



(c)

Fig. 10. Analysis results of experimental and predicted values of rheological model parameters with different enzyme contents: (a) Analysis results of parameter η , (b) Analysis results of parameter E_0 , (c) Analysis results of parameter E_1 .

4 Model Prediction

In order to verify the reliability of the model, the model was used to calculate and predict samples with different enzyme contents, and the comparison results between the calculated predicted value and the experimental value were shown in Fig. 11. According to Fig. 11, under low load (25 and 50kPa), the test value is in good agreement with the predicted value. With the increase of load, although the test value differs from the predicted value, it is basically in agreement. In general, the experimental values are in good agreement with the predicted values, which verifies the reliability of the model and indicates that the model is suitable for describing the secondary consolidation creep of organic soil.

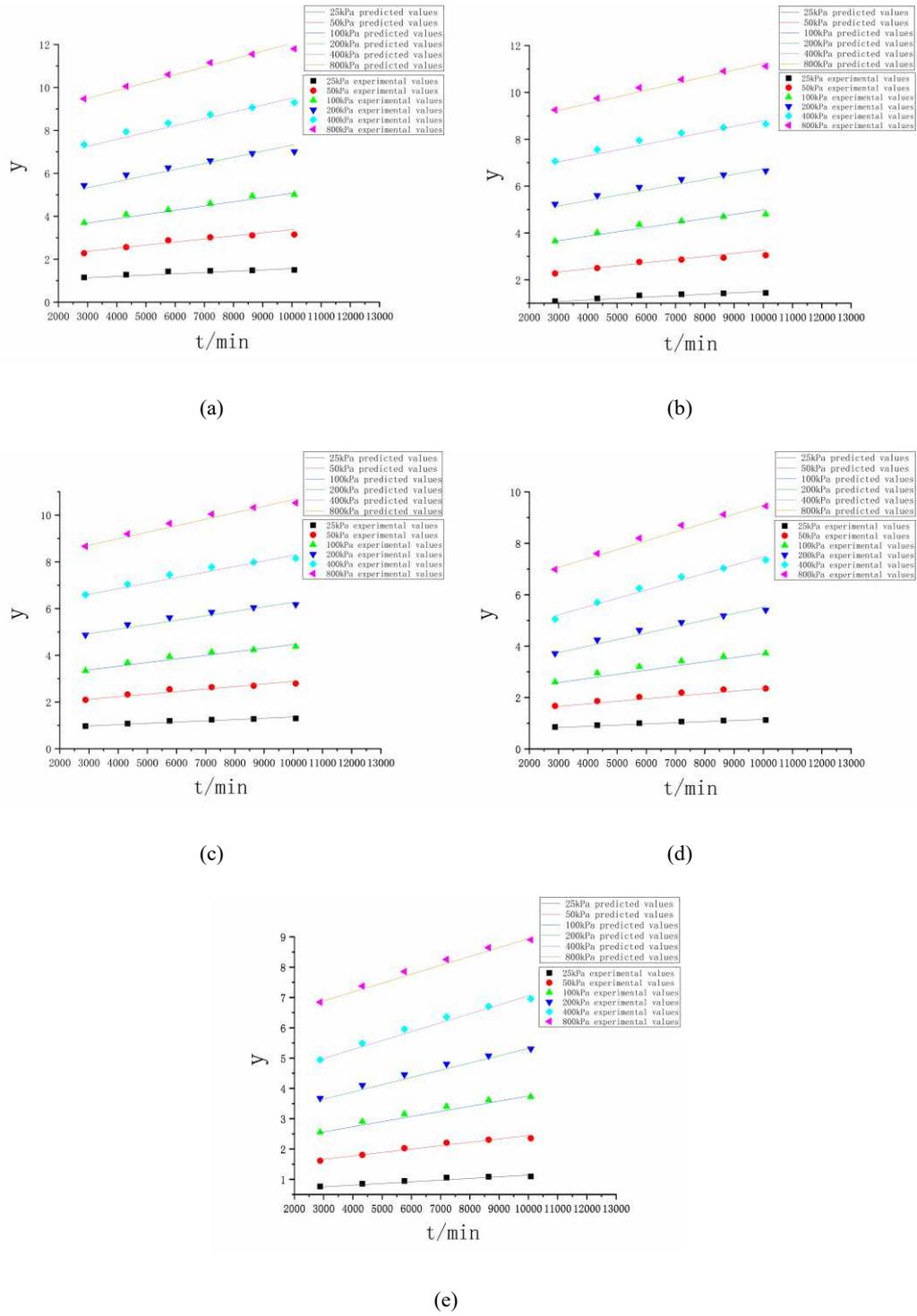


Fig. 11. Analysis results of test values and model predicted values of samples with different enzyme contents: (a) Enzyme content 0.00%, (b) Enzyme content 0.01%, (c) Enzyme content 0.02%, (d) Enzyme content 0.03%, (e) Enzyme content 0.04%.

5 Conclusion

(1) The rheological model parameters E_0 , E_1 and η of the three components of organic soil modified by enzymes were negatively correlated with the enzyme content. When the enzyme content was 0.01%, E_1 and η reached the maximum, and E_0 , E_1 and η increased with the increase of the load.

(2) The secondary consolidation coefficient C_a is related to the load. The secondary consolidation coefficient C_a of the samples with different enzyme contents shows a certain rule under all levels of loads. At about 100kPa, the secondary consolidation coefficient C_a of the samples with different enzyme contents reaches the peak value. With the increasing of load, the final secondary consolidation coefficient C_a approaches a stable value. The consolidation coefficient C_v decreased with the increase of loading under different enzyme contents. When the load is less than 200kPa, the consolidation coefficient C_v changes obviously with the load. When the load is greater than 200kPa, the consolidation coefficient C_v gradually tends to be stable. Under the same load, the consolidation coefficient C_v decreases first and then increases with the increase of the enzyme content. With the same enzyme content, the compression index C_c increases with the increase of load P , and with the same level of load, the compression index C_c decreases with the increase of enzyme content.

(3) The relationship between the secondary consolidation coefficient C_a and the compression index C_c is roughly linear. The C_a/C_c values of the samples of organic soil modified by different enzyme contents are between 0.042 and 0.1 under different loads.

(4) The experimental values are in good agreement with the predicted values, which indicates that the model is suitable for describing the secondary consolidation creep of organic soil and can be used to guide the long-term deformation prediction of organic soil foundation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the financial support provided by National International Science and Technology Cooperation Special Project (2014DFA53120); Hunan Engineering Laboratory of Manufacture and Application Technology of Modern Wood Structure Engineering Materials, Central South University of Forestry and Technology, No.HelfMTS1707; Key Discipline Construction Project of Hunan Province, No.2013GDXXK006; The Research Start-up Fund for Introducing High-level Talents in Forestry Science and Technology of Central South China, No.104-0094.

ORCID

Yixin Zhang <http://orcid.org/0000-0001-9879-9823>

References

- Bjerrum L (1967) Engineering geology of norwegian normally-consolidated marine clays as related to settlements of buildings. *Geotechnique* 17(2):83-118. doi: 10.1680/geot.1967.17.2.83
- Bouchard R, Tavenas F, Kabbaj M, Leroueil S (1985) Stress–strain–strain rate relation for the compressibility of sensitive natural clays. *Geotechnique* 35(2):159-180. doi: 10.1680/geot.1985.35.2.159
- Canakeci H, Sidik W, Kilic IH (2015) Effect of bacterial calcium carbonate precipitation on compressibility and shear strength of organic soil. *Soils and Foundations* 55(5):1211-1221. doi: 10.1016/j.sandf.2015.09.020
- Castro A, Shields DR, Mesri G, Febres-Cordero E (1981) Shear stress-strain time behavior of clays. *Géotechnique* 31(4):537-552. doi: 10.1680/geot.1981.31.4.537

- Chen YQ, Wen CP, Fang XQ (2019) Modified Yin's double-yield-surface model for bioenzyme-treated expansive soil. *Rock and Soil Mechanics* 40(9):3515-3523. doi: 10.16285/j.rsm.2018.1004
- Chen YQ, Wen CP, Fang XQ, Chen ZH, Sun Z, Wang XJ (2019) Stress-strain relationships of bioenzyme-treated expansive soil. *Journal of Central South University (Science and Technology)* 50(8):1981-1990. doi: 10.11817/j.issn.1672-7207.2019.08.026
- Chu CF, Shao L, Liu SY, Hong ZS (2006) Laboratory study quantitatively on effect of organic content on strength of cement-mixed clays. *Rock and Soil Mechanics* 27(9):1613-1616. doi: 10.3969/j.issn.1000-7598.2006.09.038
- Deng YF, Cui YJ, Tang AM, Li XL, Sillen X (2012) An experimental study on the secondary deformation of Boom clay. *Applied Clay Science* 59–60(s59–60):19-25. doi: 10.1016/j.clay.2012.02.001
- Dong H, Cheng ZH, Liu YQ, Zhu XM (2020) Experimental study of aging strength of the mucky soils improved with bio-enzyme. *Hydrogeological Engineering Geology* 47(2):84-94. doi: CNKI:SUN:SWDG.0.2020-02-012
- Feng ZG, Zhu JG (2009) Experimental study on secondary consolidation behavior of soft soils. *Chinese Journal of water conservancy* 40(5):583-588. doi: 10.3321/j.issn:0559-9350.2009.05.011
- Jiang YZ, Zhang MM, Li LQ (2008) Study on nonlinear viscoelasto-plastic creep model of rock and its parameter identification. *Chinese Journal of Rock Mechanics and Engineering* 27(4):832-839. doi: 10.3321/j.issn:1000-6915.2008.04.025
- Ge MM, Li N, Zheng JG, Zhu CH, Bo YY (2015) Prediction of the post-construction settlement of high filled embankment with considering the time depending deformation of compacted loess. *China Civil Engineering Journal* 48(S2):262-267.
- Guo Y, Xu RQ, Shao YC (2008) Study on mechanism of muddy soil stabilization. *Journal of Zhejiang University (Engineering Science)* 42(6):1071-1075. doi: 10.3785/j.issn.1008-973X.2008.06.033
- Harvey OR, Harris JP, Herbert BE, Stiffler EA, Haney SP (2010) Natural organic matter and the formation of

- calcium-silicate-hydrates in lime-stabilized smectites: A thermal analysis study. *Thermochimica Acta* 505(1):106-113. doi: 10.1016/j.tca.2010.04.007
- Hu YY, Yang P, Yu QZ (2016) Time effect of secondary consolidation coefficient of over-consolidated soil. *China Journal of Highway and Transport* 29(9):29-37. doi: CNKI:SUN:ZGGL.0.2016-09-003
- Liu ZM (2017) Experimental study on reinforcing the organic soil based on the filling function of ettringite. Southeast University. doi: CNKI:CDMD:2.1018.005678
- Ma C, Xie YJ, Long GC, Chen B, Chen LZ (2018) An integrated strength-calculation model for earth-based construction prepared by organic clay. *Applied Clay Science* 155(APR.):74-83. doi: 10.1016/j.clay.2018.01.014
- Malkawi AIH, Alawneh AS, Abu-Safaqah OT (1999) Effects of organic matter on the physical and the physicochemical properties of an illitic soil. *Applied Clay Science* 14(5-6):257-278. doi: 10.1016/S0169-1317(99)00003-4
- Mesri G (1973) Coefficient of secondary compression. *ASCE Soil Mechanics and Foundation Division Journal* 99(1):123-137. doi: 10.1061/JSFEAQ.0001840
- Mesri G (1977) Time and stress-compressibility interrelationship. *Geotechnical Engineering Division, ASCE* 103(5):417-430. doi: 10.1016/0148-9062(77)91005-1
- Miao LC, Zhang JH, Chen YN (2007) Study on compressibility of Jiangsu marine clay. *Chinese Journal of Geotechnical Engineering* 29(11):1711-1714. doi: 10.3321/j.issn:1000-4548.2007.11.019
- Nash DFT, Sills GC, Davison LR (1992) One-dimensional consolidation testing of soft clay from Bothkennar. *Geotechnique* 42(2):241-256. doi: 10.1680/geot.1992.42.2.241
- Pooni J, Giustozzi F, Robert DJ, Setunge S (2019) Durability of Enzyme Stabilized Expansive Soil in Road Pavements subjected to Moisture Degradation. *Transportation Geotechnics*. doi: 10.1016/j.trgeo.2019.100255
- Qian CX, Wang AH, Wang X (2015) Advances of soil improvement with bio-grouting. *Rock and Soil Mechanics*

36(6):1537-1548. doi: 10.16285/j.rsm.2015.06.003

Rafat SA, Rowshon J (2018) An experimental investigation on the effect of thixotropic aging on primary and secondary compression of reconstituted dredged clays. *Applied Clay Science* 162(sep.):524-533. doi: 10.1016/j.clay.2018.05.023

Ramdas VM, Mandree P, Ramchuran S, Lalloo R, Mukaratirwa S (2020) Review of current and future bio-based stabilisation products (enzymatic and polymeric) for road construction materials. *Transportation Geotechnics*. doi: 10.1016/j.trgeo.2020.100458

Saride S, Puppala AJ, Chikyala SR (2013) Swell-shrink and strength behaviors of lime and cement stabilized expansive organic clays. *Applied Clay Science* 85(nov.):39-45. doi: 10.1016/j.clay.2013.09.008

Shankar AUR, Rai HK, Ramesha MI (2009) Bio-enzyme stabilized lateritic soil as a highway material †. *Journal of the Indian Roads Congress* 70(2):143-151.

Shi XC, Wang R, Zhang ZX (2003) Study on secondary consolidation properties of Guangxi marine ooze. *Rock and Soil Mechanics* 24(5):863-865. doi: 10.3969/j.issn.1000-7598.2003.05.042

Song YJ, Lei SY, Han TL (2012) A new nonlinear viscoelasto-plastic rheological model for rocks. *Rock and Soil Mechanics* 33(7):2076-2080. doi: 10.16285/j.rsm.2012.07.012

Sun J (2007) Rock rheological mechanics and its advance in engineering applications. *Chinese Journal of Rock Mechanics and Engineering* 26(6):1081-1106. doi: 10.3321/j.issn:1000-6915.2007.06.001

Tremblay H, Duchesne J, Locat J, Leroueil S (2002) Influence of the nature of organic compounds on fine soil stabilization with cement. *Canadian Geotechnical Journal* 39(3):535-546. doi: 10.1139/t02-002

Walker LK (1969) Undrained creep in a sensitive clay. *Géotechnique* 19(4):515-529. doi: 10.1680/geot.1969.19.4.515

Wang DX, Abriak NE, Zentar R (2015) One-dimensional consolidation of lime-treated dredged harbour sediments.

- European Journal of Environmental and Civil Engineering 19(2):199-218. doi:10.1080/19648189.2014.939309.
- Wen CP (2018) K-G model of bioenzyme-treated expansive soil based on disturbed state theory. China Journal of Highway and Transport 31(2):308-318. doi: 10.19721/j.cnki.1001-7372.2018.02.033
- Wen CP, Wang XJ (2018) Study on the relationship between bioenzyme-improved expansion soil stress and strain based on the South Water Model. Chinese Journal of Rock Mechanics and Engineering 37(4):1011-1019. doi: 10.13722/j.cnki.jrme.2017.1425
- Xu RQ, Guo Y, Liu ZY (2007) Experimental study on mechanical properties of stabilized artificial organic soil. Journal of Zhejiang University (Engineering Science) 41(1):109-113. doi: 10.3785/j.issn.1008-973X.2007.01.020
- Xu WY, Yang SQ (2005) Experiment and modeling investigation on shear rheological property of joint rock. Chinese Journal of Rock Mechanics and Engineering 24(S2):5536-5542.
- Xu WY, Yang SQ, Chu WJ (2006) Nonlinear viscoelasto-plastic rheological model (Hohai model) of rock and its engineering application. Chinese Journal of Rock Mechanics and Engineering 25(3):433-447. doi: 10.3321/j.issn:1000-6915.2006.03.001
- Yahya OML, Aubertin M, Julien MR (2000) A unified representation of the plasticity, creep and relaxation behavior of rocksalt. International Journal of Rock Mechanics and Mining Sciences 37(5):787-800. doi: 10.1016/S1365-1609(00)00016-2
- Yu XJ, Yin ZZ, Dong WJ (2007) Influence of load on secondary consolidation deformation of soft soils. Chinese Journal of Geotechnical Engineering 29(6):913-916. doi: 10.3321/j.issn:1000-4548.2007.06.021
- Zhang FZ, Chen XP, Huang GY (2003) Experimental investigation of consolidation behavior of the pearl delta saturated soft clay. Soil Engineering and Foundation 17(2):26-27. doi: 10.3969/j.issn.1004-3152.2003.02.009
- Zhou QJ, Chen XP (2006) Test study on properties of secondary consolidation of soft soil. Rock and Soil Mechanics

27(3):404-408. doi: 10.3969/j.issn.1000-7598.2006.03.013

Zhu JB, Wang B, Wu AQ (2010) Study of unloading triaxial rheological tests and its nonlinear damage constitutive model of JinPing hydropower station green sandstone. Chinese Journal of Rock Mechanics and Engineering 29(3):528-534. doi: CNKI:SUN:YSLX.0.2010-03-014

Zhu JF, Rao CY, Yu QS, Liu HX, Pan BJ (2019) Experimental study on the properties of the organic soil solidified by the composite magnesium oxysulfate cement-curing agent. Chinese Journal of Rock Mechanics and Engineering 38(S1):3206-3214. doi: 10.13722/j.cnki.jrme.2018.0658

Zhu JF, Yan QS, Deng WN, Rao CY, Liu HX (2019) Model of compressive strength of cured organic soil solidified by magnesium cement complex curing agent. Journal of Zhejiang University (Engineering Science) 53(11):2168-2174. doi: 10.3785/j.issn.1008-973X.2019.11.015

Zhu JG, Feng ZG (2009) Experimental study on behaviour of secondary consolidation of soft soils under repeatedly dumped loads. Chinese Journal of Geotechnical Engineering 31(3):341-345.

Zhu W, Zeng KL, Zhang CL (2008) Influence of organic matter component on solidification of dredged sediment. Rock and Soil Mechanics 29(1):33-36. doi: 10.16285/j.rsm.2008.01.002