Journal of Mining and Earth Sciences

Website: http://jmes.humg.edu.vn

Effect of pore water chemistry on the ring shear behavior and the rate dependency of residual strength

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ARTICLE INFO

Article history:
Received 5th Aug. 2023
Revised 18th Nov. 2023
Accepted 29th Nov. 2023

Keywords:
Kaolin clay,
Pore fluid chemistry,
Rate dependency,
Ring shear behavior.

ABSTRACT

The rate dependency of residual strength plays an important role in the selection of residual strength parameters to design the remediation works for reactivated landslides. In the literature, it is shown that the rate dependency of residual strength depends on some factors such as types of soil, range of shear rates, range of effective normal stresses, and pore water chemistry. Recently, the effect of pore water chemistry on the rate dependency of residual strength soil has been examined. However, the ring shear behavior and the rate dependency of residual strength of soil having different pore fluids should be more evaluated. In this study, the effect of the pore fluids of distilled water and 1 M NaCl on the rate dependency of residual strength of kaolin clay was investigated in the Bishop ring shear apparatus. The ring shear tests were conducted at different shearing rates from 0.02 mm/min to 20 mm/min under the effective normal stress of 98 kPa. The research results showed that the pore fluid chemistry affected the shear displacement required to reach the peak strength, the vertical displacement, and the peak strength of kaolin clay. These parameters also exhibited rate dependency, especially at the fast shear rates. The research also indicated that the pore fluid chemistry had a significant effect on the rate dependency of residual strength. Accordingly, the rate dependency of residual strength of kaolin mixed with distilled water showed a positive tendency while that of kaolin with 1 M NaCl as the pore fluid was the neutral tendency.

1. Introduction

The literature showed that the residual strength of soil depended on many factors such as mineralogical compositions, particle size and

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DOI: 10.46326/JMES.2022.64(6).10

shape, Atterberg's limits, pore water pressure, shear displacement rate, and normal stress (Duong et al., 2020). Since landslides often occur at different velocities, the effect of shear rate on residual strength plays an important role in selecting appropriate parameters for designing the countermeasures. So far, the rate effect on the residual strength of various types of soil has been widely investigated (Tika et al., 1996; Skempton, 1985; Li and Aydin, 2013; Scaringi and Di Maio, 2016; Duong et al., 2018; Lian et al., 2018; Xu et al., 2018; Wang and Cong, 2019; Tiwari et al., 2020; Wang et al., 2020; Ma et al., 2021). Some investigations have shown that the rate dependency of residual strength of soil may depend on the mineralogical composition, soil density, normal stress, pore water chemistry, and Atterberg's limit. In which, the magnitude of the rate effect on the residual strength may decrease with the increase of effective normal stress (Kimura et al., 2014; Gratchev and Sassa, 2015). In particular, the rate effect on the residual strength of soil is thought to be more evident at normal stress levels of less than 100 kPa. Li and Aydin (2013) revealed that the magnitude of the positive rate dependency of the residual strength may be decreased with the increasing coarse fraction and soil density. Scaringi and Di Maio (2016) believed that the rate dependency of the residual strength can be correlated with the pore water chemistry. They showed that the level of the positive rate effect on the residual strength of bentonite might increase as the NaCl molarity in the pore fluid increased. Duong et al. (2018) indicated that the magnitude of the positive rate effect increased while the magnitude of the negative rate effect on the residual strength tended to decrease as the clay fraction (CF) and plasticity index (PI) increased. Recently, Tiwari et al. (2020) presented that the reduction of residual strength of soil dominated by kaolinite mineral with the increase of shearing rates from 0.001 mm/min to 1 mm/min was almost two times higher than that of soil dominated by montmorillonite mineral. Additionally, the research also indicated that the reduction rate (magnitude of the negative rate effect) in residual strength of soil dominated by montmorillonite with increasing shear rate could be increased as the saline pore fluid increased. However, the molarity of saline pore fluid in the research of Tiwari et al. (2020) was not provided and the rate dependency of residual strength was investigated at slow-medium shearing rates only. Yao et al. (2020) stated that the shear strength of high-plasticity clay was more sensitive to the pore water chemistry than that of low-plasticity clay.

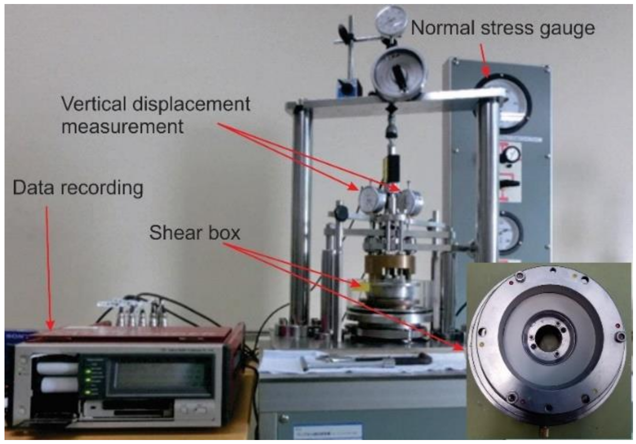

Figure 1. Bishop-type ring shear apparatus (Suzuki et al., 2017).

In general, the rate dependency of residual strength concerning pore fluid chemistry has been recently investigated (Scaringi and Di Maio, 2016; Tiwari et al., 2020). Nevertheless, these investigations mostly focus on the residual strength of bentonite containing a high content of montmorillonite mineral which is very sensitive to the pore fluid chemistry. Thus, the effect of pore fluid on the rate dependency of residual strength of other soils needs to be more evaluated, especially at fast shear rates. In this study, the effect of saline water (NaCl) in the pore fluid on the ring shear behavior and the rate dependency of residual strength of kaolin clay over a wide range of shearing rates will be investigated.

2. Material and methods

2.1. Apparatus

The common Bishop-type ring shear apparatus was employed in this study (Figure 1). The detail of this apparatus has been reported in some previous studies (Suzuki et al., 2017; Duong et al., 2018; Duong and Hai, 2021a; Duong and Suzuki, 2020, 2022). This apparatus uses a ring-shaped specimen with 6 cm of inner diameter, 10 cm of outer diameter, and 2 cm of height.

2.2. Materials

Commercial kaolin clay has been widely used to investigate the geotechnical properties of soil, especially the residual shear strength (Duong et al., 2018; Suzuki et al., 2007, 2017; Tiwari et al., 2020; Tiwari and Marui, 2003; Yao et al., 2020). This is because kaolin clay in the form of dry powder is homogeneous and easily creates the remolded sample. Additionally, the residual strength is considered to be independent of sample types and sample preparation (Stark and Vettel, 1992; Suzuki et al., 2007; Townsend and Gilbert, 1976). Thus, in this study, commercial kaolin clay in Japan in the form of powder was employed to prepare the remolded samples. Some properties of kaolin clay with different pore fluids are shown in Table 1. It can be seen that when the pore fluid is 1 M NaCl, the Atterberg's limits (liquid limit, plasticity index) and the compression coefficient (Cc) of kaolin clay decrease whereas the vertical consolidation at 100 kPa (Cv) increase.

2.3. Sample preparation and methods

The dry powder of kaolin clay was mixed with distilled water and 1 M NaCl to a water content of about 1.5 times its liquid limit in the form of slurry. The slurry was kept in a plastic box under a constant water content for one day to reach homogeneity. The slurry was then poured and pre-consolidated in a large consolidation tank at the effective normal stress of 98 kPa until finishing the primary consolidation which was based on the 3*t* method (JGS 0560-2009). The pre-consolidation procedure to create samples used in ring shear tests has been presented in some previous studies (Duong et al., 2018; Duong and Hai, 2021a; Duong and Suzuki, 2020, 2022). After pre-consolidation, the pre-consolidated samples were cut and trimmed to produce the ring-shaped specimen with an inner diameter of 6 cm, an outer diameter of 10 cm, and a height of 2 cm.

Table 1. Some properties of kaolin samples with different pore fluids (Duong and Hao, 2020).

Sample	ρ_s	CF	w_L	PI	Cc	Cv
Kaolin+ distilled water	2.645	46	77.5	42.1	0.58	200.4
Kaolin+ 1M NaCl	2.645	46	64.0	30.0	0.40	266.6

**Note: ρ_s: Specific gravity (g/cm^3); CF: Clay content (%); w_L: Liquid limit (%); PI: Plasticity index; Cc: Compression coefficient; Cv: Vertical consolidation coefficient at 100 kPa (cm^2/day).*

The ring-shaped specimens were placed in the ring shear box and re-consolidated under the effective normal stress of 98 kPa. All specimens were then sheared at the effective normal stress of 98 kPa (Overconsolidation Ratio, OCR=1) with shear displacement rates ranging from 0.02 mm/min to 20 mm/min to a shear displacement of about 314 mm (the angle of rotation = 450^0). According to Skempton (1985), for soil with a clay content of more than 40%, the shear displacement required to reach the residual strength was about 300 mm. Since the rate dependency of residual strength seems to be more evident at the level of stress of fewer than 100 kPa as mentioned above, the normal stress of 98 kPa will be used in this study. The space between the upper and lower halves of the shear box was set at 0.1 mm to mitigate the soil leakage and the frictional force between the two halves. In Bishop's type ring shear apparatus, the vertical displacement, shear displacement, shear stress, normal stress, and the frictional force between the inner circumference of the shear box and the soil sample were automatically recorded during shearing.

3. Test results and discussions

3.1. Effect of pore fluids on the ring shear behavior

The relationship between the shear stress, vertical displacement, and shear displacement of kaolin clay mixed with distilled water and 1 M NaCl is plotted in Figure 2. As shown, the shear stress increases with the increasing shear displacement and then reduces to reach the residual strength with the shear displacement of about 314 mm. Besides, all specimens show compression behavior during shearing. The detailed results of ring shear tests for kaolin clay mixed with distilled water and 1 M NaCl are listed in Table 2.

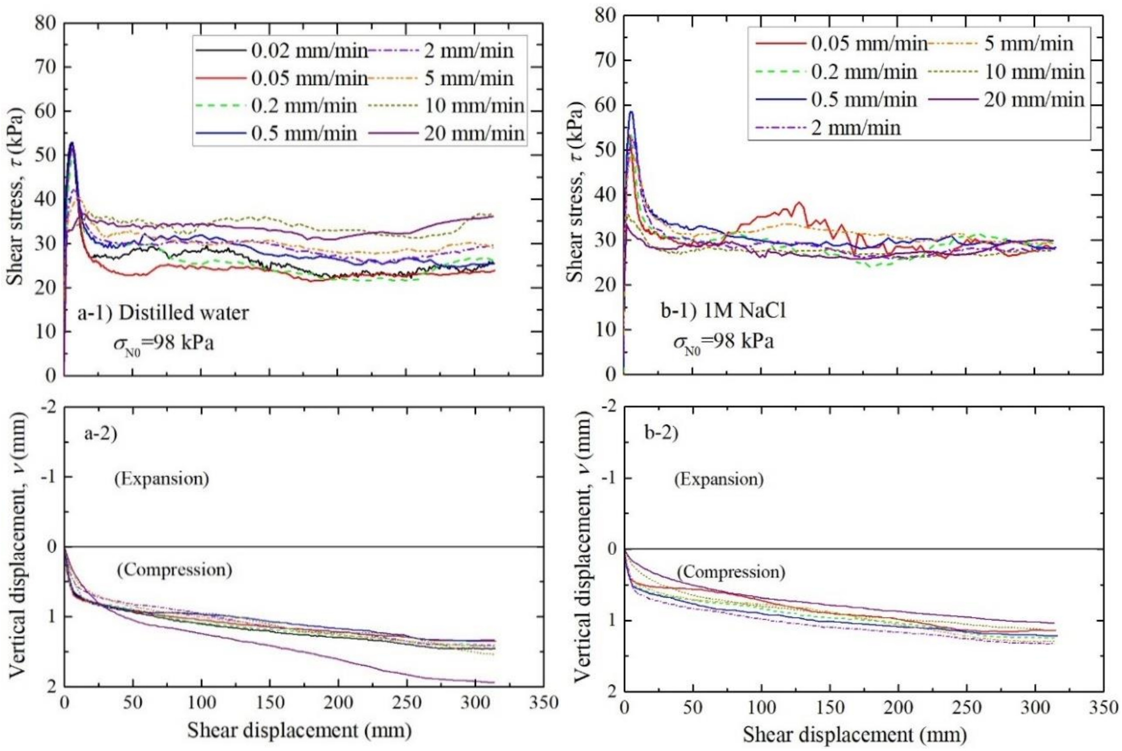

Figure 2. Relationship between shear stress, vertical displacement, and shear displacement: a) Distilled water (Duong et al., 2018); b) 1M NaCl.

Table 2. Results of ring shear tests.

Sample	W (%)	δ (mm/min)	σ_N (kPa)	τ_p (kPa)	$(\tau/\sigma_N)_p$	τ_r (kPa)	$(\tau/\sigma_N)_r$	S_p (mm)	I_B
Kaolin + distilled water	66.4	0.02	98	52.8	0.536	23.2	0.235	5.5	0.56
	69.8	0.05	98	53.3	0.526	27.5	0.233	6.1	0.48
	68.8	0.2	98	53.1	0.512	28.4	0.238	6.5	0.47
	66.6	0.5	98	58.6	0.536	30.8	0.26	6.1	0.47
	68.3	2.0	98	52.4	0.435	27.1	0.276	7.3	0.48
	69.5	5.0	98	48.8	0.414	29.2	0.289	10.6	0.40
	66.6	10	98	35.7	0.367	25.6	0.326	18.2	0.28
	71.7	20	98	33.3	0.376	26.3	0.340	14.2	0.21
Kaolin + 1 M NaCl	58.5	0.05	98	53.3	0.548	27.7	0.283	4.08	0.48
	59.2	0.2	98	53.1	0.539	28.2	0.288	5.06	0.47
	58.1	0.5	98	58.6	0.592	28.6	0.292	4.59	0.51
	57.9	2.0	98	52.4	0.535	27.1	0.276	6.07	0.48
	57.9	5.0	98	48.8	0.495	29.3	0.298	5.57	0.40
	58.3	10	98	38.1	0.392	26.7	0.272	3.04	0.25
	59.2	20	98	33.3	0.344	27.5	0.281	2.02	0.17

The relationship between the shear displacement required to reach the peak strength (Sp) and the shear displacement rate (δ) is plotted in Figure 3. As presented, the value of Sp of the kaolin mixed with distilled water is higher than that of kaolin mixed with 1 M NaCl. This can be due to the stiffness of the kaolin sample mixed with different pore fluids. As shown in Table 2, the water content of the sample mixed with 1 M NaCl is higher than that of the sample mixed with distilled water. In other words, the sample mixed with 1 M NaCl is harder than the sample mixed with distilled water. This can lead to a lower value of Sp of kaolin mixed with 1 M NaCl in comparison with that of kaolin mixed with distilled water. Figure 3 also shows that at shearing rates above 2 mm/min, the Sp of kaolin mixed with distilled water increases, whereas that of kaolin mixed with 1 M NaCl decreases with increasing shearing rates.

The relationship between the vertical displacement (settlement of soil sample) and the shear displacement rate for kaolin samples mixed with different pore fluids is shown in Figure 4. Similar to the tendency in Figure 3, the vertical displacement of kaolin clay mixed with distilled water is higher than that of kaolin clay mixed with

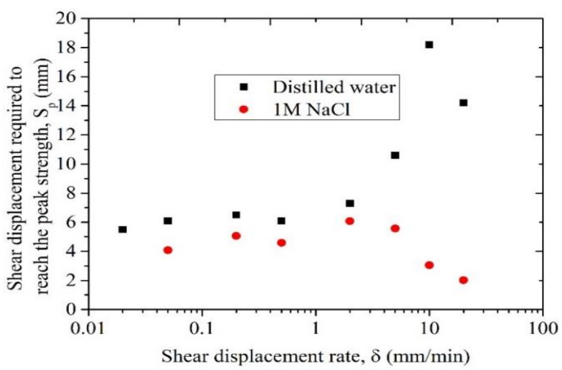

Figure 3. Relationship between shear displacement required to reach the peak strength (Sp) and shear displacement rate (δ) displacement rate (δ).

1 M NaCl. In addition, at fast shear rates above 5 mm/min, the vertical displacement in the case of distilled water increases, while that in the case of 1 M NaCl decreases as the shearing rates increase. The vertical displacement of soil samples during shearing is caused by two reasons: Soil sample consolidation and soil extrusion via the gap between the upper and lower parts of the shear box. The high vertical displacement of kaolin mixed with distilled water can be because the sample mixed with distilled water is softer than the sample mixed with 1 M NaCl. In general, the highest vertical displacement of the soil sample in this study is less than 2 mm and less than 10% of the initial sample height of 2 cm. In Bromhead's ring shear apparatus, Stark and Eid (1993) proposed the "flush" test procedure to limit the vertical displacement of 0.75 mm (15% of the initial height). Thus, in this study, the values of vertical displacement are acceptable to obtain reliable residual strength.

Based on the test results presented in Figure 2, the peak strength is gathered and the relationship between the peak stress ratio and shear displacement rate is depicted in Figure 5. As shown in this figure, the peak stress ratio of the kaolin sample mixed with 1 M NaCl is slightly higher than that of the kaolin sample mixed with distilled water. This is due to the presence of 1 M NaCl in the pore fluid leading to a decrease of the Atterberg's limits, as shown in Table 1, and results in an increase of peak strength. Figure 5 also shows that the peak strengths of both sample types are almost independent of shear rates of

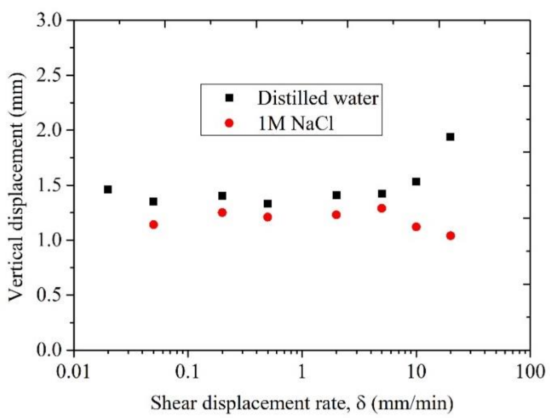

Figure 4. Relationship between vertical displacement and shear displacement rate.

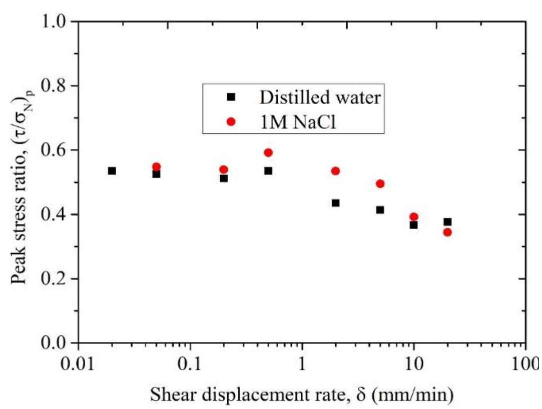

Figure 5. Relationship between peak stress ratio and shear rates.

less than 0.5 mm/min. At shear displacement rates above 0.5 mm/min, the peak strengths tend to decrease with the increase in shear rates. This tendency can be attributed to the dissipation of pore water pressure during shearing at slow and fast shearing rates (Duong et al., 2018).

The relationship between the peak and residual strengths can be expressed in terms of the brittleness index (I_B). The I_B is often used to assess the strain-softening behavior of slope failure. If there is no strength loss ($\tau_p = \tau_r$), the value of $I_B = 0$; if the strength is totally lost ($\tau_r = 0$), the value of $I_B = 1$. The rate of strength loss is an indicator of progressive failure or flow slide. The flow slide often occurs in soils having a high brittleness index. The value of I_B is determined based on the formula as follows (Bishop et al., 1971):

$$I_B = \frac{\tau_p - \tau_r}{\tau_p} = 1 - \frac{\tau_r}{\tau_p} \tag{1}$$

The brittleness index (I_B) of the sample mixed with distilled water and 1 M NaCl at different shear rates is presented in Figure 6. As shown, the values of I_B of kaolin clay mixed with distilled water and 1 M NaCl are almost similar at different shear rates. Additionally, the brittleness index tends to decrease as the shear displacement rate increases, especially at shear rates above 2 mm/min. For lightly cemented clay, Duong and Hai (2021b) also reported that the brittleness index decreased with the increase in shear rates. The decrease of I_B with increasing shear rates in this study indicates that the slope of kaolin clay may cause flow slide at the slow shear rates.

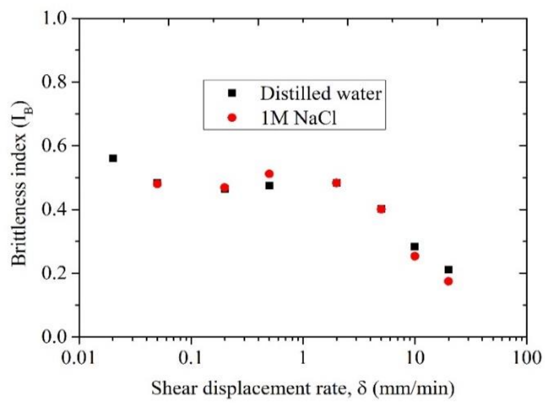

Figure 6. Relationship between brittleness index and shear displacement rates.

3.2. Effect of pore fluids on the rate dependency of residual strength

The relationship between residual stress ratio, $(\tau/\sigma_N)_r$ and shear displacement rates is presented in Figure 7. It can be seen that the residual strength of kaolin mixed with distilled water tends to increase as the shear rates increase from 0.02 mm/min to 20 mm/min (positive rate effect). The causes of the positive rate effect here can be attributed to the change of shear mode from sliding shear mode at slow shear rates to transitional shear mode at fast shear rates. The change of shear mode at fast shear rates can lead to an increase in residual strength (Skempton, 1985; Tika et al., 1996). The research results of some previous studies also reported the positive rate dependency of residual strength of some types of kaolin clay (Scaringi and Di Maio, 2016; Suzuki et al., 2017; Tika et al., 1996) (Figure 8).

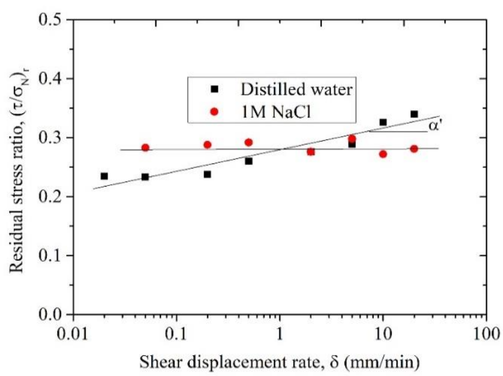

Figure 7. Relationship between residual stress ratio and shear rates.

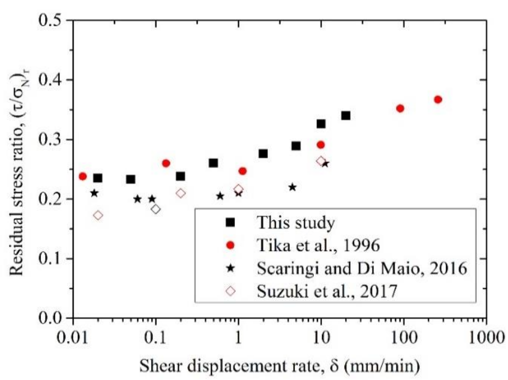

Figure 8. Relationship between residual stress ratio and shear rates for some types of kaolin clay.

For kaolin mixed with 1 M NaCl, Figure 7 shows that the residual strength is almost independent of shear displacement rates ranging from 0.05 mm/min to 20 mm/min. This tendency is different from that of kaolin mixed with distilled water. This indicates that the pore fluids significantly affect the rate dependency of the residual strength of kaolin. In the case of distilled water as the pore fluid, the rate effect coefficient as proposed by Duong et al. (2018), α = 0.035. When the pore fluid is 1 M NaCl, the rate effect coefficient, α = 0 (neutral rate effect). This phenomenon can be explained based on the effect of 1 M NaCl on the fabric of kaolin clay. When kaolin clay mixes with 1 M NaCl, the thickness of the diffuse double layer decreases and this leads to a decrease in the liquid limit and plasticity index, as shown in Table 1. According to Duong et al. (2018), the positive rate effect coefficient tended to decrease as the plasticity index decreased. Additionally, when the pore fluid is 1 M NaCl, the attractive force among clay particles increases. This can lead to aggregation and an increase in grain size (Horpibulsuk et al., 2011). The larger grain size can change the shear modes within the shear zone and result in a change in the tendency of the rate effect on residual strength. However, this hypothesis should be further investigated to clarify the effect of pore fluids on the rate dependency of residual strength.

4. Conclusions

In this study, the effect of pore fluid chemistry on the shear behavior and the rate dependency of residual strength of kaolin clay has been investigated in the ring shear apparatus. Based on the analysis of the test results, some conclusions have been made as follows:

The shear displacement required to reach the peak strength and the vertical displacement of the sample mixed with 1 M NaCl is lower than those of the sample mixed with distilled water. Additionally, the peak strength of the sample with 1 M NaCl in the pore fluid is higher than that of the sample with the pore fluid of distilled water and these peak strengths decrease with increasing shear rates above 0.5 mm/min. Regarding the strain-softening behavior, the brittleness indices of the two types of samples are almost similar and tend to decrease as the shear rates increase exceeding 2 mm/min.

The effect of the shearing rate on the residual strength of kaolin clay mixed with distilled water is higher than that of kaolin clay mixed with 1 M NaCl. Particularly, the research results showed a positive rate effect on the residual strength in the case of distilled water, whereas the neutral rate effect was exhibited for the sample mixed with 1 M NaCl. In other words, the magnitude of the positive rate effect on the residual strength of kaolin clay decreases as the ion concentration of the pore fluid increases. This phenomenon can be related to the decrease of Atterberg's limits and the increase of grain size when the pore fluid is 1 M NaCl.

Acknowledgments

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 105.08-2019.315. The authors also would like to thank the Geotechnical Lab. at Yamaguchi University for helping us conduct the experiments.

Contribution of authors

Duong Thanh Nguyen and Motoyuki Suzuki - conducted the experiments, processed data, and manuscript writing and editing; Hai Van Nguyen and Nu Thi Nguyen - manuscript writing and editing, references check.

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