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Geotechnical Characterisation of High Plasticity Offshore Clay

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Authors' contributions

This work was carried out in collaboration between both authors. Author CYL supervised the study. Author SYT managed the literature searches, design and analyses of the study and performed experimental process. Both authors read and approved the final manuscript.

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ABSTRACT

This paper gives a review on some basic geotechnical properties and compressibility behaviour of offshore clay in Malaysia. The Atterberg Limits of the normally-consolidated and reconstituted offshore clay, such as liquid limit, plastic limit and plasticity limit, are discussed. Specific gravity and particle size distribution of the offshore clay are also presented, along with the comparison of geotechnical properties with available published data of other offshore clays. The consolidation and hydraulic conductivity characteristics of high plasticity offshore clay are derived from one-dimensional oedometer test. It is found that the geotechnical properties of high plasticity offshore clay are in agreement with those of other offshore clays, especially Norwegian Drammen clay.

Keywords: Basic properties; compressibility; consolidation; high plasticity; offshore clay.

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1. INTRODUCTION

Stability of civil engineering structures depends on the soil properties such as shear strength, hydraulic conductivity and compressibility of the soil. Many civil construction activities take place in offshore clays which are fine-grained soils throughout the world such as offshore structures [1]. Offshore clays are known for their high compressibility and low strength, thus they pose many challenges to geotechnical engineers [1,2,3]. Geotechnical characterization of offshore clays is an important aspect to better understand their behaviour. In Malaysia, soft cohesive soils such as offshore clays are commonly found both in East and West of Malaysia [2].

The consolidation test is a model test in which a soil specimen is subjected to pressure in order to predict the formation that would occur to a stratum of soil under similar pressures in the ground [4]. The compressibility behaviour of offshore clay during one-dimensional consolidation can be determined by means of oedometer test. For most natural soils, the standard oedometer test with incremental loading provides a reasonable basis for estimating the magnitude of consolidation settlement [4]. The compression index (slope of the virgin compression curve on semi-log plot) of compressible soils could be predicted from stress-deformation curve, usually plotted from values of void ratio versus the log of pressure for each increment [4,5]. The time-deformation curve is used to identify primary and secondary consolidation and to obtain the coefficient of secondary consolidation.

This paper presents some geotechnical properties and compressibility behaviour of high plasticity offshore clay. Basic properties such as plasticity is an important characteristic in the case of fines soils [6]. Soil plasticity describes the ability of the soil to undergo unrecoverable deformation without cracking or crumbling. Soil plasticity is due to the presence of significant content of clay mineral particles in the soil [6].

2. SOIL MATERIAL

The high plasticity offshore clay is a natural deposited soil recovered from offshore at the seabed depths of 15-20 m in Terengganu, Malaysia.

3. EXPERIMENTAL PROGRAMME

Specific gravity tests were performed with reference to ASTM D 854 [7]. The Atterberg Limits tests were carried out in accordance to the procedures in ASTM D 4318 [8].

Incremental loading (IL) oedometer tests were undertaken on 50 mm diameter by 20dmm thick specimens. Drainage was provided through top and bottom of the specimens. The conventional IL oedometer test was performed with reference to ASTM D 2435 [9]. For high plasticity reconstituted clay materials, each loading increment was applied and maintained for 24 hours to ensure complete primary consolidation and to evaluate secondary compression behaviour. A stress increment ratio of 1 (i.e., a load ratio of 2) was used. The vertical consolidation stresses (σ_v') applied in each test were 10 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa and 400 kPa. The specimens were allowed to swell under stresses of 200 kPa, 100 kPa, 50kPa and reloaded again to 100 kPa, 200 kPa and 400 kPa. For each loading step, deformation was recorded by a digital dial gauge at specified intervals of time.

All the soil specimens are normally consolidated as they are obtained in disturbed state.

4. RESULTS DISCUSSION

4.1 Particle Size Distribution

Fig. 1 depicts the particle-size distribution curve for the Malaysia offshore clay. The clay content (fraction smaller than 0.002 mm) is about 43%, which is similar to that of Drammen clay with clay content of 45 – 50% [10].

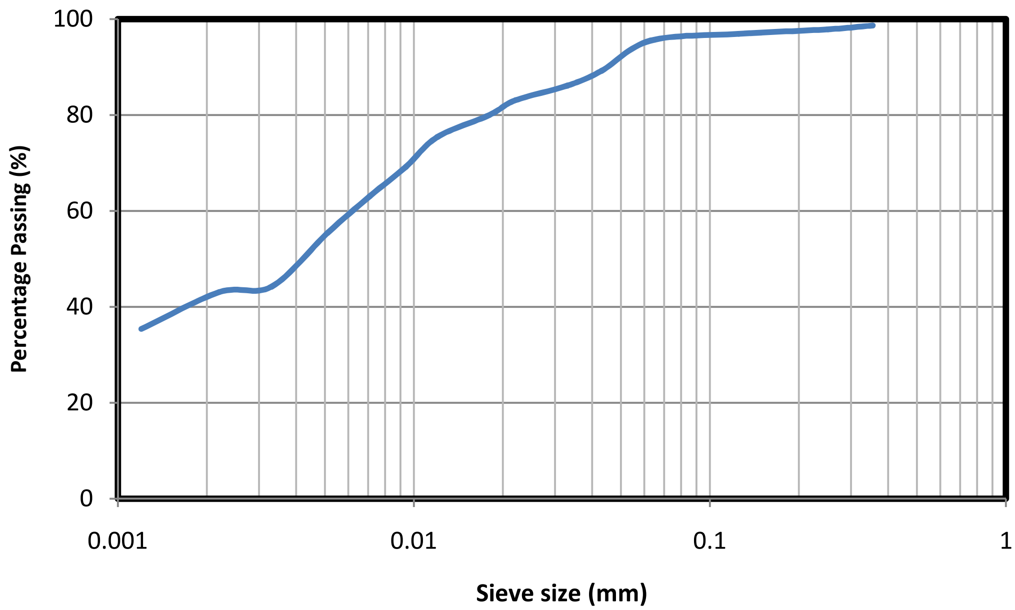

Fig. 1. Typical particle-size distribution curve for high plasticity offshore clay

4.2 Specific gravity and Atterberg Limits

The specific gravity and Atterberg Limits of high plasticity offshore clay are listed in Tables 1 and 2, respectively. The mean value for specific gravity, G_s, of the offshore clay is found to be about 2.58. The offshore clay is classified as clay with high plasticity (CH) based on plasticity chart [11].

Table 1. Specific gravity of offshore clay

Test no.	1	2	3
Specific gravity, G_s	2.54	2.64	2.56
Average G_s	2.58		

Table 2. Atterberg limits of offshore clay

Atterberg limits	Percentage (%)
Liquid Limit, LL	54
Plastic Limit, PL	27
Plasticity Index, PI	27

In order to validate the results obtained from the present study, the geotechnical properties of the present study are compared with those of other offshore clays as given in Table 3.

Table 3 shows that the plasticity index (PI) of the offshore clay is similar to that of Drammen clay although they are from different regions. Drammen clay is a type of Norwegian offshore clay which has been extensively studied by Norwegian Geotechnical Institute (NGI). Both LL and PL are primarily affected by clay fraction, clay mineral type and associated cations present [1]. The similarity of the Atterberg Limits between high plasticity offshore clay and Drammen clay could be due to the similarity of clay fraction in both offshore clays.

Table 3. Comparison of results

Soil types	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Reference
High plasticity offshore clay	2.58	54	27	27	Present study
Drammen clay (Norwegian clay)	2.76	55	28	27	[10,12,13]
Boston Blue Clay (BBC)	2.77	44	23	21	[14]
Hong Kong offshore clay	2.66	60	28	32	[15]
Shanghai Donghai offshore clay	2.75	45.1	21.3	23.8	[16]
Wenzhou China offshore clay	2.75	63.4	27.6	35.8	[17]

According to Vucetic and Dobry [18], the PI represents the amount of water required to transform remolded soil from semisolid to a liquid state, and is dependent on the composition of soil (i.e. sizes, shapes, and mineralogy of soil particles, chemistry of pore water). Plasticity index plays an important role in the cyclic strength of offshore clay. Vucetic and Dobry [18] presented the influence of the PI on the cyclic stress-strain parameters of saturated soils needed for engineering evaluations and the data evidently shows that the cyclic shear parameters depend strongly on PI. Cyclic stiffness degradation (G/G_{max})is much more pronounced for low-plasticity soils than for medium or high-plasticity soils. Vucetic and Dobry [18] have identified that PI plays a significant role in the undrained cyclic response of fine-grained soils.

4.3 One-dimensional Consolidation Test

Fig. 2 indicates the void ratio-effective stress relationship (*e*-log *p* curve) for high plasticity offshore clay. The *e*-log *p* curve is related to the stress history and degree of remolding or disturbance of the clay soil [19,20,21,22] as shown in Fig. 3. Overconsolidated clay soil is less compressible than normally consolidated clay [21]. The increase in the degree of disturbance flattens the curve considerably [20]. The *e*-log *p* curve for a normally consolidated clay soil is linear and it is referred to as the virgin compression curve [21].

One of the essential parameters for settlement calculation, which is compression index (C_c), can be derived from Fig. 2. The values of C_c of clayey soils range from 0.075 for sandy clays of low compressibility to more than 0.3 for highly compressible soft clay soils. Therefore, the compressibility index increases with increasing clay content [21]. Skempton [23] suggested that C_c of remolded clay relates closely with its associated liquid limit, and it can be expressed as:

$$C_c = 0.007\,(LL - 7) \tag{1}$$

By using the equation, the value of C_c for high plasticity offshore clay is 0.329, which is comparable to that derived from Fig. 2, that is 0.30. The values of C_c for some types of offshore clay are tabulated in Table 4.

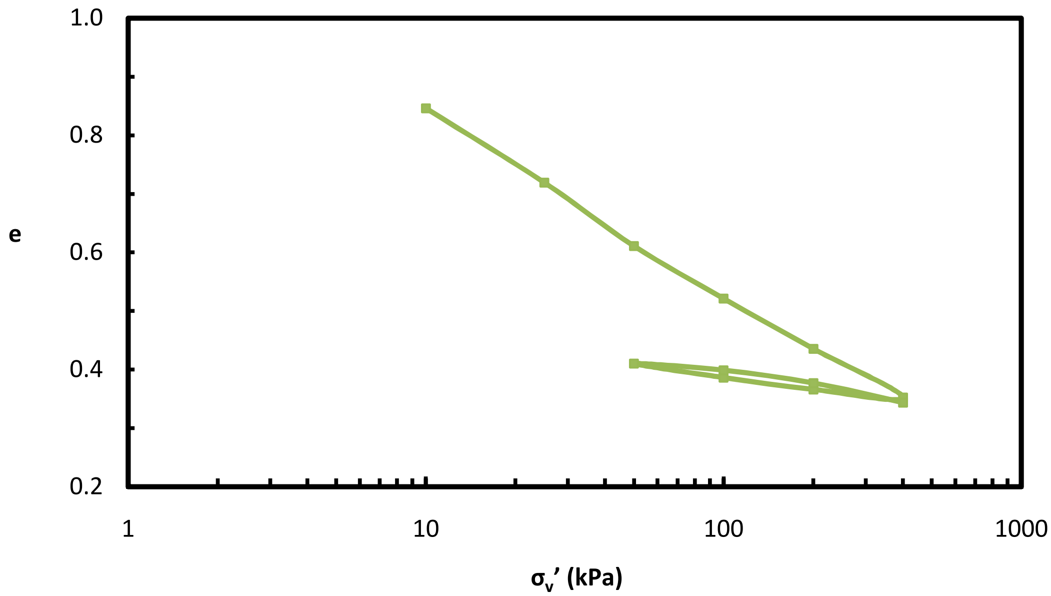

Fig. 2. Void ratio-effective stress relationship for high plasticity offshore clays

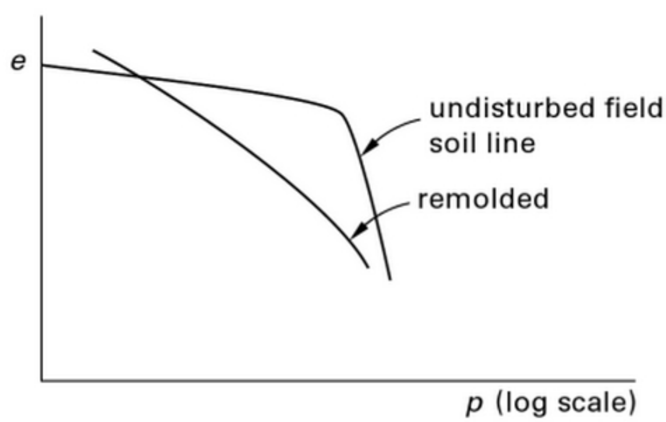

Fig. 3. Consolidation curves for remolded and undisturbed clay [19]

Table 4. Compression indices for offshore clay

Soil	Plasticity index	Compression index, C_c	Reference
High plasticity offshore clay	27	0.30	Present study
Drammen clay	31	0.45	[24,25]
Boston blue clay	21	0.21	[26]
Chicago clay	37	0.22	[26]
London clay (England)	40	0.386	[27,28,29]
Beauharnois clay	34	0.55	[26]

Fig. 4 illustrates a separate plot for the change in sample height versus log time for each load increment. The coefficient of consolidation (c_v) and coefficient of secondary compression (c_α) can be determined from the plot. These parameters are used to predict the rate of primary settlement and amount of secondary compression. Although secondary settlement is an additional parameter which is practically negligible in the case of consolidated or overconsolidated clays, it is an important consideration for muds or soft clays [30]. The coefficient of secondary consolidation, C_α, is found to range from 0.006~0.009 for high plasticity offshore clay. The C_α value is within the range for normally consolidated clay as proposed by Ladd [31] in Table 5.

Table 5. Typical values of C_α

Types of soil	C_α
Normally consolidated clays	0.005~0.02
Very plastic soils, organic sols	≥0.03
Pre-compressed clays with overconsolidation ratio > 2	<0.001
High plasticity offshore clay (present study)	0.006~0.009

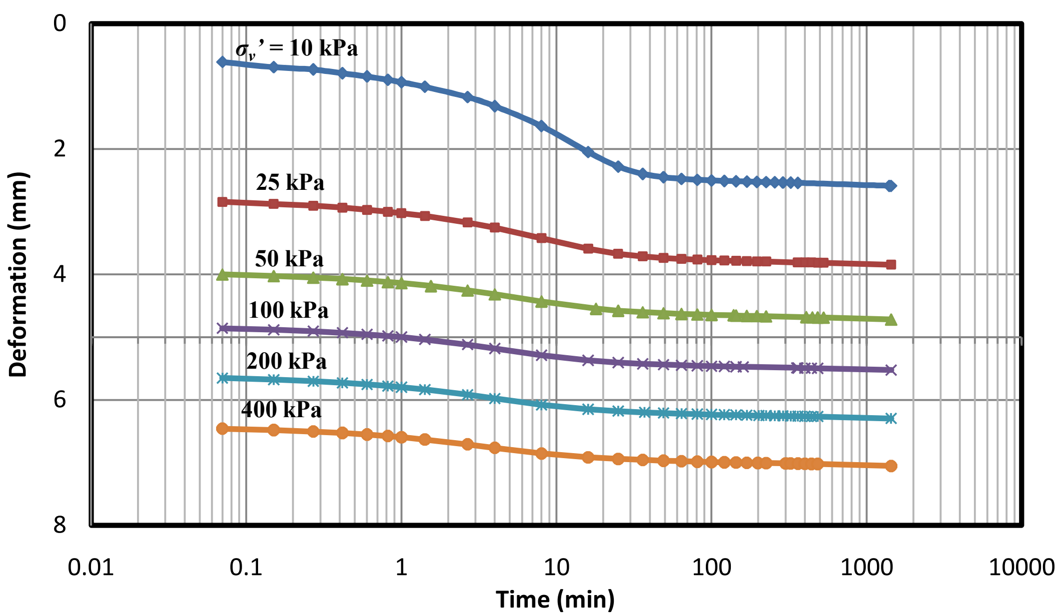

Fig. 4. Oedometer test on high plasticity offshore clay with incremental loadings

The coefficient of consolidation, c_v, determines the rate of settlement and it is calculated for each load increment [21]. The c_v values of high plasticity offshore clay which are derived using both log time and square time methods are presented in Fig. 5. Generally, intact clay specimens indicate a decrement of c_v values [32]. However, the c_v values of high plasticity offshore clay in present study increase with the increasing effective stresses. This behaviour could be explained by the influence of soil disturbance on the c_v values. According to Germaine [32], c_v behaviour over different stress levels is altered once the intact specimen is remolded completely as indicated in Fig. 6. Soil disturbance has dramatic effect on the c_v values because it obliterates the soil memory and c_v depends on a combination of compressibility and hydraulic conductivity [32,33,34,35]. The compressibility changes significantly due to disturbance but the hydraulic conductivity has only slight changes due to change in void ratio [32].

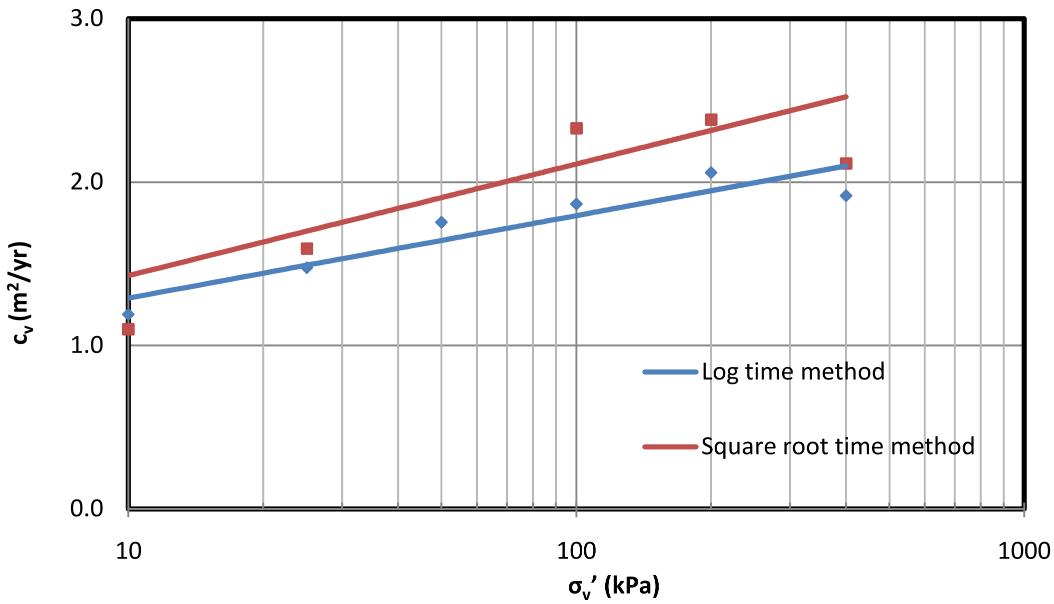

Fig. 5. Coefficient of consolidation, c_v, for high plasticity offshore clay

Typical values of c_v for various clays are tabulated in Table 6. Smaller value of c_v results in a longer time for consolidation to occur [36]. In general, the consolidation rate in the field is almost always faster than estimations based on laboratory tests based on two main reasons. Firstly, the soil is more permeable in the field, especially in the horizontal direction, than the values measured in unidirectional tests in the laboratory. Secondly, the resistance to deformation of the soil structure masks the hydrodynamic effect, and thus leads to underestimation of the hydraulic conductivity of soil [4].

The change in hydraulic conductivity, *k*, during consolidation of offshore clay specimen is shown in Fig. 7. Log time and root time methods are used to compute the *k* values and they yield similar results. The offshore clay achieves *k* value as low as 5.46 x 10^{-10} m/s at maximum vertical effective stress of 400 kPa. With increasing increments of load, the *k* values decrease, which is in agreement with Bell [21]. The *k* values for different types of clays are listed in Table 7. The *k* value represents the rate at which the pore water is expelled upon loading, and it depends on the rate at which the excess pore pressure induced by the structural load is dissipated, hence allowing the structure to be supported entirely by the soil skeleton. Thus, the hydraulic conductivity of a clay soil is important [21].

The increase in loads gives rise to a decrease in the coefficient of volume compressibility, m_v, as depicted in Fig. 8. The result is consistent with the finding of Bell [21]. The m_v values behave similarly as those of *k* values, where the decrement is controlled by the rate at which the pore water is expelled upon loading [21].

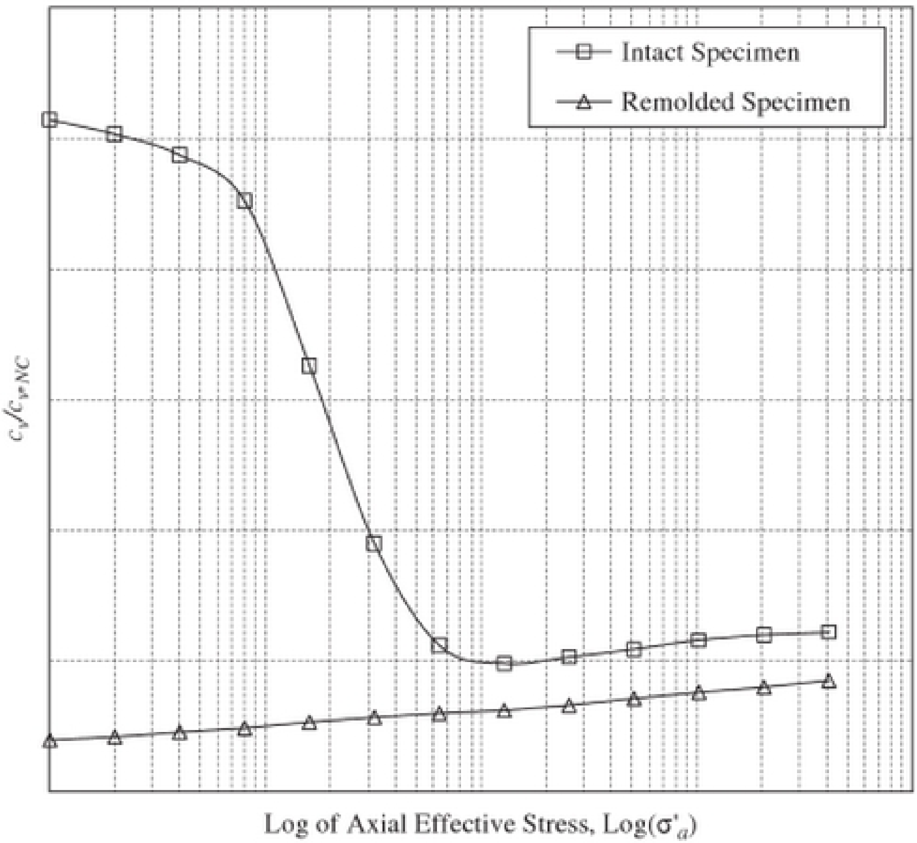

Fig. 6. Influence of stress history and soil disturbance on the consolidation coefficient, c_v [32]

Table 6. Typical values of c_v

Clay	c_v (m^2/yr)	Reference
High plasticity offshore clay	1.2~2.12	Present study
Drammen clay	1.58~3	[37,38]
Leda clay	3.15	[39]
Swedish medium sensitive clays	0.2~1.0	[40]
Chicago silty clay	2.7	[41]
San Francisco Bay Mud	0.6~1.2	[40]
Singapore offshore clay	0.5~2.0	[42]

Table 7. Hydraullic conductivity, *k*, for different clays

Clay	*k* (m/s)	Reference
High plasticity offshore clay	(6~50) x 10^{-10}	Present study
Drammen clay	27.3 x 10^{-10}	[43]
Bangkok clay	(40~600) x 10^{-10}	[44,45]
London clay	(0.5~100) x 10^{-10}	[46]
Boston blue clay	(20~1000) x 10^{-10}	[47]

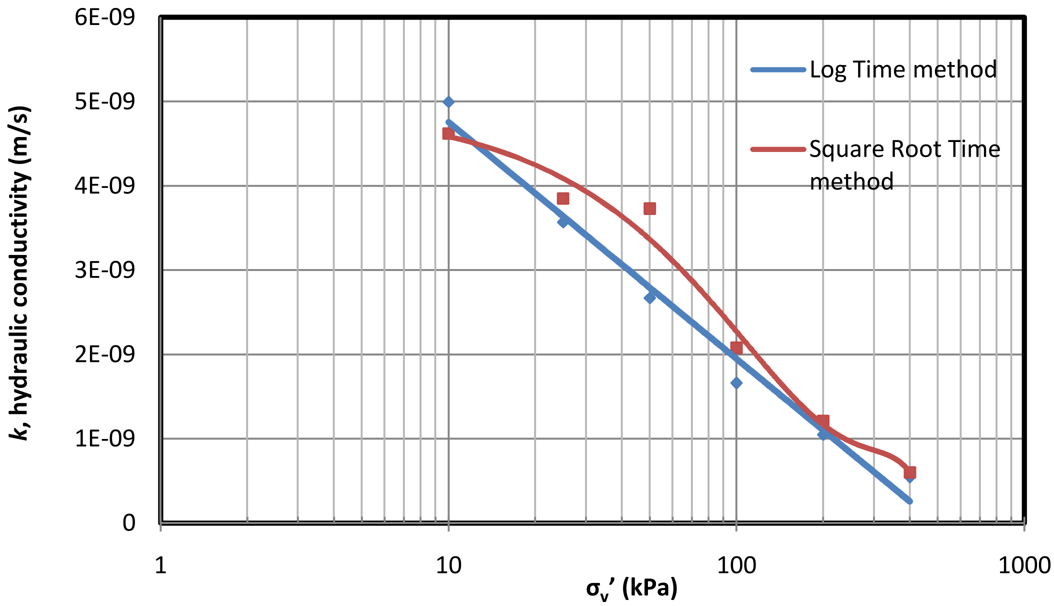

Fig. 7. Values of hydraulic conductivity, *k*, for high plasticity offshore clay

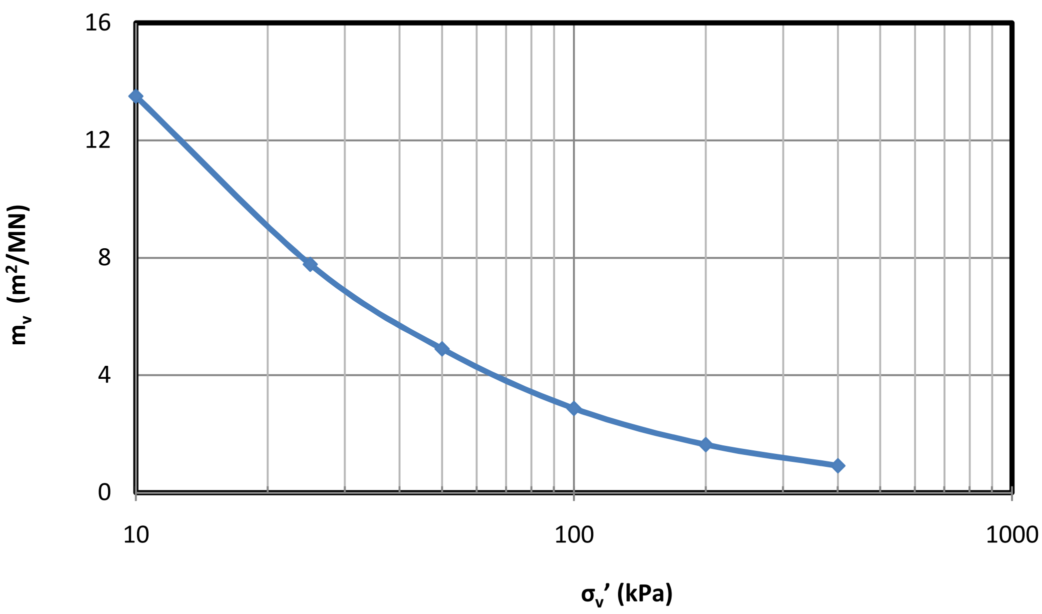

Fig. 8. Coefficient of volume compressibility, m_v, for high plasticity offshore clay

5. CONCLUSION

Some available geotechnical properties data on various offshore clays have been presented. The offshore clay is classified as clay with high plasticity (CH), with clay fraction of about 43%. The liquid limit and plasticity index are 54% and 27%, respectively. On the other hand, high plasticity offshore clay exhibits hydraulic conductivity value as low as $6x10^{-10}$ m/s at high vertical stress of 400 kPa. The compression index and coefficient of secondary consolidation are found to be 0.3 and 0.006~0.009, respectively. Interestingly, the geotechnical and compressibility properties of high plasticity offshore clay are particularly similar to those of Norwegian Drammen clay. For further recommendation, static and cyclic shear tests can be performed to better understand the static and dynamic shear behaviour of high plasticity offshore clay.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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