Reproduction of structure due to aging of marine clay by addition of small amount of cement

Reproduction de structure dû à vieillir d'argile marine par addition de petite quantité de ciment

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ABSTRACT

A new method to reproduce the agng effect of clay due to cementation in laboratory is presented. A small amount of portland cement was mixed with the slurries of three marine clays under controlling temperature. It was observed that the quasi-overconsolidation characteristics of natural marine clays of 5,000-100,000 years old were reproduced in laboratory by consolidating and curing them for 2 weeks.

RÉSUMÉ

Une nouvelle méthode de reproduire l'effet de l'agng d'argile dû à cimentation dans le laboratoire est présentée. Une petite quantité de ciment du portland a été mélangée avec le slurries de trois argiles marines sous température dirigeante. Il a été observé que le quasi-overconsolidation caractéristiques d'argiles marines naturelles de 5,000-100,000 ans a été reproduit dans le laboratoire en consolidant et les guérissant pour 2 semaines

Keywords :clay, compressibility, sedimentation, aging effects, cement,

1 COMPRESSION CHARACTERISTICS OF UNDISTURBED "AGED" MARINE CLAYS

It is known that the mechanical properties of aged clay deposits are different from those of reconstituted and reconsolidated clays in laboratory. These differences have been called "aging effects", including the delayed consolidation and the cementation due to some chemical agents such as calcium carbonate during the long period ofsedimaentation process (Bjerrum,1973).

In Osaka Bay, Pleistocene clay layers and gravel-sand layers are accumulated alternately up to the 400m depth, under the Holocene clay layer of 20m thickness. The reclamation and the construction of Kansai International Airport has made 12−14m consolidation settlemens, which were much more than those expected in the design before the construcion (Tsuchida, T.:,2000).

Fig.1 shows the *e*-log *p* curves and the change of compression index, $C_c = \Delta e / \Delta(\log p)$, of two Pleistocene clay at the depths of 91m and 128m, which were obtained by the constant rate of strain consolidation test. The *e*-log *p* curves show typical caracteristics of "aged-cemented clays", where the clays are sedimented with a structure of high void ratio and extremely large compresson took place when the overburden stress exceeded the apparent consolidationyield stresses and the compression indexes changed from 1.84−3.71 to 0.5−0.8. The uniquness of the compression curve is clearly understood by comparing them with the *e*-log *p* curve of remolded sample. The *e*-log *p* relationships of undisturbed and remolded samples, when the consolidation pressure becomes sufficiently larger than consolidation yield stress, are almost simular. The difference of both clays seems to be due to an initial structure of high void ratios of aged clays and that the destoraction of structure with increase of consolidation pressure is a reason of the large compressibility.

The mechanical properties including compression properties and of the "aged-cemented clays" has not been studied well, because the studies of clay has been carried out with the remolded and reconstituted clay samples prepared in the laboratory. Tsuchida et al. (1991) proposed the high temperature consolidation method for duplicating the structure of aged clay in laboratory, by consolidating remolded clayey slurry under 75℃ However, it is known that, comparing the un-disturbed Pleistocene Osaka Bay clays, the duplication of the structure due to aging by the high temperature consolidation is not enough. In this study, a new method to restore the structure of aged-cemented marine clay in laboratory.

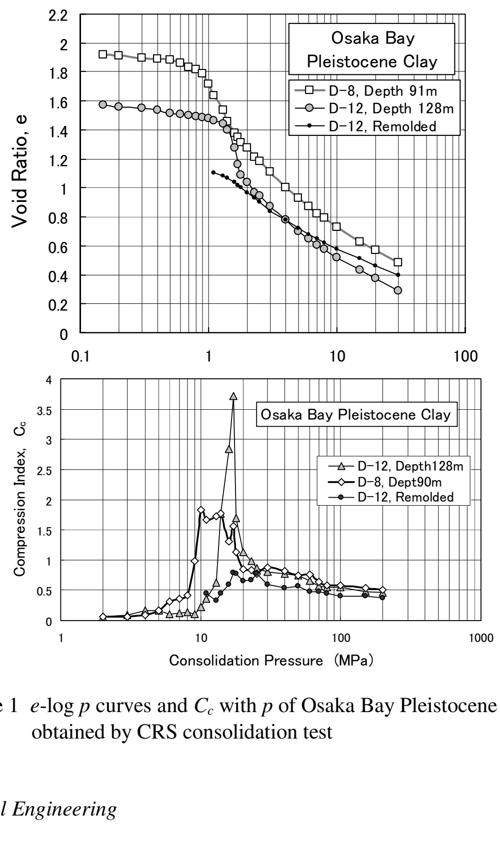

Figure 1 *e*-log *p* curves and C_c with *p* of Osaka Bay Pleistocene clays obtained by CRS consolidation test

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2 DETERMINATION OF ADDITIVE AMOUNT OF CEMENT AND TESTING PROCEDURE

In this study, a small amount of portland cement was added to slurries of 3 marine clays. Table 1 shows the index properties of marine clays used in this study.

According to Tan et. al (2001), the relationship between unconfined compression strength q_u and the additive amount of cement is given as;

$$q_u = \alpha(C - C_0) \quad (1)$$

where, α is constant. C and C_0 is the additive amount of cement shown as the ratio of cement mass to dry mass of clay, and the minimum amount of cement for the strength mobilization.

By a series of cement-mix tests of the three marine clays, the bilinier relations between q_u and C were found and the minimum additive amount of cement C_0 were obtained as shown in Table 2. Fig.2 shoes the relationship beteen q_u and the *effective additive rate of cement,* ($C - C_0$) of the three marine clays. As shown in Figure 2, when the effective additive rate is used, the strength mobilization charcteristics with cement addition of the three clays is almost same. In this study, the effective additive rate of cement ($C - C_0$) is used as a parameter of cemment addition.

The procedure to prepare the clay samples with a small amount of cement is as follows:

1)The reconstituted clay slurry is made with the initial water contents of 1.5 times liquid limit of clay.

2)The clay slurry is reserved in the refregirator under the temperature of 1-3C. The temperature controll was carried out to make the chemical reaction of mixed clay slow and to produce a uniform cemented structure.

3)The clay and the cement milk were mixed by an erectric mixer for 30 minutes. The additive amounts of cement C of the three clays are listed in Table 2.

4)The mixed clay was filled in to the consolidation mould for consolidation and cured in the room temperature (20° C).

5)Hiroshima Port clay was consolidated by the consolidation pressures 49, 98 and 192 kPa with the curing time of 1, 3, 7 and 14 days. Fukuyama Port clay and Tokyo Bay Haneda clay were consolidated by the consolidation pressures 49 kPa with the curing time of 3, 7 and 12 days.

6) At the final consolidation pressure of each test, the end of the primary consolidation was determined by the conventional $3t_e$ method, and the curing time is the time after the end of primary consolidation.

7) After the curing, the clay sample was demounted from the consolidation mould and the conventional oedometer test was carried out under the end-of-primary consolidation condition, where EOP was determined by the $\sqrt{t}$ method. The EOP loading condition was made to neglect the effect of cementation during the oedometer tests.

3 RESULTS OF E-LOG P CURVES OBTAINED BY EOP STEP LOADING CONSOLIDATION TESTS

3.1 *Apparent overconsolidation ratio and cement addition*

By adding a small amount of cement,the consolodation yield stress pc of three clays increased with the curing time. As the increase of pc is due to the cementation, the apperant overconsolidation ratio O.C.R. was determined as: p_c/(consolidation pressure,p_0). Fig.3 shows the apparent OCR with the curing time. As shown in Figure, when the effective additive rate of cement (C–C_0) is same as −1.6% or −0.6%, the OCR-curing time relationship of the three clays were almost same, respectively. When (C–C_0)= −0.6%, the apparent OCR were 2.0−3.0 with 3−12 curing days. When (C–C_0)= −1.6%,

Table 1 Consistency properties of marine clays

clay	w_L(%)	w_P(%)	I_P	ρ_S(g/cm^3)
Hiroshima Port	97.1	40.7	56.4	2.653
Fukuyama Port	99.0	45.0	54.0	2.693
Tokyo Bay Haneda	113.2	49.6	63.6	2.662

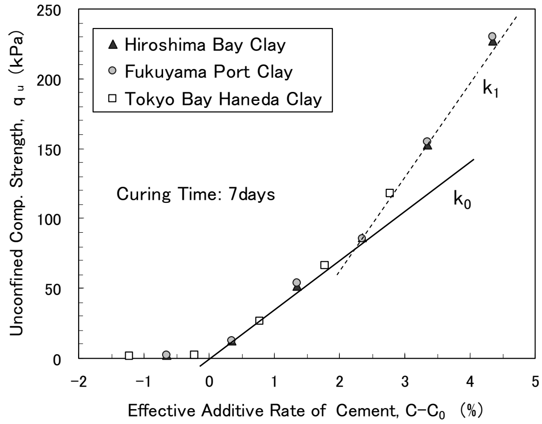

Figure 2 Strength and effective additive rate of Cement

Table 2 Minimum additive amount of cement for the strength mobilization C_0 and C of three clays

clay	C_0	C
Hiroshima Port	6.6 %	5.0%, 7.0%
Fukuyama Port	5.6 %	4.0%,5.0%
Tokyo Bay Haneda	7.2 %	5.6%

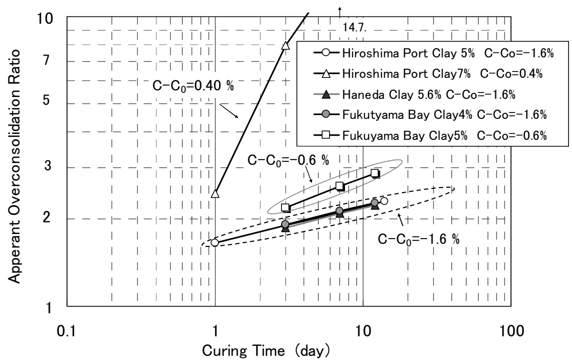

Figure 3 Apparent Overconsolidation ratio and curing time

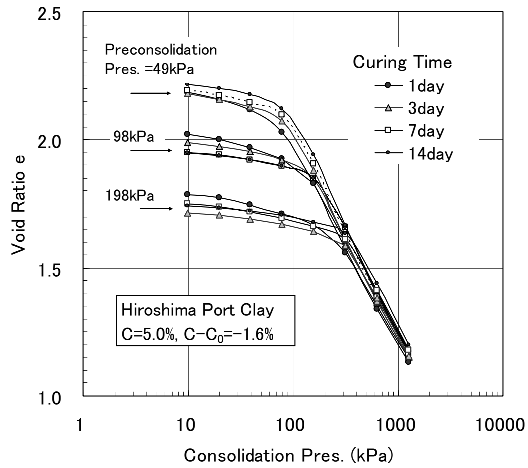

Figure 4 Change of e-logp curves and curing time (Hiroshima Port Clay, C=5%, C-C_0=-1.6%)

the apparant OCR were 1.7－2.2, and these values were close to those of undisturbed samples of Osaka Bay Pleistocene clays 5,000-1000,000 years old. When $(C—C_0)$=+0.4%, the apperant overconsolidation ratio O.C.R. of Hiroshima Port clay became more than 10 after 7 days curing. These results showed that, in order to reproduce the increase of p_c of aged marine clays due to cementation, the additive rate of cement must be much smaller than C_0, the minimum additive rate of cement for unconfined compression strength mobilization. and based on the results in this study, $(C—C_0)$=-1.6% seems to be good for reproduce the in-situ condition for about 2 weeks.

3.2 *e-log p curves of three marine clays with additive cement rate of* $(C－C_0=－1.6\%)$

Fig.4 shows the *e*-log *p* curves of Hiroshima Port clay which was mixed with 5% cement (additive cement $(C－C_0=－1.6\%)$ and consolidated and cured 1, 3, 7, 14 days under the consolidation pressure p_0=49kPa , 96 k Pa and 192 k Pa, respectively. As longer the curing time, the void ration in the normally consolidated resion became larger and it means the struvture of high water content were formed by the cement addition. However, the change of C_c as shown in Osaka Bay Pleistocene clay in Figure 1 were not shown in Fig.4.

Fig.5(a) are a e-log p curves of Fukuyama Port clay which was mixed with 4% cement (additive cement $(C—C_0=－1.6\%)$ and consolidated and cured 3,7,12 days under the consolidation pressure p_0=49kPa. In Fig.5(a), the large compressibility, when the consolidation pressure exceeds the p_c, was clearly obserbed. The change of C_c was shown in Fig.5(b). The maximum value of C_c was 2.5 and C_c decreased with the increase of consolidation pressure and finally became 1.0, which was slightly larger than C_c of Fukuyama Port Clay with no cement addition.

Figs.6(a) and 6(b) shows the *e*-log *p* curves and the change of C_c of Tokyo Bay Haneda clay which was mixed with 5.6% cement (additive cement $(C－C_0=－1.6\%)$ and consolidated and cured 3,7,12 days under the consolidation pressure p_0=49kPa. The results were almost same as those of Fukuyama Port clays. The e-log p curves and change of C_c of the two clays were similar with those of undisturbed Osaka Bay Pleistocene clays shown in Fig. 1.

4 SEDIMENTATION COMPRESSION RELATIONSHIP OF CLAY WITH CEMENTATION EFFECT

The important characteristics of aged-cemented clay is to have a structure with high water content. It is known that the rate of sedimentation of coastal marine clays were from 0.1－10mm per year. When Osaka Bay Pleistocene clay sedimented slowly for 20,000-200,000 years, it is considered that the self weight consolidation of clay deposits with the sedimentes and the cementation due to a small amount of cementing materials in clay take place simultaneously.

To reproduce the above sedimentation process, the constant-rate of consolidation pressure increase consolidation test was carried out with Hiroshima Port clay which was mixed with 5% and 7% cement (additive cement $(C－C_0=－1.6\%$ and +0.4%, respectively) . In this test, the increment of consolidation pressure .Δp was fixed as 28kPa, and the consolidation pressure was increased from p=9.8kPa to p=392kPa with 15 steps. The consolidation duration of each step was 3, 6 and 12 hours. After the consolidation pressure reached to 392kPa , step loading consolidation test was carried out with p=589, 869, 1280 kPa under the EOP condition.

Fig.7 shows the relationship between specific volume f=1+e of clay with the effective consolidation pressure p.As shown in Fig.7, the larger the additive rate of cement and the slower the loading step, the specific volume f at the same effective consolidation pressure became larger. This means that a structure of high void ratio is formed when the clay contain a cementing

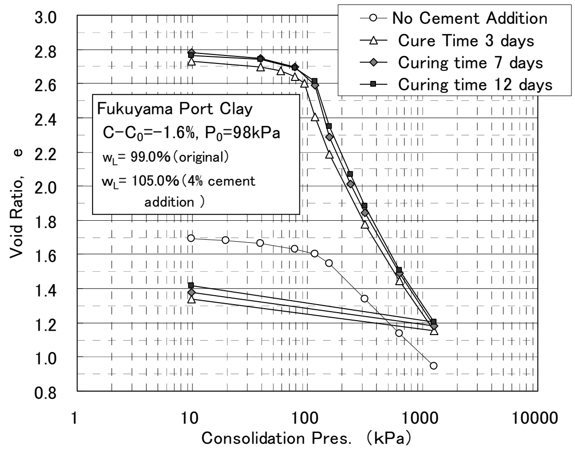

Figure 5(a) e-log p curves (Fukuyama clay, C-C_0=-1.6%)

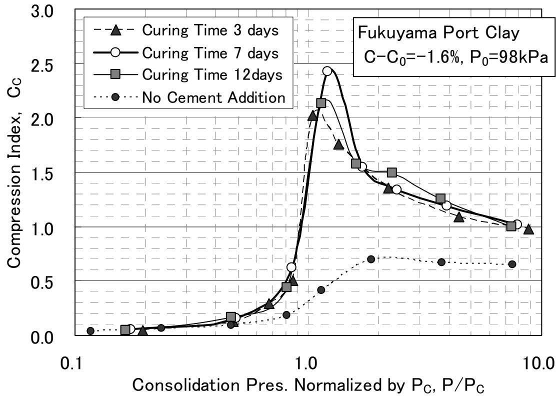

Figure 5(b) Compression Index and consolidation pressure (Fukuyama Port Clay, C-C_0=-1.6%)

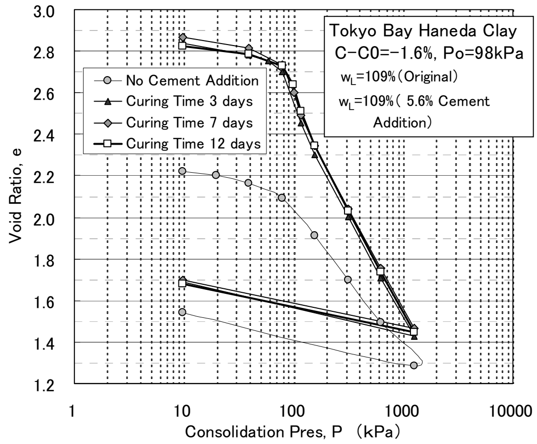

Figure 6(a) e-log p curves (Haneda clay, C-C_0=-1.6%)

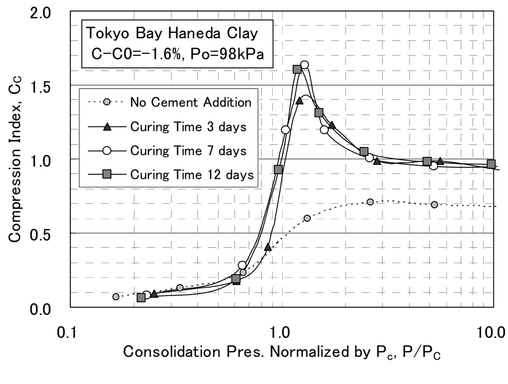

Figure 6(b) Compression Index and consolidation pressure (Haneda Clay, C-C_0=-1.6%)

agent and the sedimentation is slow enough for the cementation effects to mobilize strength.

Tsuchida (1991) proposed the standard compression curves SCC, which shows the sedimentation compression relation of general marine clays, based on the analysis of a number of *e*-log *p* curves of marine clays. The standard compression curve gives the void ratio-consolidation pressure relation of clay for an initial void ratio condition. In SCC, the normalization of void ratio of different soils is carried out to use the specific volume index defined as follows:

$$I_{sv} = \frac{\ln f}{\ln f_L} \tag{2}$$

where $f = e + 1$, is a specific volume of clay , and f_L is a specific volume of clay at the liquid limit.

Fig.8 shows the SCC for the initial void ratio of 1.5-2.0 e_L and the in-situ specific volume indexes I_{sv0} were plotted to the effective overburden stress σ_{v0}' at the sites of Kansai International Airport before the construction. As shown in Fig.8, Osaka Bay Pleistocene clay was deposited with much higher void ratio from the SCC with no aging effects. In Fig.9, the results in Fig.7 were plotted in I_{sv}-σ_{v0}' relation. As shown in Figure 9, by addition of cement, the *f* - log *p* relation moved upper direction from SCC. Comparing Fig.9 with Fig.8, it seems that the reproduction of high initial void ratio condition of Osaka Bay Pleistocene clays was made by using the conditions of the additive rate of cement 5% and the consolidation pressure increment 28kPa per 12 hours. Further, the structure can be broken as the aged clays, by the rapid increase of consolidation pressure exceeding the p_c.

5 CONCLUSIONS

In order to reproduce the compression and sedimentation properties of aged marine clays in laboratory, a small amount of portland cement was added to three marine clays. By carrying out a series of consolidation tests for the cement added clays, the following conclusions are obtained:

1) When the cement content of $(C_0 - 1.6)$% was added to the clay slurry of $1.5w_L$ water content and the clay was consolidated one-dimensionally by increasing the consolidation pressure up to 50kPa, the quasi-overconsolidation characteristics of natural marine clays of 5,000-50,000 years old were reproduced in laboratory.
2) The cement-added clays showed the typical shape of e-logp curve of aged clays, indicating the large compressibility immediately after the overburden stress exceeds the consolidation yield stress.
3) The constant-rate of pressure increase consolidation tests of Hiroshima Port clays were carried. The e-log p relationship obtained by the consolidation test of $(C_0 - 1.6)$% cement addition and the stress rate of 28kPa/12hour almost agreed well with the normalized void ratio-effective overburden stress relationship of Osaka Bay Pleistocene clays.

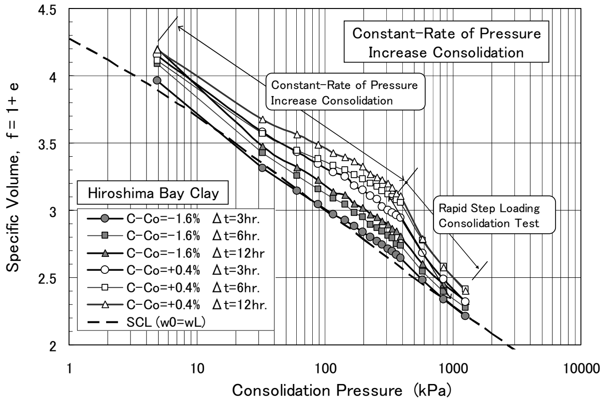

Figure 7. f-log p relation of Hiroshima Port clay with different rates of increases of consolidation pressure.

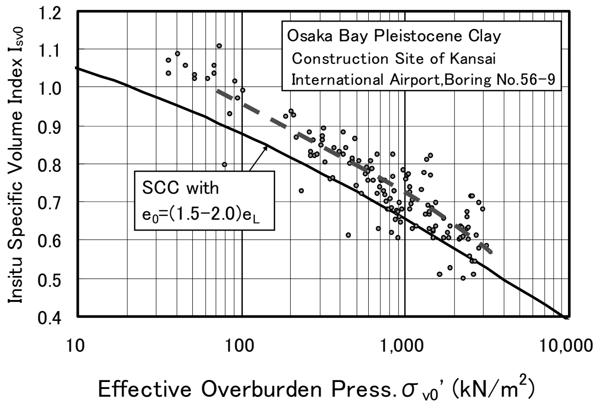

Figure 8 Relationship between I_{sv0} and σ_{v0}' at the site of Kansai International Airport (B.H. 56-9)

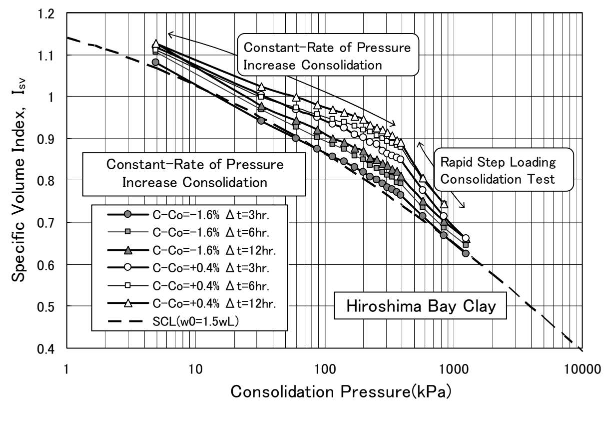

Figure 9 I_{sv} – log *p* relationship of Hiroshima Clay of (C-C_0= -1.6% and +0.4%) with different rates of increases of consolidation pressure.

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