International Journal of GEOMATE, Nov., 2018 Vol.15, Issue 51, pp.132-139
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.51.24275
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

SEALING GEOMATERIAL FOR COASTAL DISPOSAL FACILITY USING MARINE CLAY WITH THE ADDITION OF A SMALL AMOUNT OF CEMENT

Ooki Kurihara[1], Yoshito Takaoka[2], *Takashi Tsuchida[1], Takuya Shiraga[1], Ryota Hashimoto[1], and Takahiro Kumagai[3]

[1] Graduate School of Engineering, Hiroshima University, Japan; [2] Newjec Inc., Japan; [3] Penta-Ocean Construction Co., Ltd., Japan

*Corresponding Author, Received: 19 April 2018, Revised: 15 May 2018, Accepted: 7 June 2018

ABSTRACT: For secure construction and operation of a coastal waste disposal facility on a sandy seafloor, the proper bottom sealing material is one of the controlling factors. The conventional sealing material cannot mobilize enough strength against the load by covering soil and landfilling, and the ordinary cement-treated clay also has a drawback of crack generation due to shear deformation. To overcome these disadvantages of the conventional materials, the clay with the addition of a small amount of cement (CASC) was proposed as a new sealing geomaterial. Since the cement content of CASC is about 2-4%, which is lower than the minimum cement content required for strength mobilization of general cement-treated clay, it is expected to keep ductile property after the long-term consolidation. To examine the performance of CASC, a series of experimental studies (vane shear test, consolidation test, and hollow cylinder torsional permeability test (HCTPT)) was conducted for Tokuyama Port clay. The vane shear tests proved that CASC exhibits the strength development up to 3 kPa under unconsolidated condition after curing. The consolidation tests showed that the cement addition reduces the compressibility of the clay, and consequently, relatively large void ratio induces the increase in hydraulic conductivity, but CASC still could satisfy the sealing requirement. The HCTPTs revealed that hydraulic conductivity of CASC does not increase even if large shear deformation is applied while the lean-mix cement-treated clay shows permeability increase due to the crack. Considering above results, CASC was concluded to be a feasible option for the artificial sealing.

Keywords: Sealing Geomaterial, Cement, Permeability, Marine Clay, Waste Disposal Facility

1. INTRODUCTION

The waste disposal facilities have been constructed at coastal areas in Japan [1], because of difficulties in obtaining necessary sites in the land. In order to ensure environmental safety, the facilities have been constructed based on the technical criteria [2]. For the sealing layer for waste disposal facilities, the following technical conditions are required by Waste Management and Public Cleansing Law [3].

a) Continuous soil layer of 5.0 m or thicker with a hydraulic conductivity less than 10^{-7} m/s or a layer with sealing effect equivalent to or higher than the former.
b) An impermeable sheet underlay by 50 cm thick material such as clay having hydraulic conductivity equal to or less than 10^{-8} m/s.
c) An impermeable sheet underlay by 5 cm or thicker layer of asphalt or concrete having hydraulic conductivity equal to or less than 10^{-9} m/s.
d) A covering layer of non-woven fabric to be covered with two independent impermeable sheets.

To construct waste disposal facilities on the sandy seafloor, the studies on sealing geomaterial in the maritime environment have been carried out by several researchers [4]- [5]. The first waste disposal facility using the sealing geomaterial was constructed in the Seto Inland Sea in Japan [6]. Fig. 1 shows the cross-section and the picture of Sangawa Tobu waste disposal facility for industrial waste in Ehime Prefecture, Japan, in 2008 [6]. As shown in Fig. 1, a sealing layer with a thickness of 2 m was constructed on the seafloor, and the sealing geomaterial, a marine clay-bentonite mixture, was placed by tremie pipes. As shown in the right-side of Fig. 1, a steel pipe of 8 inches (20cm) diameter was used as tremie pipe, and two tremie pipes were attached to a guide pipe suspended by an 80-m crane. The position of the placement was determined by GPS and the lower end of tremie pipe was pushed into the placed clay layer to prevent water pollution.

The thickness of the sealing layer was decided as being equal to or greater than the equivalent thickness of “the soil layer of 5 m or thicker with hydraulic conductivity equal to or less than 10^{-7} m/s” which is mentioned in a), above. In order to ensure

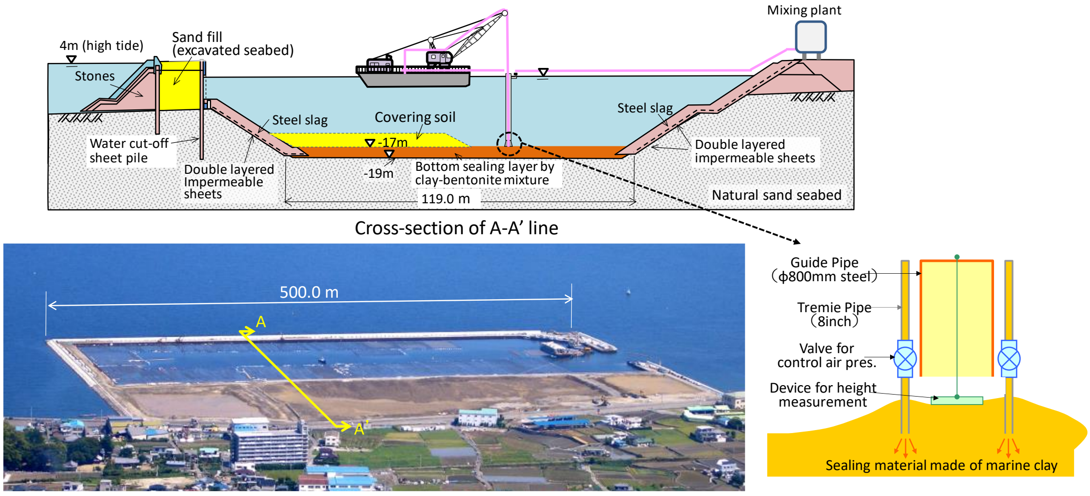

Fig. 1 Cross section of Sangawa Tobu waste disposal facility and the picture at construction work of sealing layer [6]

the fluidity at the placement, the water content of the sealing geomaterial was adjusted to approximately 1.5 times the liquid limit of the clay-bentonite mixture in a mixing plant.

Since the lift pressure acts on the sealing layer due to the water level difference between the inside and the outside of a disposal facility, it is necessary to construct a covering soil layer on the sealing layer for the stabilization and the safe waste filling. During the construction of the covering layer, it should be cared not to cause the sliding failure in the soft sealing layer. In the Sangawa Tobu case, a gelling agent (liquid glass) of 20 kg/m^3 was added to the sealing material in order to give a shear strength of 1 kPa and geotextile was further laid on the surface layer of the geomaterial for the reinforcement. Steel slug and sand were divided into 4 layers to construct a covering soil layer of 2.85 m in total.

As mentioned above, following 2 properties are required for the bottom sealing geomaterial;

1) to have a shear strength necessary to prevent the sliding failure during the construction of the covering soil layer and the subsequent filling process of the wastes.
2) to keep ductile property and to be deformable to external forces after completion of the construction in order to maintain sealing performance, that is, the low hydraulic conductivity.

The shear strength of the artificial geomaterial at Sangawa Tobu waste disposal facility was about 1 kPa, which was narrowly enough because the dumped wastes were discharged from a paper mill and the submerged weight of wastes was as extremely light as 1.2 kN/m^3. However, in the case of general wastes whose submerged weights are ranging from 5 to 8 kN/m^3, the necessary shear strength of sealing geomaterials becomes 3-4 kPa. Fig. 2 shows the strength development of slurry of

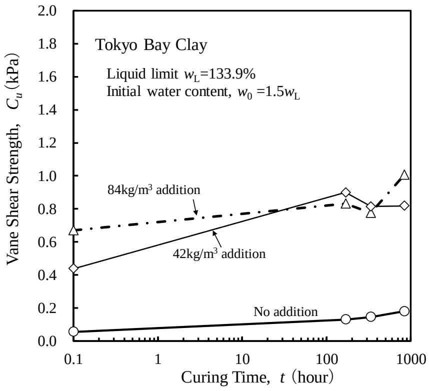

Fig. 2 Strength of Tokyo Bay clay slurry with the addition of liquid glass

Tokyo Bay clay by addition of liquid glass. The initial water content of the clay was 1.5 times the liquid limit, which is the same as the case of Sangawa Tobu disposal facility. As shown in Fig. 2, by adding liquid glass, the shear strength increased from 0.1 kPa to 0.8-1.0 kPa, but the strength increases up to 3-4 kPa cannot be expected with the long curing time.

In this study, the effect of adding a small amount of cement to clay slurry is discussed to achieve the minimum required strength of sealing geomaterial. The general cement-treated clay utilized in the construction usually shows the shear strength of 100 kPa or more. If the cement treated clay is used as a bottom sealing layer, the construction of covering layer will be easier than the case of Sangawa Tobu disposal facility because of the large strength. However, it was reported that cracks were generated in the cement-treated soil accompanied with the deformation forced by the external forces, and the hydraulic conductivity of sealing layer was increased due to the cracks [4].

Fig. 3 shows the schematic relationship between the added amount of cement (relative to the dry mass of clay) and unconfined compression strength with curing time. As shown in Fig. 3, the strength sharply increases, when the added amount of cement exceeds a certain value (minimum cement content), however, when the amount is less than that value, the strength development is not obviously observed. Udaka et al. [9] and Tsuchida et al. [10] called the cement-treated marine clay with smaller cement content than the minimum cement content "Clay with the addition of a small amount of cement (CASC)." They showed that CASC exhibits mechanical properties similar to aged natural clays, being different from the ordinary cement-treated soil. Although the properties of cement-treated clays have been extensively examined by many researchers [7]-[8], the study on CASC is very few.

In this study, the applicability of CASC to an artificial sealing geomaterial for the coastal disposal facility was studied. The sealing material requires to have enough strength development at the early stage of construction and to have the ductile property to maintain sealing performance in a long time. Using CASC sample made by high plastic marine clay, the strength development characteristics and the change in hydraulic conductivity after large shear deformation were investigated through the vane shear test, consolidation test, and the hollow cylinder torsional permeability test [11].

2. EXPERIMENT METHODS

2.1 CASC samples and the strength development of CASC

In this study, dredged Tokuyama Port clay (liquid limit w_L of 111.6%, soil particle density of 2.647 g/cm^3) and ordinary Portland cement were used for making CASC sample. The definition of CASC is based on the concept of the minimum cement content for cement-treated clay proposed by Udaka et al. [9]. Fig. 4 is the relationship between the added amount of cement (relative to the dry mass of clay) and unconfined compression strength of Tokuyama Port clay. As shown in Fig. 4, the c_0 for Tokuyama Port clay determined by Udakas' method, which was defined as the intersection of the horizontal axis (cement content) and the linear regression line, was 5%. Therefore, in this study, the cement-treated clay whose cement content is less than 5% is CASC.

Fig. 5 shows the relationship between vane shear strength and curing time of CASC of Tokuyama Port clay (the cement content is 2.0%, 3.0%, and 4.0%), the initial water content of which were 1.5w_L. After sufficiently mixing, the sample was sealed to prevent drying, and the strength was measured by a vane shear test at the predetermined periods. In Fig. 5, the strengths of Tokuyama Port clay without cement addition are also indicated for comparison. The strength increase at 672 hours without cement addition was 0.23 kPa (from 0.18 kPa to 0.41 kPa), which was caused by thixotropy. On the other hand, the CASC exhibited strength development from 0.4 kPa (just after mixing) to approx. 2.0 kPa (672 hours curing) and 2.5-3.0 kPa (2160 hours curing). It should be noted that the strength development behaviors were almost identical independent of the amount of cement content.

As described above, the CASC of Tokuyama Port clay showed the strength development up to about 3 kPa, which is enough for secure

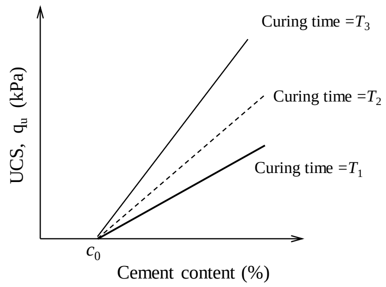

Fig. 3 The relationship between added amount of cement and unconfined compression strength

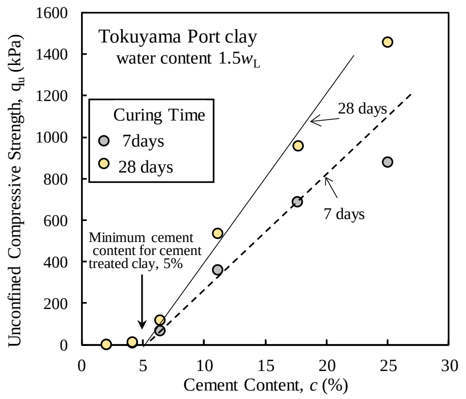

Fig. 4 Unconfined compressive strength with cement content (Tokuyama Port clay, curing time is 7 and 28 days)

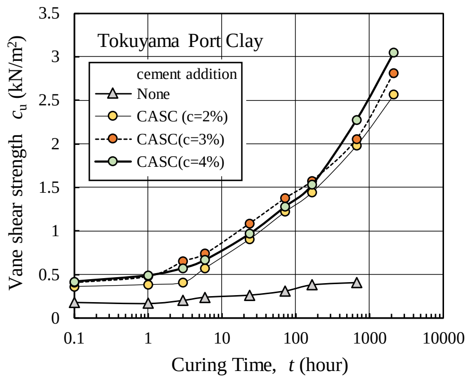

Fig. 5 Shear strength mobilization with time (Tokuyama Port clay and CASC)

construction of the sealing layer. Therefore, from the viewpoint of strength, the use of the CASC would be a feasible option in the construction of the coastal waste disposal facility. The experiment programs were made to study the hydraulic conductivity of CASC with consolidation and the change of hydraulic conductivity after large deformation.

2.2 Consolidation Test of CASC

To investigate the influence of the addition of a small amount of cement on the hydraulic conductivity, a series of consolidation tests was conducted, and the hydraulic conductivity was estimated. The specimens were the cement-treated Tokuyama Port clay (initial water content ratio: $1.5w_L$), with the cement content of 2.0% and 4.0%. After the mixing, the specimen was filled into a consolidation ring with a height of 20 mm and a diameter of 60 mm, and the curing was carried out for 7 days in the testing apparatus. Then, a step loading consolidation test with 1-hour loading time was conducted for eight consolidation stresses from 4.9 kPa to 627.2 kPa with consolidation stress increment ratio $\Delta p/p$ = 1. For each consolidation stress, the end of primary consolidation was judged by the $\sqrt{t}$ method. For comparison, the tests were conducted for Tokuyama Port clay without cement addition as well.

2.3 Hollow Cylinder Torsional Permeability Test

For the long-term secure operation of the coastal waste disposal facility, high ductility that enables to follow the deformation of the seafloor and the wastes is an important property for the sealing geomaterial. The hydraulic conductivity of the sealing layer must be kept sufficiently small even if the large shear deformation is caused by the external forces (e.g. earthquakes). In this study, the permeability characteristics of CASC sample of Tokuyama Port clay after applying the large shear deformation was investigated by the hollow cylinder torsional permeability test (HCTPT), which was developed by one of the authors [11]. Fig. 6 shows the structure of HCTPT apparatus. The device is designed based on the standard type of hollow cylinder torsional shear test described in the standard of Japanese Geotechnical Society (JGS 0551) [12], and two porous stones and the pipes are additionally installed to measure the hydraulic conductivity (see Fig. 7).

In the test procedure, the specimen is firstly consolidated in K_0 condition with the effective axial consolidation pressure of 150kPa and the back pressure of 100 kPa. After the completion of consolidation, the torsional shear strain was given

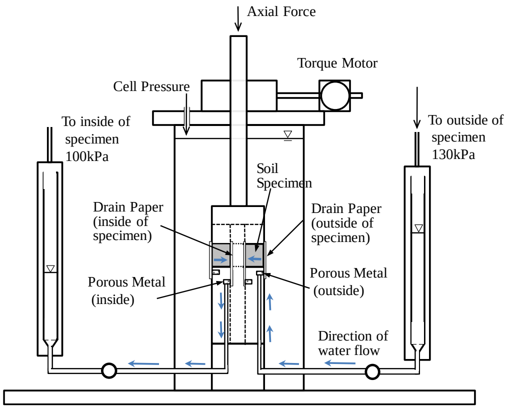

Fig. 6 Hollow cylinder torsional permeability device

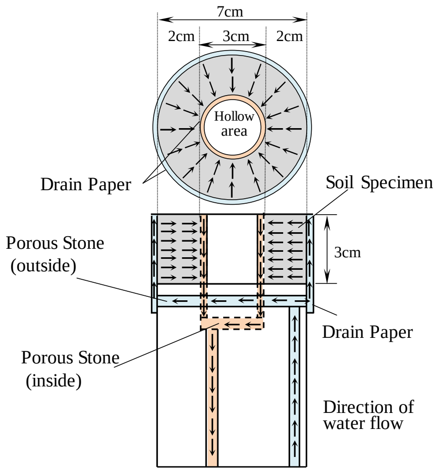

Fig. 7 Water flows around the specimen in HCTPT

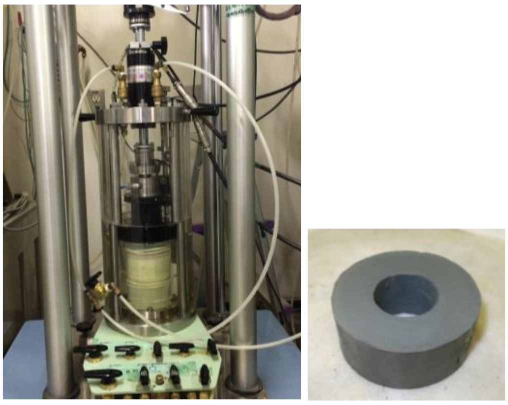

Photo 1 HCTPT and CASC specimen

in undrained condition. After the shear deformation, the permeability test was carried out by applying the water pressure difference of 30 kPa between the outer and the inner surface of the specimen. The direction of the water flow in the permeability test is illustrated in Fig. 7, where the arrows show the water flow. Water comes from a burette connected with the outer porous stone to another burette

Table 1 Mixing conditions and experimental conditions of samples

	Cement content (%)	Initial water content w_0(%)	Curing time and consolidation pres. in preparation (CASC)*	Consolida-tion Pres. (kPa)	Largest shear strain (%)	Unconfined compressive strength (LCTC)
Clay with the addition of a small amount of cement (CASC)	3%	1.5w_L	3 days under 49 kPa	150	20%	
			7 days under 49 kPaa	100	20%	
	4%	1.5w_L	3 days under 49 kP	150	20%, 5%×4**	
			7 days under 49 kPa	150	20%	
Lean-mix cement-treated clay (LCTC)	15%	2.0w_L	4 days	20	20%	151 kPa
			7 days		20%	220 kPa
	10%	1.5w_L	3 days	150	20%, 5%×4**	205 kPa

* Curing time after the completion of consolidation. **Sample was given 20% strain with 4 steps, 5%,10%,15% 1nd20%

connected with the inner porous stone. By recording the time history of the water flow, hydraulic conductivity of the specimen in the horizontal direction, which means parallel to the sheared plane, was measured. Photo 1 shows the HCTPT apparatus and the specimen of Tokuyama Port clay with small amount cement addition. The outer diameter, inner diameter and the height of specimen are 7cm, 3cm and 3cm, respectively.

Table 1 shows the mixing conditions and experimental conditions of samples conducted in this study. The CASC specimens were prepared with the conditions that the cement content was 3% or 4% and the initial water content was 1.5 times the liquid limit w_L. For comparison, the same test was carried out for the cement-treated clay with relatively high unconfined compressive strength (150~200 kPa). These specimens are called "lean-mix cement-treated clay (LCTC)" hereafter because their cement contents are smaller than that of the general mixing condition of the cement-treated soil. The experiments of the LCTC were carried out for two samples with different mixing conditions; a cement content of 15% and an initial water content of 2w_L, and a cement content of 10% and an initial water content of 1.5w_L.

For preparing the CASC specimens, a slurry sample mixed with cement with a small amount of cement was placed in a consolidation container having a diameter of 12 cm and a height of 25 cm and subjected to preliminary consolidation at three stages of 12.3 kPa, 24.5 kPa, and 49 kPa. The consolidation ends of the 1st and 2nd stages were judged by the $\sqrt{t}$ method, and that of the 3rd stage was judged by the 3t method. The end of consolidation determined by the 3t method was regarded as the start time of curing, and curing was conducted for a predetermined period of time. For preparing the LCTC specimens, a slurry sample was filled in a mold having a diameter of 15 cm and a height of 6 cm and cured for a predetermined time in the water.

In K_0 consolidation, CASC was subjected to K_0 consolidation up to the prescribed consolidation pressure by adjusting the axial pressure and lateral pressure while observing lateral strain. For the LCTC, the axial pressure and the lateral pressure were adjusted to keep K_0 value (0.40) of the reconsolidated Tokuyama Port clay during the test.

3. RESULTS AND DISCUSSION

3.1 Hydraulic conductivity of CASC measured by consolidation test

Fig. 8 shows the relationship between consolidation pressure and hydraulic conductivity. Hydraulic conductivity of the CASC was 2 to 4 times larger than that of no cement added clay. The increasing rate of hydraulic conductivity tends to be high under small consolidation pressure range and decreases as the consolidation pressure increases. The e-log p curve is shown in Fig. 9. With the addition of a small amount of cement, the bonding structure was formed in the clay, and the higher void ratio was maintained at the same consolidation pressure. This typical property of the CASC was also shown in Udaka et al. [9] and Tsuchida et al. [10]. Fig. 10 shows the relationship between the hydraulic conductivity and the void ratio. Since the relationship between them is almost constant regardless of cement addition, it is clear that the cause of the high hydraulic conductivity of the

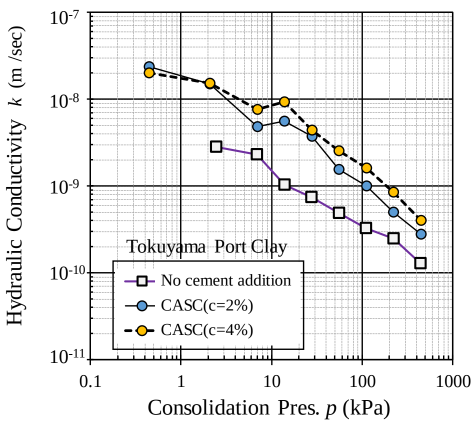

Fig. 8 Consolidation pressure – hydraulic conductivity relationship of Tokuyama Port clay and CASC

CASC is an increase in the void ratio due to the addition of a small amount of cement.

As described above, the higher void ratio of the CASC made by cement addition induced the increase of hydraulic conductivity. Therefore, this property should be considered in the design process. It should be noted that the initial water content of the clay dealt in this study was only 1.5w_L from the viewpoint of ensuring fluidity when constructing the sealing layer by underwater placing. However, when the hydraulic conductivity of CASC made of 1.5w_L water content does not satisfy the hydraulic conductivity requirement, in order to satisfy the requirement, it may be necessary to modify a construction method to compensate for the lack of fluidity and reduce initial water content.

3.2 Results of HCTPT

3.2.1 Shear strength properties of CASC

Fig. 11 shows the change in shear stress and pore water pressure of CASC. Fig. 11 also shows the result of the specimen of Tokuyama Port clay consolidated at 150 kPa and sheared. The legend in Fig. 11 shows the cement content c and curing time. Although the no cement added specimen showed monotonous strain hardening behavior, the CASC showed the strain softening curves after reaching the peak strength. The stepwise sheared specimen (5% × 4) showed the increase of the peak shear strength compared with the continuously sheared one because of the consolidation due to drainage after shearing. The ultimate shear stress of c = 3%, 7 days cured specimen was larger than that of the others, but there was no significant difference of shear stress at the first peak. The final strength almost agreed with the specimen of Tokuyama Port clay with no cement addition, excluding c = 4%, 3 days cured, sheared at every 5% specimen and c = 3%, 7 days cured specimen. The pore water pressure increment of each specimen of CASC almost agreed with the specimen of Tokuyama Port clay. From these facts, it is considered that when a small amount of cement is added, the initial strength is obtained as shown in Fig. 5 in the unconsolidated state, but after the consolidation (reclamation), the CASC indicates almost same mechanical behavior as the clay without cement addition.

3.2.2 Hydraulic conductivity change due to large shear deformation

Fig. 12 shows the relationship between the shear strain applied to the specimen and the hydraulic conductivity obtained by the permeability test after shearing. The hydraulic conductivity at shear strain 0% is the value measured before shearing. The LCTC has a higher hydraulic conductivity than CASC. This is because LCTC has low compressibility and the void ratio hardly decreases

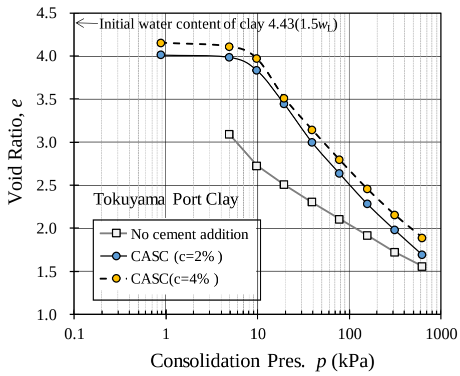

Fig. 9 *e*-log *p* relationship of Tokuyama Port clay and CASC

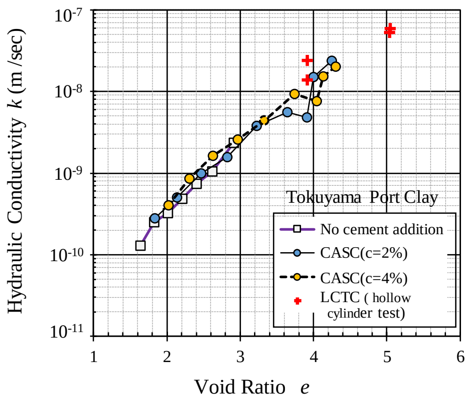

Fig. 10 Void ratio – hydraulic conductivity relationship of Tokuyama clay with no cement addition, CASC, and LCTC

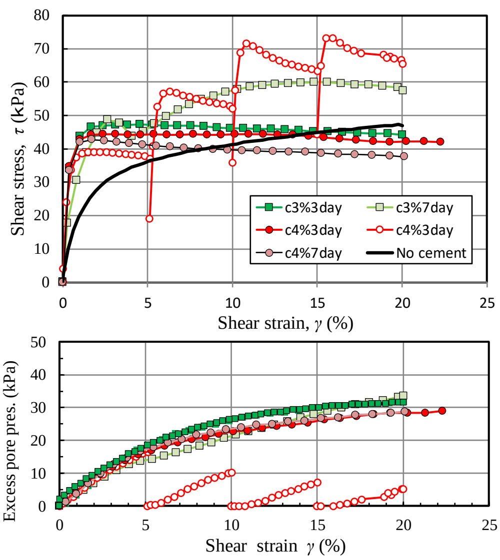

Fig. 11 Stress-strains curve and pore pressure-strain curves of CASC specimens

during the consolidation process, on the other hand, the CASC shows relatively small void ratio due to consolidation. The hydraulic conductivity of every specimen of LCTC after shearing was higher than that before shearing. On the other hand, in the case of CASC, hydraulic conductivity was almost the same or slightly decreased.

Fig. 13 compares the rate of change of hydraulic conductivity when the largest shear deformation was applied to the specimen. The change rate of hydraulic conductivity, X, is defined as follows.

$$X = \frac{k}{k_0} \tag{1}$$

Here, k_0 is the hydraulic conductivity before shearing (m/s), and k is the hydraulic conductivity after shearing (m/s).

In the case of the specimens of LCTC, the hydraulic conductivity after shearing was more than twice of that before shearing. Photo 2 is the specimen of LCTC after the test. The cracks caused by shear deformation were observed, and this is considered to be the reason why the hydraulic conductivity increased. Photo 3 shows the specimen of CASC, and no cracks were observed in all cases. The specimens, c = 4%, 3 days and 7 days cured, showed good agreement in the change rate of hydraulic conductivity with shearing. However, the change rate of hydraulic conductivity of the specimens, c = 3%, 3 days and 7 days cured, did not agree with each other, and this is thought to be due to the difference in consolidation pressure. When comparing specimens with c = 3% and c = 4%, the change rate of hydraulic conductivity of c = 4% was larger than that of c = 3%. This result showed that even if the difference in the cement content is small, the amount of cement affects the change rate of hydraulic conductivity. However, since the hydraulic conductivity did not exceed the value before shearing, these materials showed the ductile property after consolidation, and it is considered that it is possible to use a material with the cement content of c = 3-4% as a sealing material.

In the case of the stepwisely sheared specimen of LCTC, the hydraulic conductivity increased at the time of shearing at 5%, and the hydraulic conductivity was kept almost constant during the subsequent shearing steps 10, 15, 20%. This means that cracks occurred when sheared at 5% and the crack governed the permeability in the following tests. On the other hand, in the case of the stepwisely sheared specimen of CASC, the hydraulic conductivity slightly decreased due to shearing at 5% and 10% but did not change at 15% and 20%, and the increase in hydraulic conductivity was not observed.

From the above result, under the condition in this study, the hydraulic conductivity of CASC did not increase during the shear deformation. On the other hand, the hydraulic conductivity of the LCTC was greatly increased due to deformation, and there was a clear difference between them.

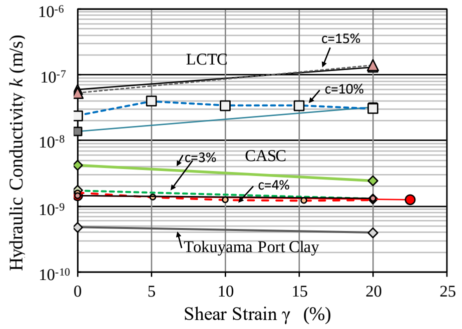

Fig. 12 Shear deformation and hydraulic conductivity after shear (CASC and LCTC)

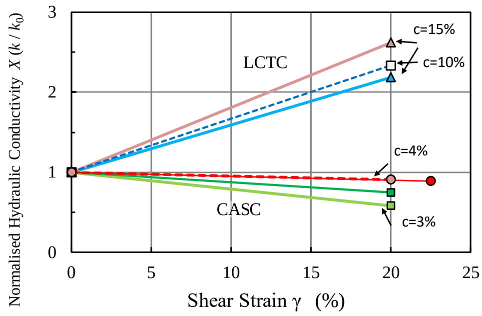

Fig. 13 Normalized hydraulic conductivity and shear deformation of CASC and LCTC

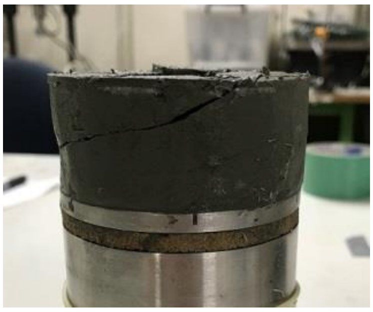

Photo 2 LCTC specimen after shear (cement content 15%, w_0=2w_L, 7 days)

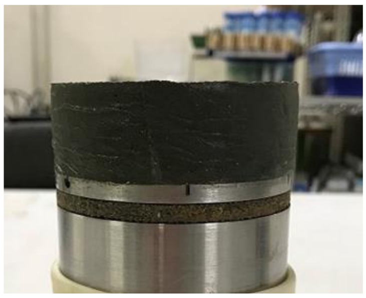

Photo 3 CASC sample after shear (cement content 3%, w_0=1.5w_L, 3 days)

4. CONCLUSION

For secure construction and operation of a coastal waste disposal facility on a sandy seafloor, the proper bottom sealing material is one of the controlling factors. The conventional sealing material cannot mobilize enough strength against the load by covering soil and filling of wastes. The ordinary cement-treated clay also has a drawback that crack generates due to shear deformation. To overcome these disadvantages of the conventional materials, the clay with the addition of a small amount of cement (CASC) was proposed as a new sealing geomaterial. Since the cement content of CASC is about 2-4%, which is lower than the minimum cement content required for strength mobilization of general cement-treated clay, it is expected to keep ductile property and adequate strength for construction. To examine the performance of CASC, a series of the experimental study (vane shear test, consolidation test, and hollow cylinder torsional permeability test (HCTPT)) was conducted for Tokuyama Port clay. The conclusion is summarized as follows.

1) With the addition of a small amount of cement, the clay of $1.5w_L$ water content showed the strength development about 3 kPa in unconsolidated condition with curing time. From the viewpoint of giving a strength necessary for construction, the addition of a small amount of cement can be a feasible choice instead of addition of liquid glass.
2) Because of the bonding structure formed in CASC, the compressibility of CASC is reduced compared to that of without cement addition. Thus, the CASC shows larger hydraulic conductivity than the clay without cement addition under the same consolidation pressure. It may be necessary to modify a construction method in order to compensate for the lack of fluidity and reduce initial water content.
3) Changes in hydraulic conductivity before and after shear deformation were examined by hollow cylinder torsional permeability test. In case of the lean-mix cement-treated clay (cement content of 10% and 15%), cracks occurred in the specimen by the 20% of the shear deformation, and consequently, hydraulic conductivity was increased. On the other hand, the hydraulic conductivity of the CASC decreased due to the shear deformation in all the cases, which is due to that the CASC kept the ductile property after the consolidation.
4) CASC in this study satisfied the requirements of sealing geomaterial on the strength development at the early stage and the ductile property after consolidation.

5. REFERENCES

[1] Osaka Bay Regional Offshore Environmental Improvement Center. (2015). http://www.osakawan-center.or.jp/ (in Japanese).

[2] Waterfront Vitalization and Environment Research Foundation. (2008). Manual of Design, Construction and Management on Seawalls for Controlled Waste Disposal (Revised Edition). (in Japanese).

[3] Prime Minister's Office and Minisy of Health and Welfare. (1977). Ministerial Ordinance that establishes technical standards relating to the final disposal site of general waste and final disposal site of industrial waste, Ministerial Ordinance No. 1. (in Japanese).

[4] Watabe, Y., Yamada, K., and Saitoh, K. (2011). Hydraulic conductivity and compressibility of mixtures of Nagoya clay with sand or bentonite. Geotechnique, 61(3), 211-219.

[5] Ueno, K., Yamada, K., and Watabe, Y. (2008). Proposal of sealing geomaterial for waste disposal sites in coastal area, Journal of Japan Society of Civil Engineers, G 64(2), 177-186. (in Japanese).

[6] Kawasaki, T., Yamada, K., and Ueno, K. (2009). Case Report of Sealing Geomaterials for Waste Disposal Sites in Coastal Area, Jiban to Kensetsu, 27(1), 187-194. (in Japanese).

[7] Uddin, K., Balasubramaniam, A.S., and Bergado, D.T. (1997). Engineering behavior of cement treated Bangkok soft clay. Geotechnical Engineering Journal, 28, 89-119.

[8] Horpibulsuk, S., Miura, N., and Bergado, D.T. (2004). Undrained shear behavior of cement admixed clay at high water content, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 130(10), 1096-1105.

[9] Udaka K., Tsuchida T., Imai Y., and Tang, Y. X. (2013). Compressive characteristics of reconstituted marine clays with developed structures by adding a small amount of cement, Journal of Japanese Geotechnical Society, 8(3), 425-439.

[10] Tsuchida T., Hirahara T., Hiramoto, S., and Udaka, K. (2014). Undrained shear characteristics of reconstituted and reconsolidated marine clays with addition of a small amount of cement, Journal of Japanese Geotechnical Society, 9(1), 71-84.

[11] Hsu, P. H., Katayama, Y., Tsuchida, T., and Athapaththu, A.M.R.G.(2015). Horizontal permeability of clay mixtures under large shear deformations, 5th I.C.G.C.M.E. , Osaka, Japan.

[12] Japanese Geotechnical Society. (2009). Method for torsional shear test on hollow cylindrical specimens of soil, JGS 0551-2009.