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Kasama, Kiyonobu
Graduate School of Engineering, Kyushu University

Zen, Kouki
Graduate School of Engineering, Kyushu University

Iwataki, Kiyoharu
Ministry of Land Infrastructure and Transport, Kyushu Regional Development Bureau Director

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HIGH-STRENGTHENING OF CEMENT-TREATED CLAY BY MECHANICAL DEHYDRATION

KIYONOBU KASAMA[i], KOUKI ZEN[ii] and KIYOHARU IWATAKI[iii]

ABSTRACT

A technique called the cement-mixing and mechanical dehydration method (CMD) as one of recycling techniques for soft clay slurry is developed. In order to evaluate the effectiveness of the CMD for increasing the strength of soft clay, a series of unconfined compression tests and several durability tests were performed together with the literature review of unconfined compressive strength in cement-treated soils. Moreover, a series of constant strain rate consolidation tests were also performed to evaluate the effects of cement content and dehydration speed on the permeability of cement-treated clay. The following conclusions are obtained: 1) Literature review and theoretical considerations on the shear strength of cement-treated soils show that an additional treatment for the purpose of increasing the density of cement-treated specimen is effective for increasing the shear strength of cement-treated soil. 2) The mechanical dehydration of soft clay with high pressure is accelerated by cement mixing, where the coefficient of consolidation of cement-treated clay increases as the cement content increases. 3) The high-strength specimen having the unconfined compressive strength of more than 20 MPa can be created from soft clay treated by the CMD with the cement content of over 20% and the dehydration pressure of 20 MPa.

Key words: cement, cement stabilization, dehydration, marin clay, recycle, unconfined compressive strength (**IGC**: D6/D10)

INTRODUCTION

Cement-treated soils (namely, cement mixed soils) have been developed in the field of geotechnical engineering, and cement-mixing has been widely utilized as a recycling technique for construction surplus soils, construction sludge, dredged materials and industrial wastes (e.g. Tang et al., 2001; Porbaha et al., 1999; Zou and Li, 1999). Tsuchida et al. (2001) reported basic engineering properties of cement-treated soils with lightweight additives, such as a foam or expanded polystyrol beads. The main factors affecting the shear strength of the cement-treated soils include the types and amounts of binder/cement (e.g., Terashi and Tanaka, 1981; Clough et al., 1981), physico-chemical properties of the in situ soil (Kamon and Katsumi, 1999), curing conditions (Consoli et al., 2000) and effectiveness of the mixing process (Larsson, 2001, Omine et al., 1998).

Cement-treated soils can be utilized for future practical applications in various fields of geotechnical engineering provided that the strength can be well-controlled with a wide range of the strengths. For example, Elkins and Thompson (1997) reported recycling facilities changing dredged materials into non-hazard ceramic granules, while Tay et al. (2002) presented the potential use of marine clay mixed with industrial sludge as concrete aggregate material. Netzband et al. (2002) introduced a recycling facility at Hamburg port in Germany where dredged material has been used beneficially as a sealing material in the construction of the dredged material disposal sites and also utilized as raw material in brick fabrication. Soft clay, when reproduced as a stronger type of soil comparable to concrete material, can be used for such construction materials as blocks, bricks and tiles.

From this background, a technique called the cement-mixing and mechanical dehydration method (CMD) as one of recycling techniques for soft clay slurry, construction surplus soil, etc. has been developed by the authors. In the CMD procedure, soft clay mixed with cement is dehydrated with high pressure for the purpose of increasing the strength. The purpose of this paper is to produce high-strength cement-treated clay having a comparable strength to concrete. First, a literature review is carried out to examine the maximum unconfined compressive strength of cement-treated soils and to clarify the sample preparation for increasing the strength. Then, in order to clarify the fundamental dehydration properties of cement-treated clay, a series of constant strain rate consolidation tests were performed as a function of

[i] Research Associate, Graduate School of Engineering, Kyushu University, Japan (kasama@civil.kyushu-u.ac.jp).
[ii] Professor, ditto.
[iii] Ministry of Land Infrastructure and Transport, Kyushu Regional Development Bureau Director, Japan.
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dehydration speed and cement content. Finally, in order to evaluate the effect of mechanical dehydration with high pressure on the unconfined compressive strength of cement-treated clay, a series of unconfined compression tests and durability tests were performed on soft clay specimens prepared as a function of cement content, dehydration pressure and dehydration mode.

LITERATURE REVIEW OF THE UNCONFINED COMPRESSIVE STRENGTH

The strength of cement-treated soils is in the intermediate range of magnitude between that of soil and rock. Therefore, not only the approach from the viewpoint of soil mechanics but also the rock mechanics' approach is needed in the evaluation of the strength of cement-treated soil. Since the cement-treated soil is combined with a stabilizer such as cement, it is needless to say that the strength is deeply dependent on the mix proportion and curing condition similar to concrete. The strength properties of cement-treated soils have been widely examined through unconfined compression tests which are favored due to their simplicity and ability to represent properties at low confining pressures. It is known that the unconfined compressive strength, q_u of cement-treated clayey soils is equivalent to the undrained shear strength at zero consolidation pressure similar to cohesive soil, while q_u of cement-treated sandy soil is equivalent to the drained shear strength at zero consolidation pressure as reported by Zen et al. (1990). Accordingly, measured q_u for cement-treated soil is considered to be shear strength under a different drain condition depending on the soil type. However, in order to collect a number of data for the strength of cement-treated soils, the magnitude of q_u is used as a reference strength to express the shear strength of cement-treated soils in this paper. The maximum q_u in cement-treated soils was investigated based on the literature review of the proceedings of 26th to 34th Japan National Conference on Geotechnical Engineering. Further, the relationships between the maximum q_u and the physical properties of an original soil before cement-mixing, cement content and sample preparation were also examined.

From the content of the proceedings, soil type, initial water content, wet soil density, plasticity index, weight ratio of cement to dried soil (called ''cement content''), cement weight per wet soil volume of 1 m^3 (called ''cement amount'') and curing period were examined together with the magnitude of q_u. Soil type was classified into gravel, sandy soil, cohesive soil, organic soil, volcanic cohesive soil, waste and unusual soil according to JGS-0051 (Japanese Geotechnical Society, 2000). Cohesive soil was classified into clay and silt if indicating liquid limit and plasticity index. Volcanic soil was classified into Kanto loam and Kuroboku (volcanic pumiceous black soil). As for unusual soil, Masado (decomposed granite), peat and diatom soil were selected.

Table 1 summarizes sample number, mean q_u, maximum q_u and the coefficient of variability of q_u, COV_{q_u}. It is observed that three of the largest mean q_u values are obtained in Masado, sandy soil and cohesive soil in order of value. COV_{q_u} except for gravel ranges form 0.6 to 1.6, which is much larger than that expected for the undrained shear strength of natural clays. Clay, volcanic soil and silt indicate high COV_{q_u} suggesting that the COV_{q_u} increases with decreasing grain size of original soil. As for the maximum q_u, 25 MPa, 23 MPa and 20 MPa are obtained in clay, Masado and sandy soil, respectively.

Table 1. Statistical value for unconfined compressive strength of cement-treated soil

Soil type		Number	Mean (MPa)	COV_{q_u}	Maximum (MPa)
Gravel		3	1.58	0.08	1.70
Sandy soil		97	4.77	0.89	20.00
Cohesive soil	Silt	57	1.92	1.41	11.50
	Clay	24	4.72	1.57	25.00
	Unknown	45	2.92	0.82	8.00
Organic soil		6	1.15	1.13	4.20
Volcanic soil	Kanto loam	57	1.86	0.96	6.00
	Kuroboku	11	0.26	0.85	0.87
	Other	22	0.63	1.50	4.00
Waste		18	3.49	1.20	18.00
Unusual soil	Masado	12	10.74	0.64	23.00
	Peat	10	0.43	1.10	1.75
	Diatom soil	4	3.24	0.61	5.50

COV_{q_u}: the coefficient of variability of unconfined compressive strength

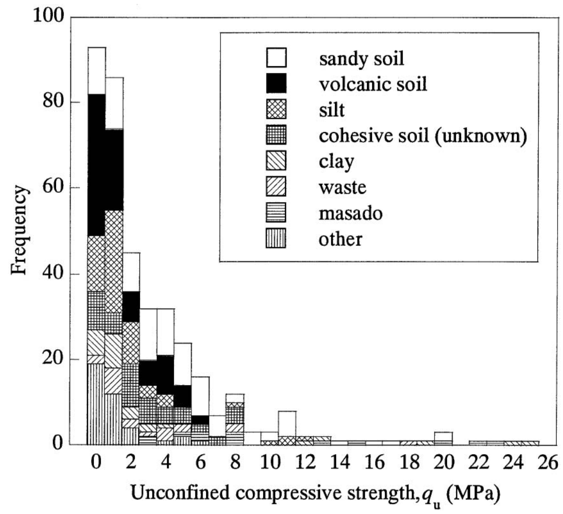


Fig. 1. Histogram of unconfined compressive strength

Figure 1 shows the histogram of q_u for all the samples. The results of gravel, organic soil, peat and diatom soil are shown in the category of ''other'' in Fig. 1. It shows that the frequency drastically decreases with increasing strength and about 90% of all data ranges less than 8 MPa. Comparing the strength in terms of soil type, sandy soil and Masado indicate larger strength suggesting that

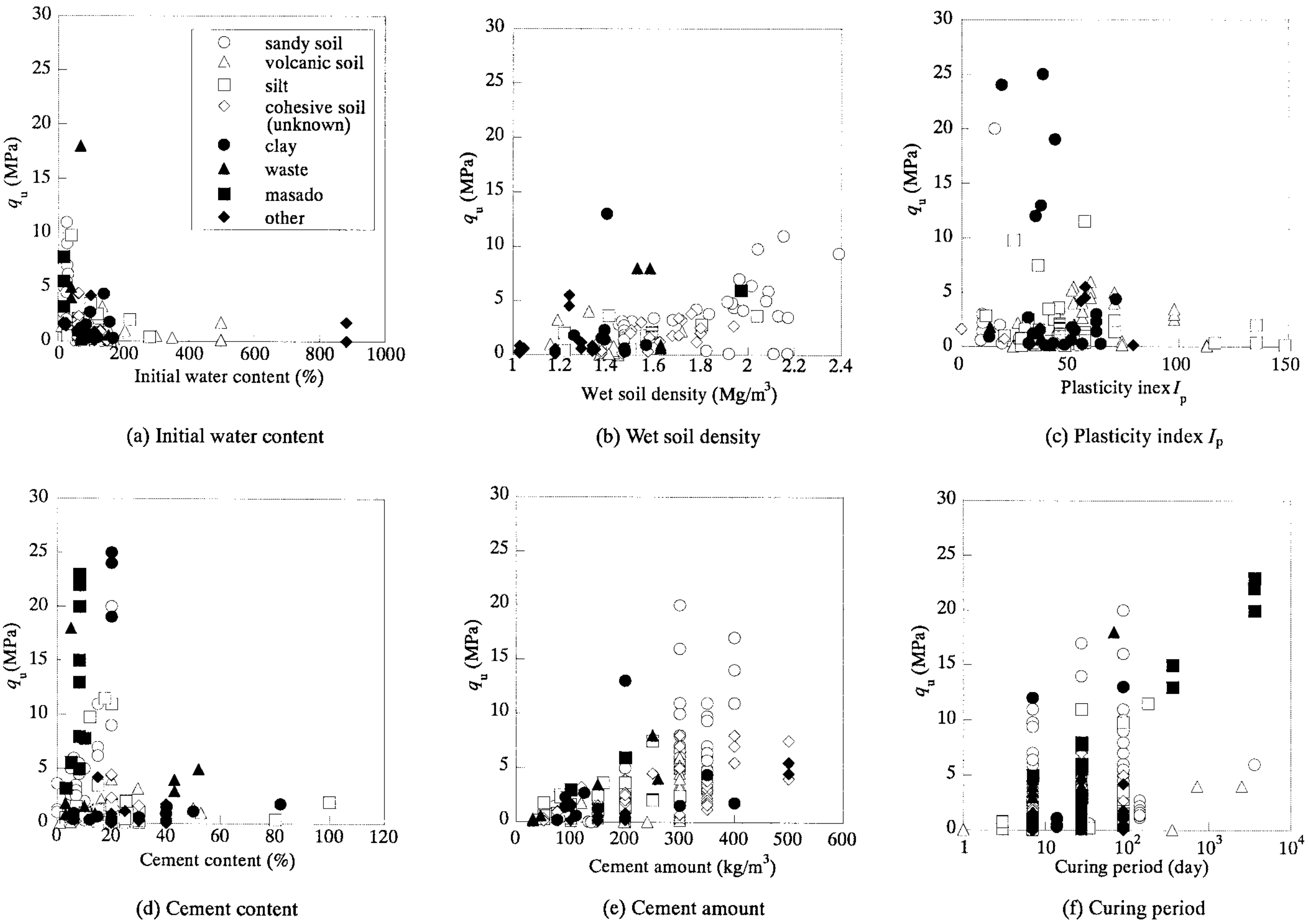


Fig. 2. q_u **against parameter related to cement-treated soil**

q_u of cement-treated soils generally increases with increasing grain size. Based on the results of literature review, q_u more than 20 MPa is defined as a high-strength, which is an objective strength obtained by the CMD in this paper.

Figure 2 shows the relationships between q_u and six indexes (initial water content, wet soil density, plasticity index, cement content, cement amount and curing period). It should be noted that there are some lacking indexes in data sets of q_u, even though cement content and cement amount are converted mutually as far as possible. The following findings were obtained from Fig. 2:

(1) q_u decreases with increasing initial water content, while most of the initial water contents are fewer than 200% (Fig. 2(a)). In addition, q_u increases with increasing wet soil density and the increase in the rate of q_u against wet soil density depends on the soil type (Fig. 2(b)). It can be concluded that q_u of cement-treated soils depends on the specimen density (water content), and also increases with increasing density irrespective of the soil type.

(2) q_u is not dependent on the plasticity index (Fig. 2(c)). q_u greater than 20 MPa is obtained in cohesive soil with the plasticity index of 10–50 and in sandy soil with the plasticity index of about 10.

(3) There is no strong correlation between q_u and cement content based on the results that high-strength is not obtained for specimens with the cement content of over 30% (Fig. 2(d)). In addition, as the cement amount showing a high-strength in Fig. 2(d) is roughly plotted to be around 100 kg/m^3 in Fig. 2(e), it can be seen that there is also no strong correlation between q_u and cement amount. From Figs. 2(d) and 2(e), q_u greater than 15 MPa was obtained in Masado with cement content of 8%, in clay with cement content of 20% and in sandy soil with cement amount of 300～400 kg/m^3. The current research suggests that it is possible to produce a high strength specimen irrespective of the soil type, cement content and cement amount.

(4) q_u increases with curing period (Fig. 2(f)). Especially, q_u for cement-treated Masado is still increasing beyond the curing period of 10 years.

In order to investigate the details for producing a high-strength cement-treated soil, Table 2 summarizes soil physical properties, cement compositions (cement content and cement amount), and sample preparations for cement-treated soils indicating the largest q_u values.

The cement-treated soil with the largest q_u value was Kawasaki clay (initial water content = 102.3%, ρ_s = 2.633 Mg/m^3, w_L = 71.8%, I_p = 37.4, sand content = 4%, silt

Table 2. Physical property of soil and sample preparation for maximum q_u

	Kawasaki clay	Masado	Toyoura sand*
q_u	25 MPa	23 MPa	20 MPa
Soil type	Clay	Unusual soil	Sandy soil
Cement type	Portland	Portland	Portland blast-furnace slag cement type B
Cement content	20%	8%	300 kg/m^3
Water content	102.3%	12.0%	39.5%
ρ_s	2.633 Mg/m^3	2.620 Mg/m^3	2.700 Mg/m^3
w_L	71.8%	35.7%	—
I_p	37.4	7.6	—
Gravel content	0%	48%	0%
Sand content	4%	38%	100%
Fine content	96%	14%	0%
Silt content	45%	—	0%
Clay content	51%	—	0%
L_i	10.9%	—	—
Curing condition	Under water	Standard curing condition**	Standard curing condition**
Curing period	28 days	10 years	91 days
Additional treatment	Consolidation by 10 MPa	Compaction with rammer of 2.5 kg	Consolidation by 0.1 MPa for 24 hours
Reference	Morita et al. (1992)	Mishima et al. (1993)	Nakama et al. (1998)

*: Toyoura sand mixed with diatom soil by 20% in dry weight
**: Temperature = 21 ± 3°, Humidity ≥ 95%

content = 45%, clay content = 51%, L_i = 10.9%) mixed with cement 20%. The characteristic of sample preparation was to dehydrate the specimen with a pressure of 10 MPa after cement-mixing, and then curing the specimen in underwater condition. The specimen cured for 28 days had q_u of 25 MPa.

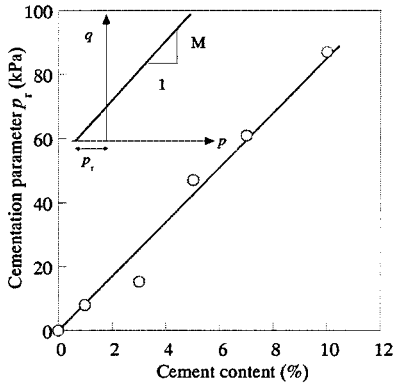
The cement-treated soil with the second largest q_u value was Masado (initial water content = 12%, ρ_s = 2.620 Mg/m^3, w_L = 35.7%, I_p = 7.6, gravel content = 4%, sand content = 37.5%, F_c = 14.2%, clay content = 51%, L_i = 10.9%) mixed with cement 8%. The characteristics of sample preparation was to adjust the water content after cement-mixing to an optimum water content of original soil by compacting with rammer of 2.5 kg, 25 times each layer according to JGS-0811 (JGS, 2000). After the sample compaction, specimens were cured under the temperature of 21 ± 3° and the humidity of more than 95% (called ‘‘standard curing condition’’) for 6 days. Then, specimens were cured in underwater condition at the temperature of 21 ± 3° for a day. Finally, specimens were cured under the standard curing condition for 10 years. The q_u cured for 7 days, 28 days, 1 year and 10 years were 5 MPa, 8 MPa, 13 MPa and 23 MPa, respectively.

The soil with the third largest q_u value was Toyoura sand (ρ_s = 2.700 Mg/m^3, sand content = 100.0%) mixed with diatom soil 20% to enhance pozzolan reaction of cement. The initial water content of the mixture was 39.5%, and the cement content of Portland blast-furnace slag cement type B is 300 kg/m^3. After cement-mixing in mold (ϕ300 mm × height 360 mm), the mixture was consolidated with the vertical stress of 0.1 MPa for 24 hours. After the consolidation, specimens were cured under the standard curing condition. The specimen cured for 91 days had q_u of 20 MPa.

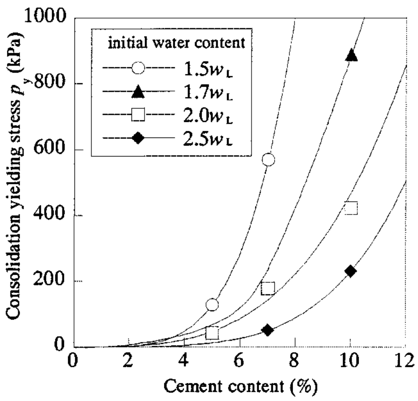
It can be concluded that excessive cement content and cement amount are not necessary for high-strengthening cement-treated specimens. On the other hand, the common characteristics of these sample preparations were to perform additional treatments for the purpose of increasing the specimen density by consolidation and compaction after cement-mixing.

THEORETICAL CONSIDERATION ON THE HIGH-STRENGTHENING

In the earlier study (Kasama et al., 2006), the undrained shear strength of cement-treated soils was evaluated based on the results of isotropic consolidation and undrained triaxial shear compression tests. The undrained shear strength of cement-treated soil can be evaluated by dividing the stress state into normally consolidated and quasi-over consolidated regions irrespective of the different soil types. The undrained shear strength slightly increases with the increasing confining pressure under the quasi-over consolidation and then increases at



(a) Cementation parameter p_r and cement content



(b) p'_y and cement content

Fig. 3. The values of p_r and p'_y

a constant rate in the normally consolidated state. The equivalent undrained shear strength ratio $s_u/(p'_c+p'_r)$ can be expressed as;

$$\frac{s_u}{(p'_c+p'_r)}=\alpha\times R^n \tag{1a}$$

$$R=\frac{p'_y+p'_r}{p'_c+p'_r} \tag{1b}$$

where, α and n are experimental parameters, and p'_c is a consolidation pressure under undrained shearing. p'_r is a cementation parameter representing the cementation effect. Yield stress ratio R is defined by Eq. (1b) to express a stress state in quasi-over consolidation. This yield stress ratio is equivalent to the overconsolidation ratio for cases where $p'_r=0$. Characteristics of Eq. (1) are:

(1) The equivalent undrained shear strength ratio of cement-treated soils, $s_u/(p'_c+p'_r)$, can be evaluated as a unique function of the yield stress ratio, R irrespective of cement content and initial soil density.

(2) In case of $p'_r=0$, Eq. (1a) is equivalent to the undrained shear strength evaluation for overconsolidated cohesive soil (Murthy et al., 1982; Mitachi and Kitago, 1976; Mayne, 1980).

(3) Cementation parameter p'_r and yield stress ratio R are primal factors influencing the undrained shear strength of cement-treated soils.

The values of p'_r and p'_y in Eq. (1) are dependent on cement content as shown in Fig. 3. Figure 3(a) is the relationship between p'_r and cement content showing that p'_r increases linearly as cement content increases. Figure 3(b) is the relationship between consolidation yield stress p'_y and cement content showing that p'_y increases exponentially with the cement content, but decreases with increasing initial water content.

Here, Eq. (1) is analyzed for the purpose of obtaining a high-strength cement-treated soil assuming that α and n are constant irrespective of cement content. In order to increase s_u in Eq. (1a), it is effective to increase $(p'_c+p'_r)$ and R. However, it can be considered that the contribution of $(p'_c+p'_r)$ to the increment of strength is relatively small at low range of consolidation pressure such as an unconfined condition. On the other hand, R can be expected to increase by increasing the value of p'_y, which is one of components of R in Eq. (1b). In order to increase p'_y, it is effective to increase cement content and increase the formation density of specimen (decrease the initial water content) as shown in Fig. 3(b). Finally, a mechanical dehydration with high pressure following cement-mixing can be proposed to obtain a high-strength cement-treated soil in this paper.

HIGH PRESSURE DEHYDRATION PROPERTY

Sample Preparation and Test Procedure

In order to clarify the fundamental dehydration properties of cement-treated clay under high pressure, a series of constant strain rate consolidation tests according to the JGS-0412 (JGS, 2000) were performed. Soft clays dredged at Kumamoto and Ube ports in Japan were used to prepare cement-treated specimens (called ''Kumamoto clay'' and ''Ube clay'', respectively). The physical properties of Kumamoto and Ube clays are $\rho_s=2.614$ Mg/m^3, $w_L=101\%$, $I_p=63.8$ and $\rho_s=2.571$ Mg/m^3, $w_L=132\%$, $I_p=90.9$, respectively. Kumamoto and Ube clays in slurry of $1.5w_L$ were mixed with cement content 10% and 20% of Portland blast-furnace slag cement type B. After careful mixing for 10 minutes, the mixture was gently poured into the mold (60 mm in diameter and 20 mm in height) by spoon. In order to remove air bubbles in the mixture, the mold with the mixture was thoroughly tapped in the lower part of the mold with a hammer, and immediately followed by constant strain rate consolidation tests to a consolidation pressure of 5 MPa. In order to raise the degree of saturation of specimen, a back pressure of 198 kPa was applied in the consolidation process. The constant strain rate consolidation test was started in 5 minutes after finishing cement-mixing. In order to examine the effect of dehydration speed on the dehydration properties of cement-treated clay, the constant strain rates r of 0.014, 0.050, 0.140 and 0.200 mm/min were selected. The test conditions are summarized in Table 3.

Consolidation Pressure and Cement Content

Figure 4 shows the relationship between consolidation pressure and the elapsed time from starting consolidation for cement-treated Kumamoto clay. The constant strain rate, r, for Figs. 4(a) and 4(b) are 0.014 mm/min (the smallest case) and 0.200 mm/min (the largest case), respectively. It can be observed that the consolidation pressure slightly increases at the low range of consolidation pressure and then increases sharply at the end of consolidation up to 5 MPa. The consolidation pressure of $r=0.014$ mm/min for a given elapsed time over 200 minutes increases with increasing cement content, while the relationships between consolidation pressures and elapsed time for $r=0.200$ mm/min show similar trend irrespective of the cement content. Accordingly, it can be seen that the effect of the elapsed time on the dehydration properties increases with the increasing elapsed time as the chemical reaction of cement agent is a function of the elapsed time. In other words, the elapsed time has little influence on the dehydration properties temporarily after cement-mixing, which is roughly estimated to be 70 minutes from Fig. 4(b). Similarly, Watabe et al. (2001) had reported that there was no strength increase in cement-treated clay for about 30 minutes after cement-mixing based on the results of vane shear test for cement-treated clay.

Table 3. Experimental condition for one-dimensional consolidation tests using constant rate of strain loading

Soil	Kumamoto clay Ube clay
Cement type	Portland blast-furnace slag cement type B
Cement content	0, 10, 20%
Size of specimen	ϕ60 mm × H20 mm
Initial water content	$1.5w_L$
Maximum loading stress	5 MPa
Constant strain rate	0.014, 0.050, 0.140, 0.200 (mm/min)

e-log p_t Relationship

Figure 5 shows the e-log p_t for cement-treated Kumamoto clay with $r=0.014$ mm/min. The void ratio of untreated clay remarkably decreases up to about 0.1 MPa, which was supposed to be due to the stress relaxation between specimen and test apparatus, and then decreases linearly in e-log p_t space. On the other hand, the void ratio for a given consolidation pressure increases with increasing cement content, while the difference of void ratio between cement-treated and untreated clays decreases as the consolidation pressure increases. Similar results were also obtained in cement-treated Ube clay as shown in Kasama et al. (2002). Kusakabe and Morio (1995), Miura et al. (2001) and Rotta et al. (2003) had also reported similar characteristics for cement-treated Kaolin (cement amount 8 kg/m^3 and one-dimensional consolidation pressure of 4.9 kPa), cement-treated Ariake clay (the ratio of clay and water/cement ratio of 7.5, 10 and 15, and the initial water content of 1.0, 1.5, 2.0 and $3.0w_L$) and cement-treated silty sand (cement content of 0–3% and curing isotropic stress of 98–1960 kPa), respectively.

Figure 6 is the e-log p_t for cement-treated Kumamoto clay with cement content of 20% as a function of the constant strain rate. It can be seen that the e-log p_t with $r=0.140$ mm/min coincides with that of $r=0.200$ mm/min suggesting that there is no influence of the chemical reaction of cement agent on the e-log p_t relationships for the both constant strain rate. It can be characterized that, however, e-log p_t relationship shifts to positive side of p_t with decreasing r, and especially e-log p_t with $r=0.014$ mm/min does not even show linear relationships in e-log p_t space, which is supposed to be due to continuous generations and degradations of cementation produced by the chemical reaction of cement agent in

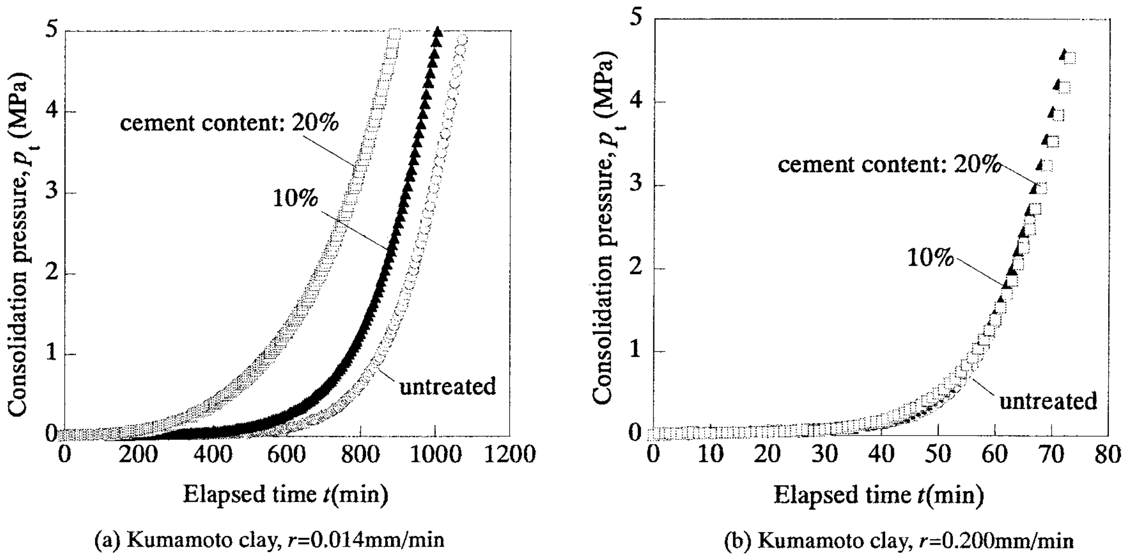


Fig. 4. Consolidation pressure against elapsed time

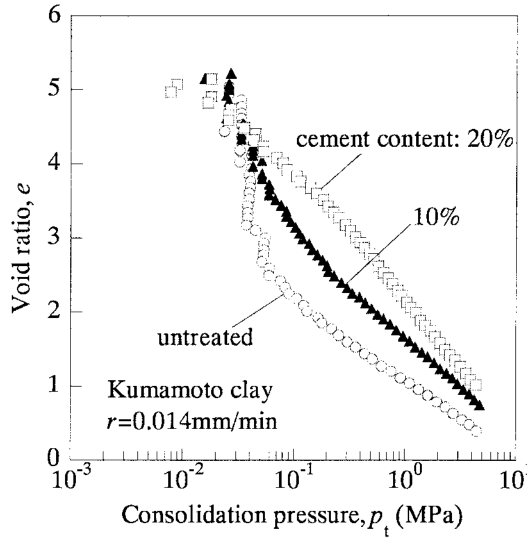


Fig. 5. e-log p_t in terms of cement content

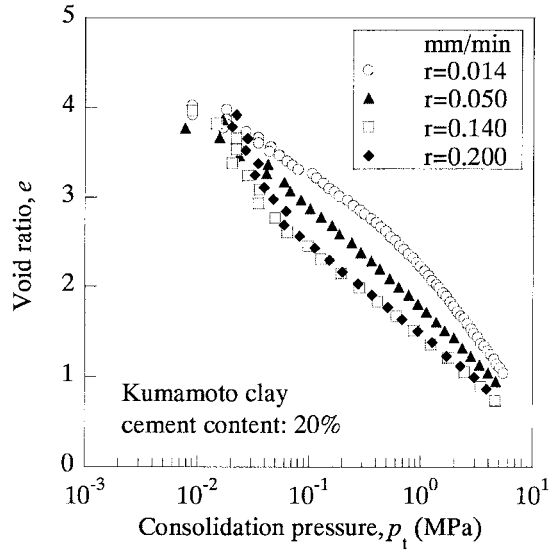
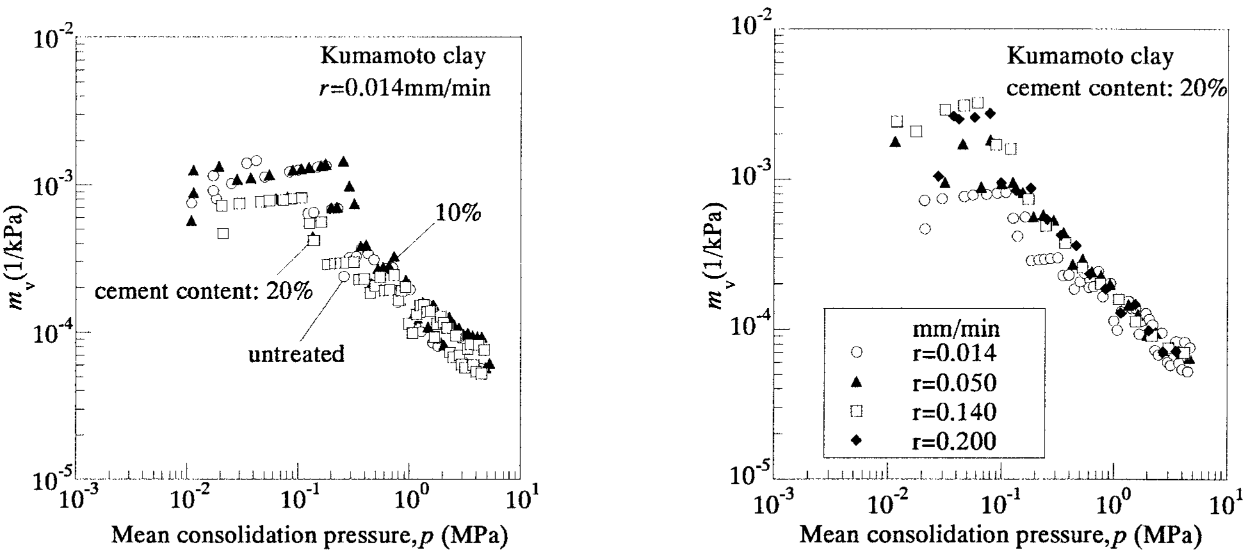


Fig. 6. e-log p_t in terms of constant strain rate



(a) Cement content

(b) Constant strain rate

Fig. 7. Coefficient of volume compressibility, m_v

specimens. Therefore, it can be concluded that e-log p_t of cement-treated clays is greatly affected by the constant strain rate and the cement content. It can be followed that the cement-treated clay becomes less compressive with increasing elapsed time from cement-mixing. By reconsidering these results for the purpose of increasing the density of cement-treated clay effectively, it can be concluded that it is useful to dehydrate the cement mixture with a large dehydration speed immediately following cement-mixing.

Coefficient of Volume Compressibility

Figures 7(a) and 7(b) show the coefficient of volume compressibility m_v for cement-treated Kumamoto clay with $r = 0.140$ mm/min and cement content = 20%, respectively. Although there is some scatter in the test results, especially at low mean consolidation pressure, similar m_v for a given mean consolidation pressure was observed irrespective of cement content and constant strain rate. Accordingly, it can be considered that m_v of cement-treated clay is equivalent to that of untreated clay irrespective of cement content and dehydration speed.

Coefficient of Consolidation

Figure 8 is the coefficient of consolidation c_v for cement-treated Kumamoto clay with $r = 0.200$ mm/min showing that c_v greatly decreases up to about 10^{-1} MPa and then keeps almost constant value similar to untreated clay. It can be emphasized that c_v for a given mean consolidation pressure increases in proportion to cement content. In order to evaluate the effect of cement content and constant strain rate on the coefficient of consolidation, c_v at mean consolidation pressure of 1 MPa is plotted as a function of constant strain rate r in Fig. 9. It

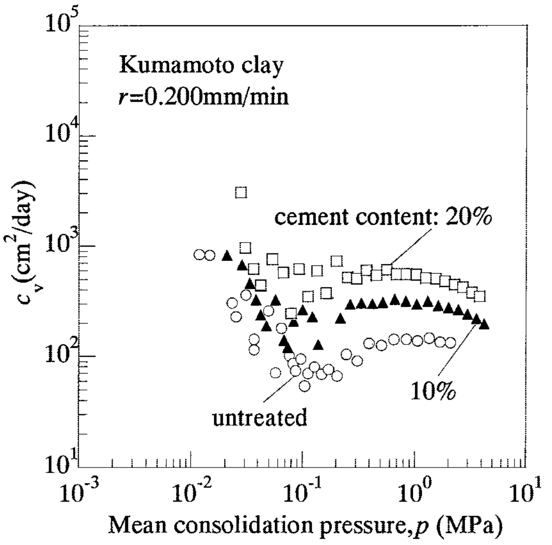


Fig. 8. c_v **and mean consolidation pressure**

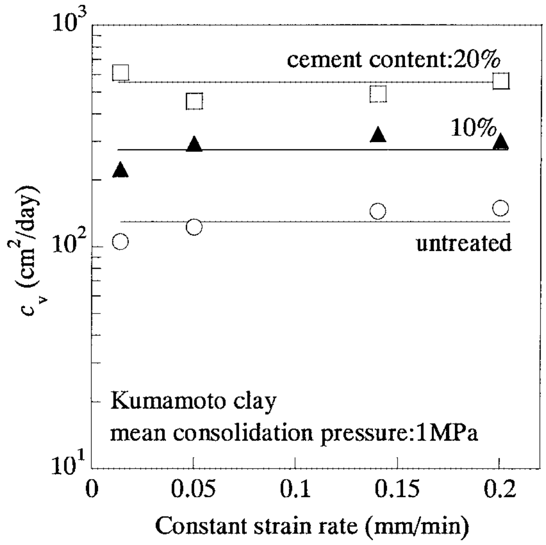


Fig. 9. c_v **at 1 MPa and constant strain rate**

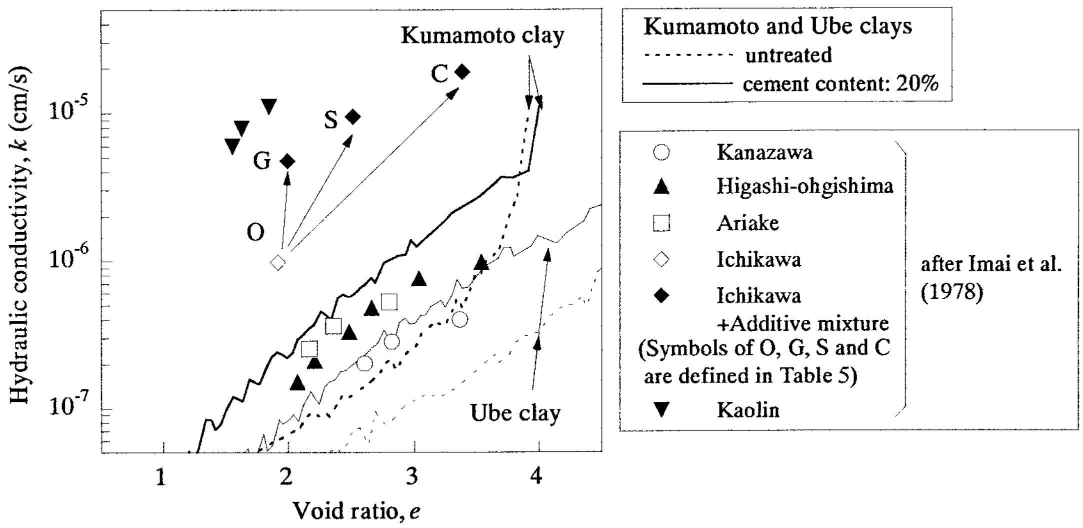


Fig. 10. Hydraulic conductivity and void ratio, after Imai et al. (1978)

can be seen that c_v at the mean consolidation pressure of 1 MPa is almost constant parameter irrespective of r, and thus the magnitude of c_v for cement content = 10% and 20% are about 2.5 and 5.0 times that of untreated clay, respectively. Therefore, it is expected that the dehydration of cement-treated clay following cement-mixing is temporarily accelerated as the cement content increases.

Hydraulic Conductivity and Void Ratio

In order to evaluate the effect of increasing cement content on the hydraulic conductivity of cement-treated clays, the hydraulic conductivity k $(= m_v \times c_v \times \gamma_w)$ calculated by measured m_v and c_v is shown against void ratio in Fig. 10. The test results of five clays reported by Imai et al. (1978) are also shown in Fig. 10. The physical properties of these clays and the additive mixtures for Ichikawa clay are shown in Tables 4 and 5 respectively. It should be noted that the activity, A, in Table 4 was a plasticity index divided by the percentage of clay fraction smaller than 2 microns. Imai et al. (1978) found that the hydraulic conductivity of clay increased with decreasing activity A. It can be characterized that k of cement-treated Kumamoto and Ube clays for a given void ratio increase with increasing cement content similar to Ichikawa clay with the additive mixture. Similarly, Katsumata et al. (1997) reported that cement agents were more effective materials for dehydration of clay with high water content clay than a general flocculant such as PAC (poly aluminum chloride) from the test results of filter test according to API standard (American Petroleum Institute standard). Moreover, Sogabe et al. (1996) reported that sedimentation velocity of clay particles increases with the addition of cement, which was considered to be caused by the flocculation of clay particles due to the chemical cohesion of cement agent.

Table 4. Physical properties of tested material, after Imai et al. (1978)

Source	ρ_s (Mg/m^3)	Liquid limit (%)	Plasticity index	C.F.* (%)	A**
Kumamoto clay	2.614	101.0	63.8	42.0	1.52
Ube clay	2.571	132.0	90.9	—	—
Kanazawa	2.615	118.1	82.3	41.8	1.97
Higashi-ohgishima	2.669	113.7	80.2	50.5	1.59
Ariake	2.685	105.4	67.2	54.0	1.24
Ichikawa	2.674	83.8	51.7	39.0	1.33
Kaorin	2.713	45.8	16.4	31.5	0.52

*C.F.: Clay fraction smaller than 2 microns
**A: Activity (Plasticity index/C.F.)

Table 5. Additive mixtures for Ichikawa clay, after Imai et al. (1978)

Symbol	Additive mixture	Additive weight to specimen weight
O	None	0 ppm
G	Waterglass	200 ppm
S	Waterglass +Slake lime	200 ppm +20,000 ppm
C	Waterglass +Portland cement	200 ppm +20,000 ppm

Table 6. Sample preparation for dehydrated cement-treated clay

Soil	Kumamoto clay	
Cement type	Portland blast-furnace slag cement type B	
Dehydration mode	Constant strain mode (1 mm/min)	Constant stress mode 5, 10, 15, 20 MPa
Cement content	10, 15, 20%	10, 15, 20, 30%
Initial water content	$1.5w_L$	
Curing period	7, 28, 91 days	
Curing condition	Temperature = 21 ± 3°, Humidity ≥ 95%	

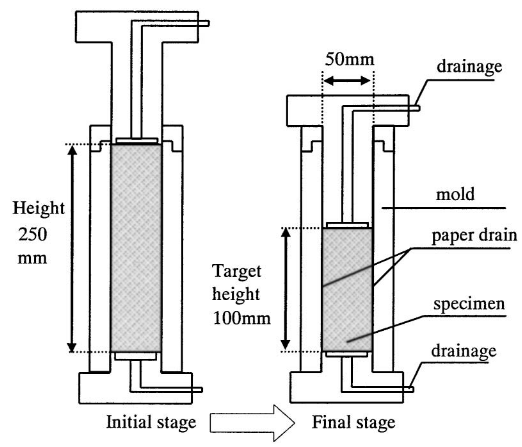


Fig. 11. Schematic diagram of mold for mechanical dehydration

UNCONFINED COMPRESSIVE STRENGTH

Sample Preparation and Test Procedure

In order to evaluate the effect of mechanical dehydration with high pressure on the unconfined compressive strength of cement-treated clay, dehydrated cement-treated specimens were prepared as a function of cement content, dehydration pressure and dehydration mode. Figure 11 shows the schematic diagram of the mold to dehydrate cement-treated clay. The inner mold size is (ϕ)50 mm × (height)250 mm. The characteristics of the mold are following;

(1) In order to facilitate dehydration from specimen, paper drains were placed at the top and the bottom of specimen and also around of the cylindrical surface of specimen.

(2) The specimen was dehydrated under two dehydration modes. One was that loading plate on the top of specimen was pressed at constant strain rate of 1.0 mm/min (called ''constant strain mode''). The other was that specimen was dehydrated under constant stress (called ''constant stress mode'') until the consolidation was completed based on the judgment employing the 3*t* method (JGS, 1999).

(3) As for constant strain mode, the specimen with initial height of 200 mm was dehydrated until the height was 100 mm, which is the standard size of specimen (50 mm in diameter and 100 mm in height) for unconfined compression test. Thus, the specimens after the dehydration could be directly used for unconfined compression test.

(4) As for dehydration pressure in constant stress mode, 5, 10, 15, 20 MPa were selected. The initial height of specimen was 250 mm. After dehydration, the height of specimens was adjusted by cutting to fit the standard size of specimen for unconfined compression test.

The sample preparation for dehydrated cement-treated clay is summarized in Table 6. In order to examine the variability of density in the dehydrated specimen, the water content in vertical direction of dehydrated specimen was measured. Moreover, a series of unconfined compression tests were carried out for dehydrated specimens cured for 27 days under the standard curing condition (the temperature of 21 ± 3° and the humidity of more than 95%).

Constant Strain Mode and Constant Stress Mode

Figure 12 shows the relationships between dehydration pressure and elapsed time from starting of dehydration for dehydrated specimens with constant strain mode showing that the dehydration pressure gradually increases at the low range of dehydration pressure and then increases sharply with increasing elapsed time. The dehydration pressure for a given elapsed time increases with increasing cement content, which follows that the dehydration pressure for the specimen with cement content of 20% is about 1.5 times that of 10% cement content specimen at the end of dehydration.

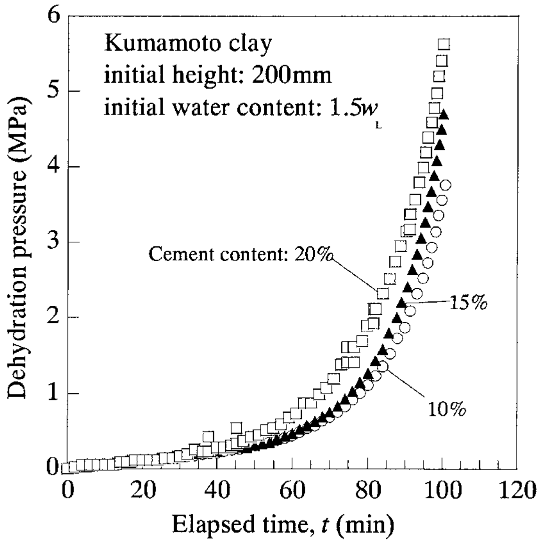


Fig. 12. Dehydration pressure and elapsed time under constant strain mode

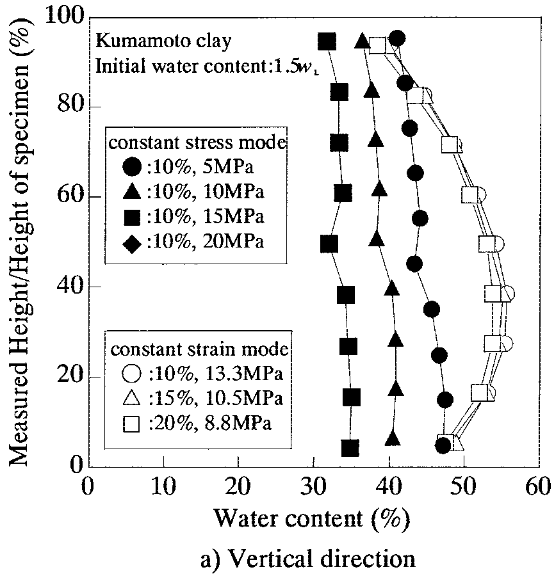


Fig. 14. Water content of specimen in vertical directions

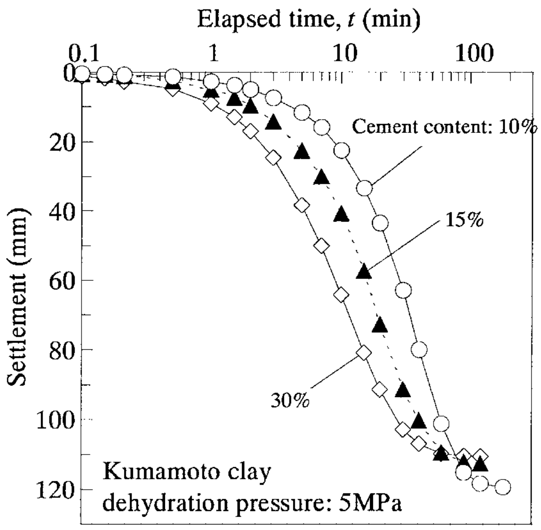


Fig. 13. Time-settlement curve under constant stress mode

Figure 13 is the time-settlement curve for the dehydrated specimen with constant stress mode, which is similar to a typical time-settlement curve of cohesive soils. It can be seen that settlement for a given elapsed time increases with increasing cement content while the final settlement at the end of dehydration decreases with increasing cement content, which suggests that the dehydration of cement-treated clays is accelerated as cement content increases as expected from the result of constant strain rate consolidation test for cement-treated clay in prior section.

Distributions of Water Content

In order to examine the variability of density in the dehydrated specimen, the water content in the vertical direction of the specimen is shown in Fig. 14. The vertical axis in Fig. 14 is normalized by the height of the specimen. It can be seen that there is a local difference of water content in the specimen and thus the water content for dehydrated specimen with constant stress mode is smaller than that for dehydrated specimen with constant strain mode for a given dehydration pressure. In addition, the difference of maximum and minimum water contents for dehydrated specimens with constant strain mode is larger than that for dehydrated specimens with constant stress mode. As the variability of water content in specimens has influence on the strength of specimen, it is expected that specimen dehydrated with constant strain mode shows lower strength than that for dehydrated specimen with constant stress mode. Subsequently, it can be suggested that the constant stress mode is better than constant strain mode for the purpose of increasing the specimen density uniformly and effectively.

Unconfined Compressive Strength

Figure 15 shows the unconfined compressive strength q_u of dehydrated cement-treated clays as a function of dehydration pressure and cement content for specimens cured for 28 days. It can be seen that q_u sharply increases up to the dehydration pressure of 5 MPa and then increases constantly while the increase rates of strength against dehydration pressure depend on the cement content and dehydration mode. Although q_u increases with cement content in both of dehydration modes, q_u for constant stress mode is larger than that for constant strain mode. It is worth noting that cement-treated clay dehydrated with constant stress mode achieve a target strength of 20 MPa (maximum $q_u = 25$ MPa) while the q_u of cement-treated clay without mechanical dehydration is about 1.1 MPa for cement content of 30%.

In order to evaluate the specimen density on unconfined compressive strength of cement-treated clay, q_u is plotted against the dry density of specimen in Fig. 16. The dry density used here is the mean value in the dehydrated specimen although there is a variability of density in dehydrated specimen as shown in prior section. It is seen

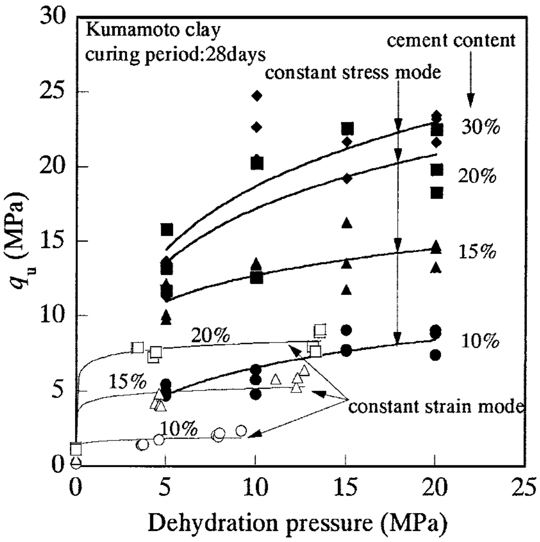


Fig. 15. q_u **against dehydration pressure**

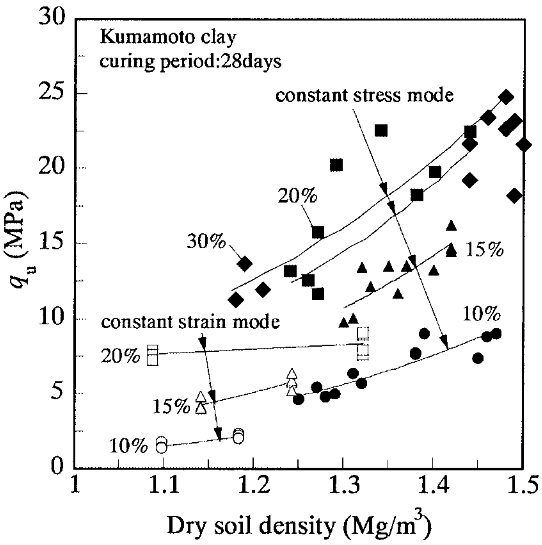


Fig. 16. q_u **and dry soil density**

that q_u increases with the increasing dry density and also increasing cement content while the increase rate of strength is different for both dehydration modes. The difference of q_u between constant strain and constant stress modes for a given dry density are related to the local difference of density in dehydrated specimens, which is linked to the difference of failure pattern for specimen after unconfined compression test. Namely, the specimens dehydrated with constant strain mode generally broke into pieces around the middle part of specimens showing a high water content (as shown in Fig. 14) while specimens dehydrated with constant stress mode show a typical failure pattern with an inclined shear crack through the specimen similar to concrete. Moreover, as there is no strength increase for specimens mixed with cement of over 20% under constant stress dehydration, it is suggested that there is an upper limit for the unconfined compressive strength obtained by the CMD although the correlations of cement content with specimen density

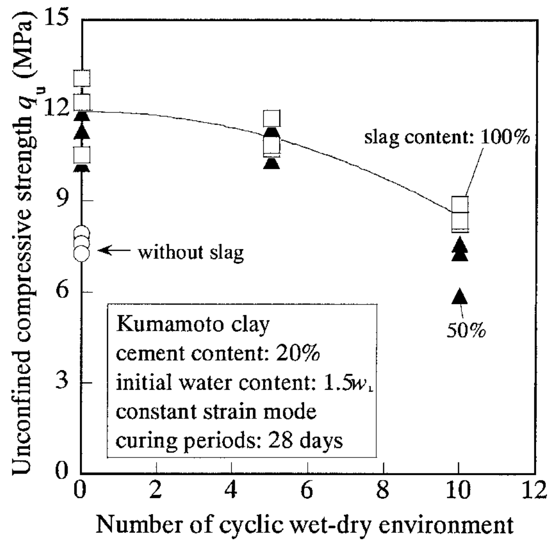


Fig. 17. q_u **under cyclic wet-dry environment**

produced with the CMD should be clarified in future studies.

DURABILITY AND CURING CONDITION

Sample Preparation and Test Procedure

Sekine et al. (1996) and Rollings et al. (1999) have reported the durability of cement-treated clay suggesting that the strength of specimen drastically decreases under cyclic wet-dry environment due to cracks generated inside the specimen. In this study, in order to improve the durability of specimen produced by the CMD, a blast-furnace slag was mixed together with cement before the mechanical dehydration for the purpose of reinforcing the soil structure of specimen taking advantage of the latent hydraulicity of a blast-furnace slag. In order to examine the improvement effect of mixing a blast-furnace slag on the durability of specimen produced by the CMD, a series of durability tests were performed for dehydrated cement-treated clay with a blast-furnace slag ($\rho_s = 2.640$ Mg/m^3, $U_c = 2.2$, $D_{50} = 0.59$, $F_c = 1.57\%$) cured for 28 days. The content of a blast-furnace slag in specimen was 50% and 100% per dry soil sample weight (called ''slag content''). As for durability tests, unconfined compression tests after cyclic wet-dry environment, slaking tests according to JHS-110 (Japan Highway Standard, 1992), water absorption tests according to JHS-111 (JHS, 1992), abrasion resistance tests according to ASTM C-779 and swelling tests due to water absorption were performed for dehydrated cement-treated specimens with cement content of 20% and constant strain mode.

Durability and Improvement Effect of Slag

Figure 17 shows q_u of dehydrated cement-treated specimens as a function of the cyclic wet-dry environment. It should be noted that one cycle of wet-dry environment means that specimen was exposed in underwater condition with the temperature of 25° for a day and then in dry condition with the temperature of 110° for a day. It was

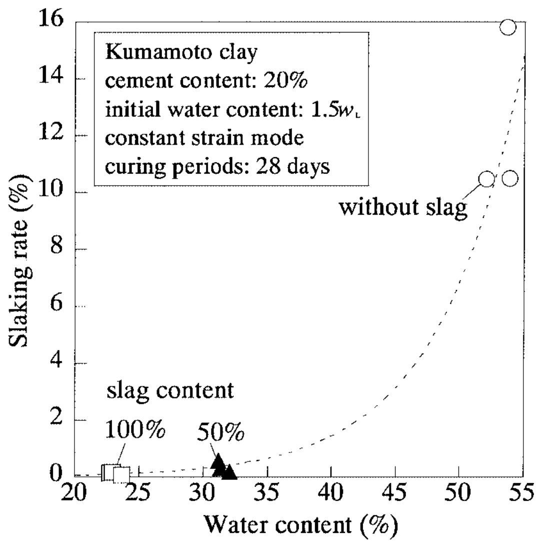


Fig. 18. Slaking rate against water content

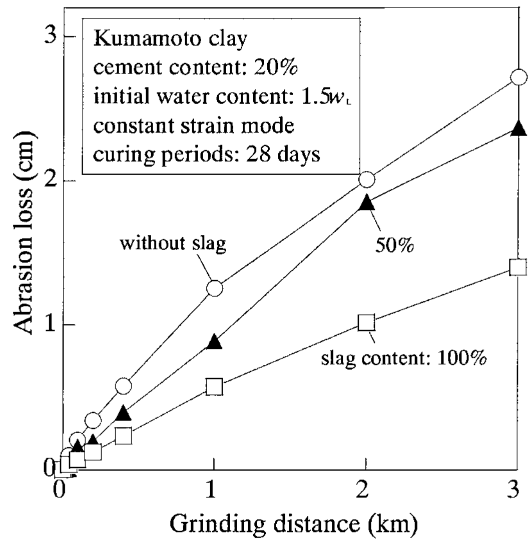


Fig. 20. Abrasion loss against grinding distance

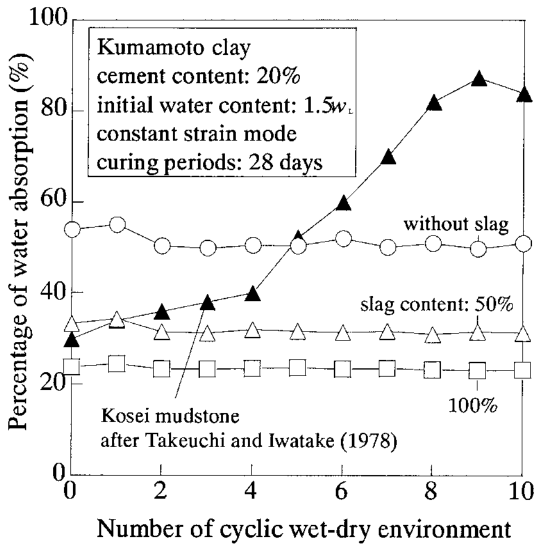


Fig. 19. Water absorption under cyclic wet-dry environment

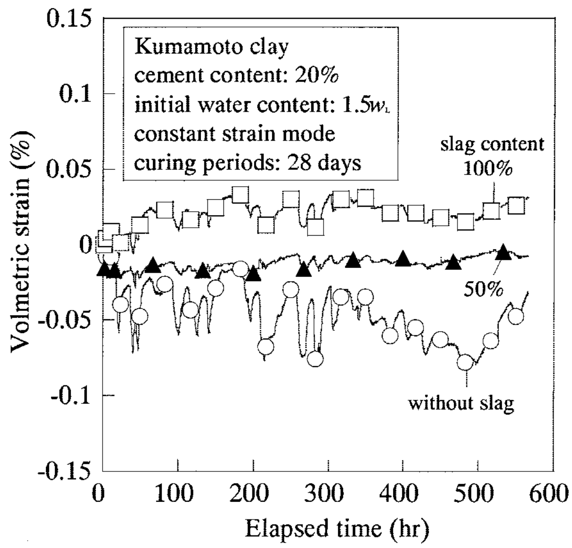


Fig. 21. Volumetric strain against elapsed time

observed that the specimens without slag broke into pieces after only one time of the cycle wet-dry environment, which follows that dehydrated cement-treated clay is vulnerable to a sharp thermal change similar to cement-treated clay. On the other hand, the ruin of specimens can be prevented by mixing slag irrespective of the number of cyclic wet-dry environment and thus the q_u for specimen with slag does not show drastic reduction in addition that the q_u prior to cyclic wet-dry environment increases with increasing slag content.

Figure 18 is the test result of slaking tests showing that the slaking rate for dehydrated cement-treated specimens with slag 50% and 100% were less than 1% while those of specimen without slag was 10–15%. One of reasons for decreasing slaking rate by mixing slag is that the shrink of specimen due to water evaporation can be prevented by increasing slag content and also it is effective for reinforcing the soil structure of specimen by mixing slag.

Figure 19 shows the percentage of water absorption against the number of cyclic wet-dry environment. The test result of Kosei mudstone, which was one of typical mudstones with a vulnerability to cyclic wet-dry environment reported by Takeuchi and Iwatake (1978), is also shown in Fig. 19. It can be seen that the percentage of water absorption for dehydrated cement-treated specimens indicate almost constant value decreasing with slag content while that for the Kosei mudstone increases with number of cyclic wet-dry environment.

Figure 20 shows the test result of abrasion resistance tests for dehydrated cement-treated specimen. The abrasion resistance tests according to ASTM C-779 have been used to evaluate the abrasion resistance of concrete material, in which specimens loaded by 8.8 kPa were ground against Toyoura sand measuring the grinding loss of specimen (call ''abrasion loss'') and grinding distance. Large abrasion loss refers to vulnerable materials to abrasion. It can be seen that the abrasion loss of dehydrated cement-treated specimen linearly increases

Table 7. The influence of curing condition for the unconfined compressive strength

Cement content	Slag content	Curing condition	Dehydration mode	q_u at 91 days
20%	0%	Standard*	Constant strain mode	10.4 MPa
		Air**		3.9 MPa
		Underwater***		8.2 MPa
	50%	Standard*		16.4 MPa
	100%	Standard*		21.3 MPa
		Air**		9.1 MPa
		Underwater		23.3 MPa
30%	0%	Standard*	Constant stress mode 20 MPa	29.9 MPa
		Air**		28.9 MPa
		Underwater***		23.9 MPa

*: Temperature 21 ± 3°, Humidity ≥ 95%
**: Temperature 21 ± 3°, Humidity ≤ 10%
***: Temperature 21 ± 3°

with grinding distance, but decreases with increasing slag content.

Figure 21 shows the volumetric strain due to water absorption as a function of the elapsed time after submerging specimens into underwater. It can be seen that the volumetric strain for specimens with slag was so small and stable irrespective of the slag content that the swelling of specimen due to water absorption can be ignored in practical use. From the test results of several durability tests, it can be concluded that it is effective to mix cement-treated clay with slag before mechanical dehydration for improving the durability of dehydrated cement-treated clay.

In order to examine the influence of curing condition on the strength of dehydrated cement-treated specimen, unconfined compression tests were performed for the specimen cured for 91 days under air condition (the temperature of 21 ± 3° and the humidity less than 10%), standard curing condition (the temperature of 21 ± 3° and the humidity of more than 95%) and underwater condition (the temperature of 21 ± 3°) respectively. Table 7 summarizes q_u, dehydration mode, slag content, cement content and curing condition. It can be seen that q_u of specimens with constant strain mode for underwater condition was almost equal to that of standard curing condition while q_u of air condition was less than half of underwater condition due to cracks in specimen induced by the dry shrinkage of specimen. On the other hand, q_u in constant stress mode was more than 20 MPa for three curing conditions. Although further investigation on the long-term influence of curing condition on the strength of dehydrated cement-treated specimen will be needed, it can be concluded that dehydrated cement-treated clay maintain the high-strength in both of standard curing and underwater conditions.

CONCLUSIONS

This study has investigated the unconfined compressive strength property and durability of soft clay treated by cement-mixing and mechanical dehydration with high pressure together with the literature review of sample preparation for increasing the unconfined compressive strength of cement-treated soils. Moreover, a series of constant strain rate consolidation tests were performed to evaluate the effect cement-mixing on the dehydration property of soft clay.

The following conclusions are obtained:

(1) The literature review and theoretical considerations on the shear strength of cement-treated soil show that additional treatments for the purpose of increasing the density of cement-treated specimen, such as consolidation and compaction, are effective for increasing the unconfined compressive strength of cement-treated soil.

(2) The dehydration properties of cement-treated clay depend on the elapsed time after cement-mixing in addition to cement content, which is attributed to the chemical reactions of cement agent. It can be concluded that the dehydration of soft clay with mechanical dehydration is accelerated by cement mixing, where the coefficient of consolidation c_v of cement-treated clay for the cement content of 10% and 20% are about 2.5 and 5.0 times that of untreated clay.

(3) The mean unconfined compressive strength for Kumamoto clay mixed with cement content of over 20% and dehydrated with constant stress of 20 MPa is almost 20 MPa, which is comparable to concrete material. It can be concluded that mechanical dehydration following cement-mixing for the purpose of increasing the density of cement-treated specimen is effective for increasing the unconfined compressive strength.

(4) While cement-treated clay dehydrated with high pressure is vulnerable to a sharp thermal change similar to cement-treated clay, it is useful to mix cement-treated

clay with blast-furnace slag for improving the durability. Although the unconfined compressive strength of dehydrated cement-treated clay reduce with elapsed time in cyclic wet-dry environment and dry condition (the temperature of $21 \pm 3°$ and the humidity less than 10%), the unconfined compressive strength is stable under underwater condition and wet condition such as the temperature of $21 \pm 3°$ with the humidity of more than 95%.

ACKNOWLEDGEMENT

The result of literature search by the technical committee of JGS on the engineering property and test method of cement-treated soil was partly used in the literature review of the unconfined compressive strength of cement-treated soils in this study. A grateful acknowledgement is made to Professor Hidetoshi Ochiai, Associate Professor Guangqi Chen, Associate Professor Noriyuki Yasufuku and Associate Professor Kiyoshi Omine of Kyushu University for their helpful advice and encouragement.

NOTATION

s_u: undrained shear strength
α: inclination of failure envelop in normally consolidated state in p'-q space
p'_r: cementation parameter
p'_c: consolidation pressure
p'_y: consolidation yield stress
R: yield stress ratio
p_t: consolidation pressure during one-dimensional test using constant rate of strain loading

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