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Friction behavior of controlled low strength material–soil interface

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Abstract. A controlled low strength material (CLSM) is a highly flowable cementitious material used for trench backfilling. However, when applying vertical loads to backfilled trenches, shear failure or differential settlement may occur at the interface between the CLSM and natural soil. Hence, this study aims to evaluate the characteristics of the interface friction between the CLSM and soils based on curing time, gradation, and normal stress. The CLSM is composed of fly ash, calcium sulfoaluminate cement, sand, silt, water, and an accelerator. To investigate the engineering properties of the CLSM, flow and unconfined compressive strength tests are carried out. Poorly graded and well-graded sands are selected as the in-situ soil adjacent to the CLSM. The direct shear tests of the CLSM and soils are carried out under three normal stresses for four different curing times. The test results show that the shear strengths obtained within 1 day are higher than those obtained after 1 day. As the curing time increases, the maximum dilation of the poorly graded sand–CLSM specimens under lower normal stresses also generally increases. The maximum contraction increases with increasing normal stress, but it decreases with increasing curing time. The shear strengths of the well-graded sand–CLSM interface are greater than those of the poorly graded sand–CLSM interface. Moreover, the friction angle for the CLSM–soil interface decreases with increasing curing time, and the friction angles of the well-graded sand–CLSM interface are greater than those of the poorly graded sand–CLSM interface. The results suggest that the CLSM may be effectively used for trench backfilling owing to a better understanding of the interface shear strength and behavior between the CLSM and soils.

Keywords: backfill; CLSM; curing time; direct shear test; interface friction

1. Introduction

A controlled low strength material (CLSM), which is known as a cementitious backfill material, flows like a liquid and self-levels without compacting. CLSMs with high flowability are widely used for several applications, including trench backfilling and void filling (ACI 229 1999, NRMCA 1999). Unlike the conventional compacted soil, CLSMs can allow rapid construction, have minimal noise and labor, and allow access to restricted areas, although the cost of using CLSMs is slightly higher. In some cases, CLSMs can be designed for low compressive strength for potential re-excavation, but they require early-age strength to support traffic loads within several days after curing (Ling *et al.* 2018).

CLSMs typically consist of fly ash, fine aggregate, water, cement, and chemical admixtures. However, to reuse a variety of waste materials and byproducts in the CLSM mixture, many researchers have developed various mixed designs of CLSMs. By using alum sludge generated from water treatment, Wang *et al.* (2018) proposed a new type of CLSM based on its flowability, stiffening time, and compressive strength. For a mixed design of rapid hardening CLSM, Zhang *et al.* (2018) used recycled fine aggregates generated by construction and demolition of buildings or infrastructures. Lim *et al.* (2017) developed an electrically conductive CLSM containing copper slags produced from ores during smelting. By using pond ash and red mud, Do and Kim (2016) and Do *et al.* (2015) reported the engineering properties of pond ash-based CLSM. To characterize the early-age properties of CLSMs, Byun *et al.* (2016) investigated the elastic wave characteristics of CLSMs according to the curing time and proportions of sand to silt. Tűrkel (2007) carried out direct shear tests to evaluate the shear strength of CLSMs. When applying vertical loads to backfilled trenches, shear failure or differential settlement may occur at the interface between the CLSM and natural soil. However, the interface friction between the CLSM and natural soils around the trenches has not been studied yet. The shear strength and behavior at the interface between the CLSM and soils are investigated in this study.

Particulate–continuum interfaces are present in many geotechnical structures, such as deep foundations and retaining walls. Accordingly, the interface shear behavior and strength between soils and continuum materials have been studied from the geotechnical engineering perspective (Chu and Yin 2005, 2006, Shakir and Zhu 2009, Xu *et al.* 2012, Yang *et al.* 2012, Liu *et al.* 2014, Hossain and Yin

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2015, Zhang *et al.* 2016, Ilori *et al.* 2017, Xiao *et al.* 2017, Wu and Yang 2017, Lin *et al.* 2018, Samanta *et al.* 20018). Generally, the friction characteristics of the particulate–continuum interface have been quantified using simple or direct shear testing devices. Previous studies showed that the friction characteristics of the particulate–continuum interface are different from the internal shear resistance of the soil. Several researchers investigated the effects of the matric suction of a soil and the temperature of the interface between soil and cementitious materials on the shear behavior and strength (Liu *et al.* 2014, Hossain and Yin 2015, Xiao *et al.* 2017). Other researchers have focused on the effect of continuum properties, such as surface roughness, on the interface shear behavior and strength (Chu and Yin 2005, 2006, Yang *et al.* 2012). Frost *et al.* (2002) summarized a series of previous studies on the coupled effect of surface roughness and hardness on the interface shear behavior and strength. Nevertheless, potential factors influencing the interface friction between the CLSM and natural soils, e.g., curing time and normal stress, still require further investigation.

This study presents the interface shear strength and behavior between the CLSM and soils based on the curing time, gradation, and normal stress. First, the components, mix design, and mechanical properties of CLSMs are introduced, followed by the index properties of two soils. Subsequently, the condition and procedure of the direct shear tests are explained. The shear stress and normal displacement curves obtained from the interface between the CLSM and soils are elaborated. Finally, the effects of curing time, gradation, and normal stress on the interface friction of the CLSM are discussed in terms of the shear strength, maximum dilation, maximum contraction, and friction angle.

2. Materials

2.1 CLSM

In this study, the CLSM is composed of fly ash, calcium sulfoaluminate (CSA) cement, sand, silt, water, and an accelerator. The CSA cement and fly ash were used as binders in the mixed design. The CSA cement contains ordinary type I Portland cement and a calcium sulfoaluminate-based expansive admixture at a 9:1 ratio by weight to catalyze the hydration reaction. The chemical compositions of the CSA cement and fly ash are summarized in Table 1. The fly ash is primarily composed of calcium oxide (CaO) and silica (SiO_2), and it is crucial in increasing the flowability of the CLSM. However, a large amount of fly ash can retard the hardening of the CLSM. Jumunjin sand, a typical standard sand in Korea, was used. Note that Jumunjin sand is called poorly graded sand in this paper. The grain size distributions of coarse particles between 2 mm and 0.075 mm were obtained from sieve analysis. For the fine particles smaller than 0.075 mm, a laser diffraction particle size analyzer was used. Poorly graded sand and silt with mean diameters of 0.59 and 0.02 mm, respectively, were used as fine aggregates. To reduce the setting time, an alkali-free setting accelerator was added.

Table 1 Chemical compositions of the CSA cement and fly ash

Material component	SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	K_2O	Na_2O	P_2O_5	TiO_2
CSA cement	18.9	4.34	61.1	2.77	5.62	1.00	0.13	0.15	0.25
Fly ash	20.4	9.16	40.8	7.02	11.4	1.04	0.82	0.42	0.40

Table 2 Mixed proportion by weight of the CLSM

Component by weight	Fly ash	CSA cement	Sand	Silt	Water	Accelerator
Proportion	1	0.3	6.3	0.7	2.05	0.018

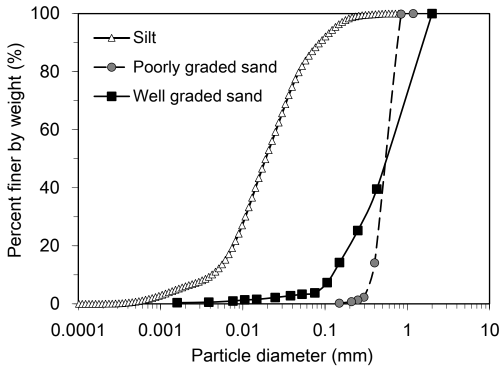
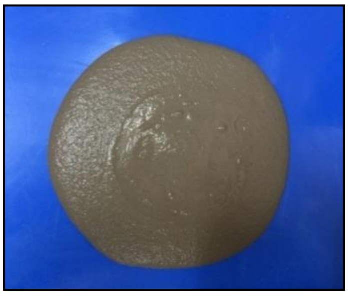


Fig. 1 Grain size distribution curves of silt and the two sands used in this study

The components of the CLSM were mixed according to the proportion as summarized in Table 2. First, the fly ash, CSA cement, and fine aggregates in dry condition were batched. Second, water and accelerator were included. Finally, after mixing all the components for 3 min, the samples were cured in a chamber where the temperature of 25°C and relative humidity of 100% were maintained. Note that the samples in the chamber were not submerged but were in wet condition in the air. To investigate the early-age strength characteristics, the samples were cured up to 7 days only.

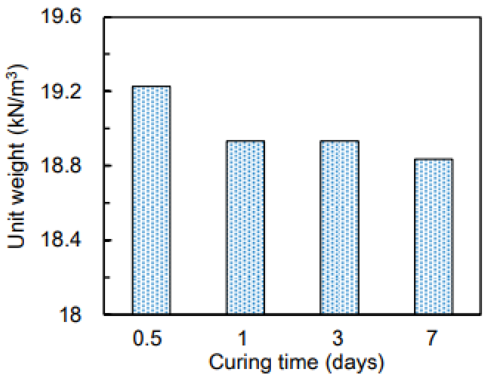
The pictures of the CLSM specimens during the flow and unconfined compressive strength tests are shown in Fig. 2. In accordance with the ASTM D 6103, the flow test was carried out after mixing and preparing the specimens. The measured flow for the CLSM used in this study was 203 mm, which is high flowability. To characterize the effect of curing time on the strength and density, a series of cylindrical CLSM samples with a diameter of 5 cm and height of 10 cm were prepared. Subsequently, the unit weights of the cylindrical samples were measured at 0.5, 1, 3, and 7 days. Further, unconfined compressive strength tests were carried out during each curing time. Fig. 3 shows that as the curing time increases, the unit weight decreases from 19.2 to 18.8 kN/m^3, whereas the unconfined compressive strength increases from 43 to 808 kPa. These results demonstrated that as the hydration continued, the solid network connected between the cement clusters developed throughout all the material, and the rest of the water remaining in the pore spaces of the CLSM samples should evaporate.



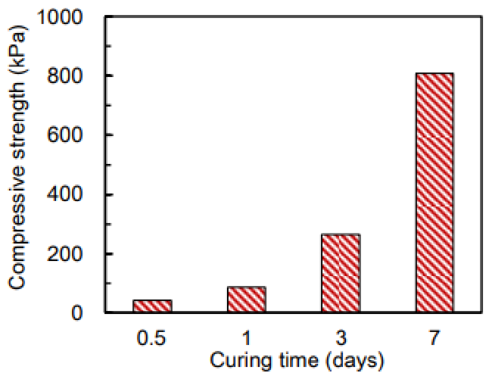
(a) Flow test

(b) Unconfined compressive strength test

Fig. 2 Pictures of the CLSM



(a) Unit weight



(b) Compressive strength

Fig. 3 Properties of the CLSM in terms of the curing time

2.2 Soils

To investigate the interface friction between the CLSM and soils, poorly graded and well-graded sands were used. Jumunjin sand was used as the poorly graded soil, and the well-graded sand was sampled at ground level in Seoul. The grain size distributions of these two sands are plotted in Fig. 1. The mean diameters of the poorly graded and well-graded sands were 0.59 and 0.70 mm, respectively. The well-graded sand had a wide grain size distribution with the coefficient of uniformity of 7.8, whereas the particle size of the sand with a coefficient of uniformity of 1.8 was relatively uniform. Based on the similar mean diameters and different coefficients of uniformity of the two sands, the effect of gradation on the interface friction of the CLSM will be discussed in the following sections. Although particle angularity is one of most dominant particle properties for interface shear strength, the effect of particle angularity was disregarded in this study. Note that the interface shear strength is rarely influenced by particle angularity under normal stresses of less than 100 kPa (Dove and Frost 1999).

3. Direct shear test

3.1 Test condition

Direct shear tests were carried out to evaluate the interface friction between the CLSM and soils. A direct shear testing apparatus controlled using two servo motors was used in this study. The upper and lower shear boxes for the specimen had an inner space of 80 mm width and 80 mm length, as shown in Fig. 4. The specimen heights prepared in the upper and lower boxes were 37 and 35 mm, respectively. The 1-mm gap between the upper and lower boxes prevented the friction between the two boxes, and the upper box attached to the testing apparatus restricted its rotation during shearing. The cured CLSM samples were placed into the lower box, and then the soils were compacted in the upper box. The unit weights of the poorly graded and well-graded sands compacted in the upper box were 14.6 and 15.3 kN/m^3, respectively. Three normal loads corresponding to the normal stresses of 25, 50, and 100 kPa were applied to the surface of soils through the servo motor.

After stabilizing the normal displacement induced by a normal load, the lower box was moved horizontally. A

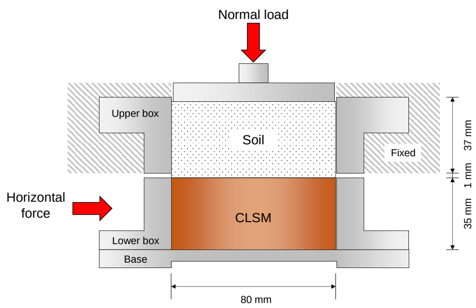
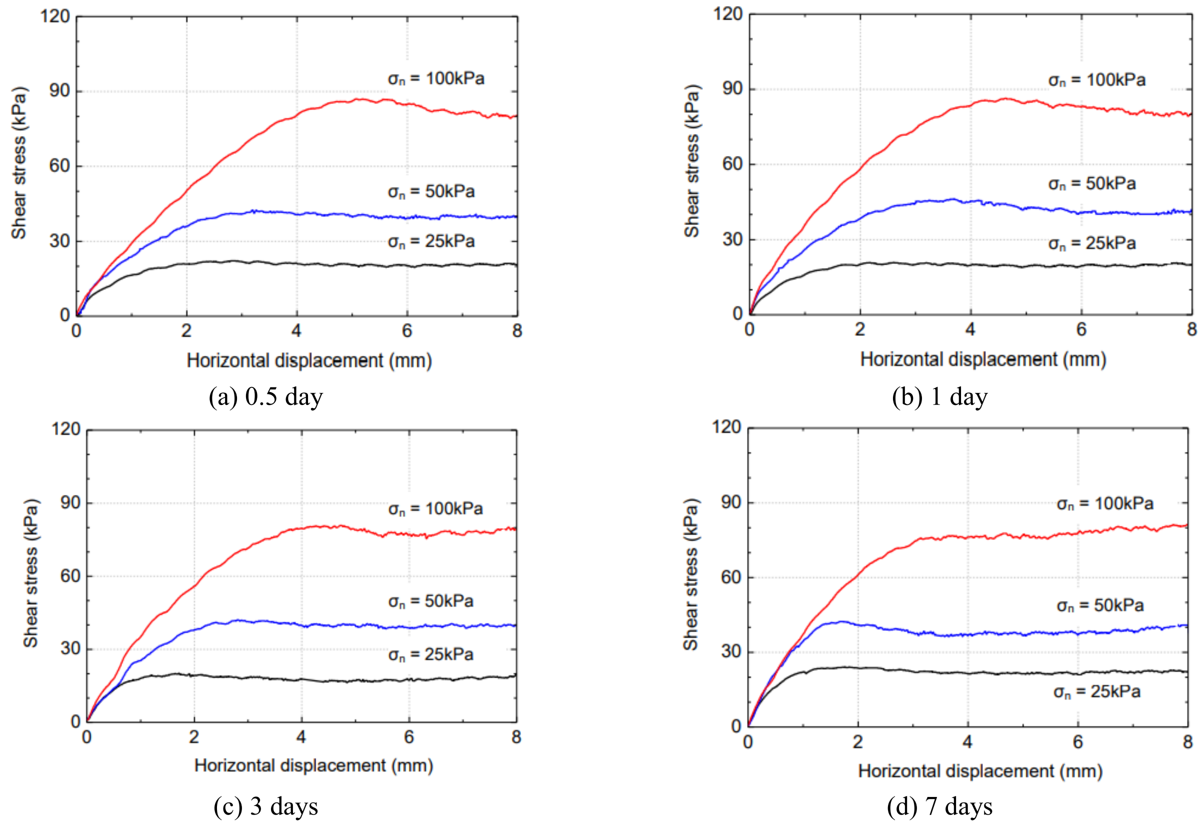


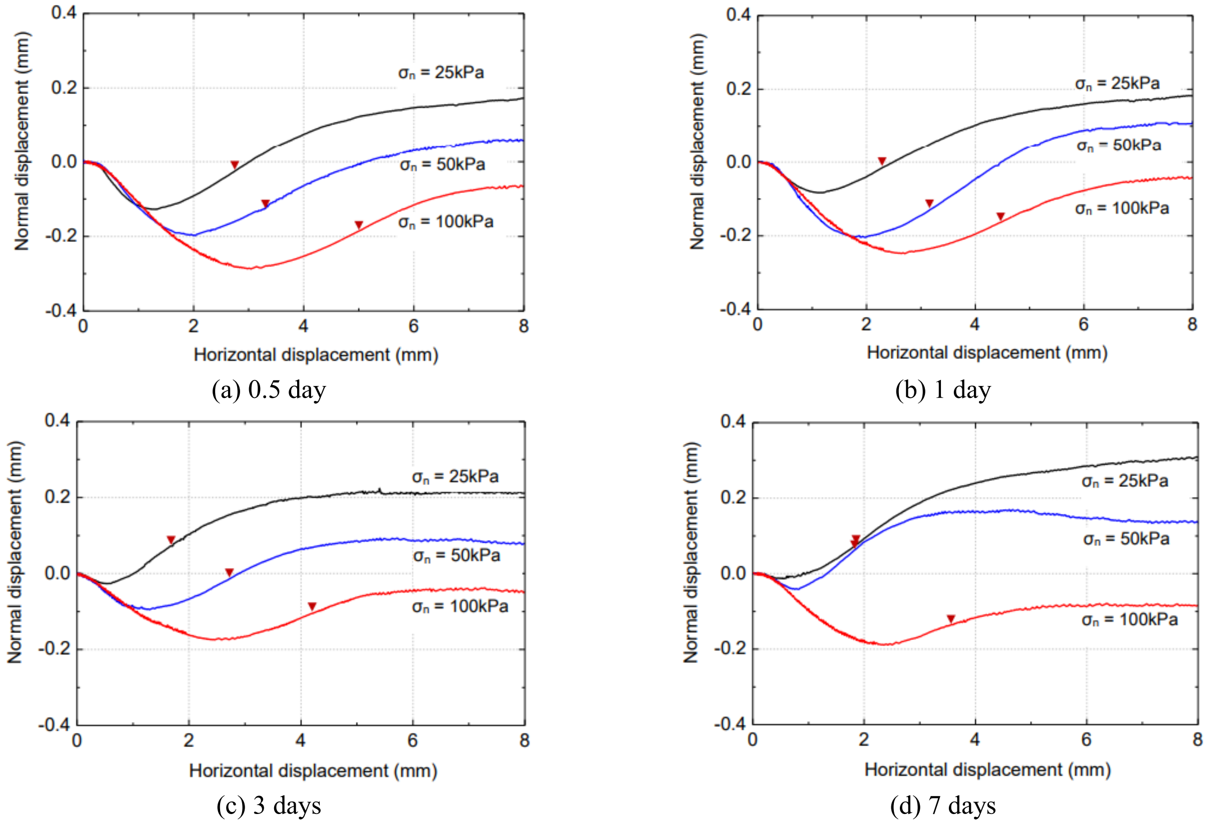
Fig. 4 Schematic drawings of the direct shear test for evaluating the interface friction between the CLSM and soil



(a) 0.5 day (b) 1 day

(c) 3 days (d) 7 days

Fig. 5 Shear stress curves for the poorly graded sand–CLSM interfaces during shearing

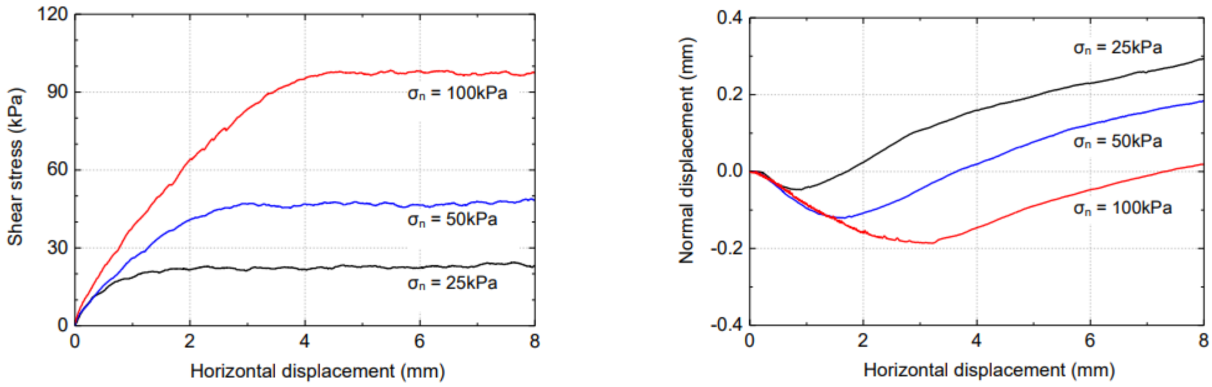


(a) 0.5 day (b) 1 day

(c) 3 days (d) 7 days

Fig. 6 Normal displacement curves for the poorly graded sand–CLSM interfaces during shearing

shearing rate of 0.4 mm/min was maintained during shearing. The interface frictions between the upper and lower boxes were measured up to a horizontal displacement of 8 mm.



(a) Shear stress (b) Normal displacement

Fig. 7 Direct shear test results for the well-graded sand–CLSM interfaces during shearing on 3 days

3.2 Poorly graded sand–CLSM interface

The variation in shear stress between the poorly graded sand and CLSM along the horizontal displacement for four different curing times is plotted in Fig. 5. Generally, the shear stress initially increased with increasing horizontal displacement, then reached a constant value. As the normal stress increased, the peak shear stress and the corresponding horizontal displacement also increased. Meanwhile, the horizontal displacement corresponding to the peak shear stress decreased as the curing time increased.

The normal displacement curves of the shear behavior at the poorly graded sand–CLSM interface are plotted in Fig. 6. Generally, the normal displacement initially decreased with increasing horizontal displacement. As the normal stress increased, the lowest normal displacement, which is also called the maximum contraction, increased. The positive and negative normal displacements indicated the dilation and contraction of the sheared specimen, respectively. After the maximum contraction, the normal displacement increased steadily and then dilated in the normal stresses of 25 and 50 kPa. In the normal stress of 100 kPa, the specimens could not dilate because of the higher confining pressure. The horizontal displacement corresponding to the maximum contraction increased as the normal stress also increased. Meanwhile, as the curing time increased, the horizontal displacement corresponding to the maximum contraction decreased. Like the shear behavior of soils, the horizontal displacement at the steepest slope of the normal displacement curve generally corresponded to the peak state of the shear stress, as marked with solid triangles in Fig. 6. In most cases, the normal displacements at approximately 8 mm of the horizontal displacement were stable.

3.3 Well-graded sand–CLSM interface

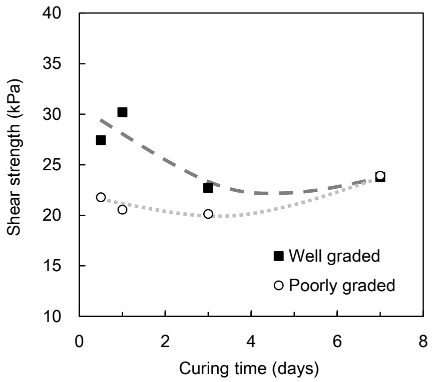
To characterize the effect of soil gradation on the interface friction, direct shear tests by using the well-graded sands and CLSM were also carried out. The typical curves of shear stress and normal displacement obtained 3 days after the curing are plotted in Fig. 7. Like the test results for the poorly graded sand–CLSM interface, the shear stress initially increased with increasing horizontal displacement and then stabilized at a certain value. As the normal stress increased, the peak shear stress and the corresponding horizontal displacement also increased. In normal displacement, contraction occurred initially, then was followed by the dilation. As the normal stress increased, the maximum contraction and the corresponding horizontal displacement also increased. Generally, the trends of the shear stress and normal displacement curves along the curing time for the poorly graded sand–CLSM and well-graded sands–CLSM interfaces were similar. However, their shear stress and normal displacement values were different. The normal displacement curves for the well-graded sands–CLSM interface showed an inclined slope around the final horizontal displacement unlike those of the poorly graded sand–CLSM interface. Although the well-graded sand–CLSM interface did not show a constant volume, the peak shear stress at the interface can be calculated.

4. Analyses and discussion

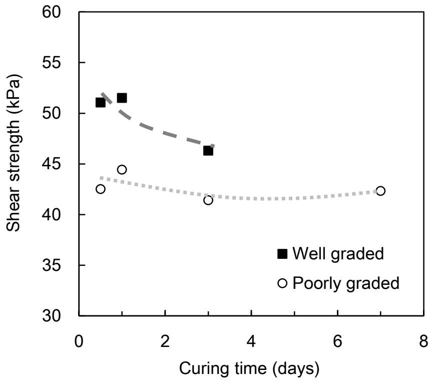
In this study, direct shear tests were carried out using the CLSM under three different normal stresses on four curing times. Given that natural soil was placed around the CLSM, two different soils were used that have similar mean diameters but different grain size distributions. To evaluate the effects of curing time, gradation, and normal stress on the interface friction of the CLSM, the results of the direct shear tests were analyzed on the basis of four different friction characteristics: (1) shear strength, (2) maximum dilation, (3) maximum contraction, and (4) friction angle. The detailed results on the four different friction characteristics are discussed in the following sections.

4.1 Shear strength

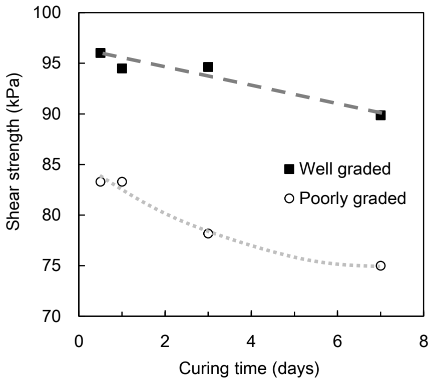
The direct shear tests were conducted under a constant normal load during the shearing. Accordingly, the normal stresses applied to the specimens slightly increased with increasing horizontal displacement, because the interface area decreased. Thus, the shear stress divided by the corresponding normal stress is defined as the stress ratio. On the basis of the stress ratio curve, the maximum stress ratio was selected. Moreover, after multiplying the maximum stress ratio by the targeted normal stress, the



(a) 25 kPa



(b) 50 kPa



(c) 100 kPa

Fig. 8 Variation of shear strength with the curing time under three different normal stresses

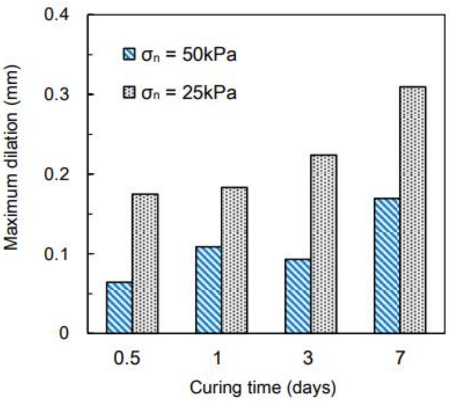


Fig. 9 Maximum dilation of the poorly graded sand–CLSM specimens during shearing under two different normal stresses

shear strength was calculated.

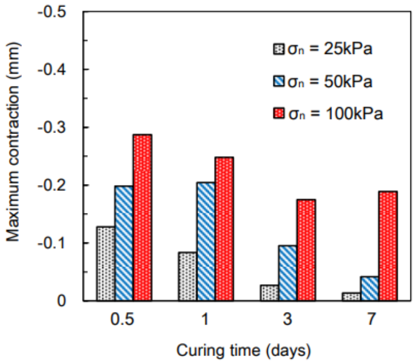
The shear strengths under the three different normal stresses along with the curing time are plotted in Fig. 8. Generally, the specimens cured within 1 day showed the highest friction between the CLSM and soils. When a hard material slides across a softer material, plowing occurs on the surface of the softer material, resulting in a higher friction force (Dove and Frost 1999). Considering the low compressive strength of the CLSM and the relatively high strength of individual soil particles reported by Nakata *et al.* (2001), the soil particles can penetrate into the surface of the CLSM after applying a normal load. Subsequently, the plowing of soil particles can be generated during shearing, resulting in the abrasion and removal of the CLSM. Given that the plowing depends on the relative hardness of the two materials, it can greatly influence the interface friction in the early hardening process. Therefore, the friction within 1 day was the highest, although the compressive strength within 1 day was much smaller than the later values. After 1 day, the shear strengths of both poorly graded and well-graded sands decreased, except for the poorly graded sand–CLSM specimen with a 25 kPa normal stress in 7 days. The result clearly showed that the plowing effect decreased as the curing time increased. Note that hardening continued as the curing time also increased. Unlike the normal stresses of 25 and 50 kPa, the shear strengths under the normal stress of 100 kPa consistently decreased up to 7 days. This result implied that the plowing effect on the interface friction was more dominant under the higher normal stress than under the lower normal stresses. Further, in the higher normal stress, the contact area of the soil particles increases (Dove and Frost 1999); hence, the interface friction increases.

4.2 Maximum dilation

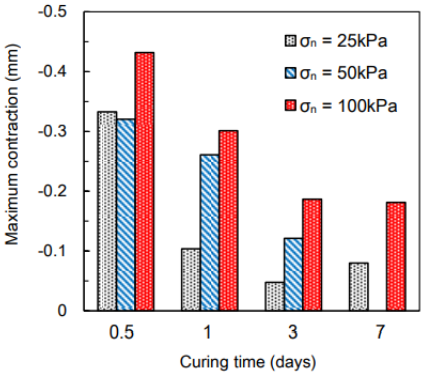
The maximum dilations of the poorly graded sand–CLSM specimens under the normal stresses of 25 and 50 kPa are plotted in Fig. 9, which indicates that the maximum dilation increased with increasing curing time. Thus, the shearing resistance between the CLSM and soils under the low normal stresses can be significantly influenced by the interlocking of soil particles. Particularly, the interlocking of soils was the most remarkable 7 days after the curing because of the hardened surface of the CLSM. The result was in good agreement with the shear strength of the poorly graded sand–CLSM specimen under the 25 kPa normal stress at 7 days, as shown in Fig. 8(a).

4.3 Maximum contraction

The variation in the maximum contraction during shearing along with the curing time of the CLSM–two soil specimens is plotted in Fig. 10. In both soils, the maximum contraction on 0.5 day was the highest, except for the normal stress of 50 kPa of the poorly graded sand–CLSM specimen. The results showed that the cementitious materials were not perfectly hardened by the curing time of 0.5 day. Considering the lower compressive strength of the CLSM at the early curing time, the plowing effect was the most significant at the curing time of 0.5 day. Generally, the maximum contraction for both soils increased with the increase in the normal stress. For the gradation, the



(a) Poorly graded sand



(b) Well-graded sand

Fig. 10 Maximum contraction under three different normal stresses

maximum contraction of the well-graded sand–CLSM specimens was greater than that of the poorly graded sand–CLSM specimens, especially for the curing time within 1 day. The result showed that the well-graded sands with wide range of grain size distributions can more easily contract during shearing than the poorly graded sand. Note that before shearing, the unit weights of the poorly graded and well-graded sands were almost the same.

4.4 Friction angle

The relationship between shear strengths and normal stresses measured on day 0.5 is plotted in Fig. 11. In both soils, the shear strength linearly increased with increasing normal stress. Generally, the shear strength of the well-graded sand–CLSM interface was greater than that of the poorly graded sand–CLSM interface. The wider contact area of the well-graded sand particles induced the higher shear resistance. Santamarina *et al.* (2002) reported that the specific surface of soils depends on the coefficient of uniformity, as well as the mean diameter. Note that the poorly graded and well-graded sands had equal mean diameters but different coefficients of uniformity. The higher difference in the shear strength at the 100 kPa normal stress could also have contributed to the wider contact area of the particles, resulting from a higher normal stress.

Based on the linear Mohr–Coulomb failure criterion, the friction angles of four different curing times are summarized in Table 3. These friction angles for the four different curing times were well established with the coefficients of determination of greater than 0.97. The

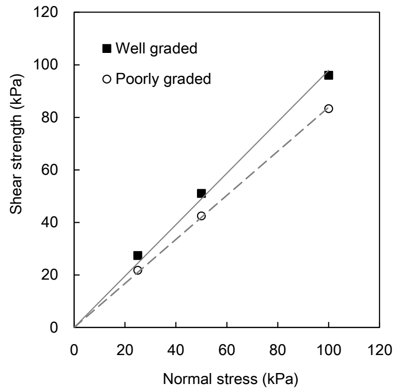


Fig. 11 Shear strengths versus normal stresses on 0.5 day

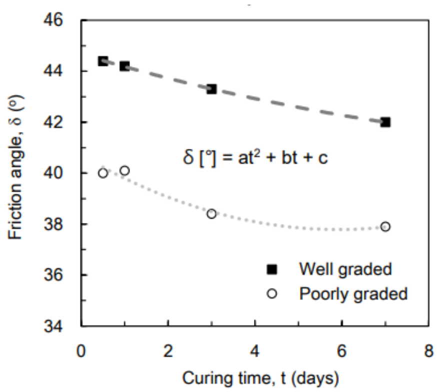


Fig. 12 Variation of friction angles with the curing time

Table 3 Interface friction angles and coefficient of determination with curing time

Curing time		0.5 day	1 day	3 days	7 days
Poorly graded sand	Friction angle, δ [°]	40.0	40.1	38.4	37.9
	Coefficient of determination, R^2	0.999	0.997	0.997	0.970
Well-graded sand	Friction angle, δ [°]	44.4	44.2	43.3	42.0
	Coefficient of determination, R^2	0.993	0.976	1.000	0.999

Table 4 Summary of the parameters of the friction angle models with curing time

Soils	Parameters			Coefficient of determination, R^2
	a	b	c	
Poorly graded sand	0.084	-0.9857	40.697	0.959
Well-graded sand	0.018	-0.5071	44.666	1.000

changes in friction angles during the curing time are plotted in Fig. 12. In both soils, the friction angles decreased as the curing time increased. The trends of the friction angles (δ) against the curing time (t) in both soils were well matched with the second-order polynomial regression models, as represented by the following equation.

$$\delta[^\circ] = at^2 + bt + c \tag{1}$$

where a, b, and c are the model parameters for the second-order polynomial and the unit of the curing time (t) is days.

The values for the three model parameters and coefficients of determination are summarized in Table 4. Although the shear strengths were influenced by the magnitude of the normal stress, the friction angles were rarely affected by that magnitude within the same range of the normal stress. That is, the interface friction angles between the CLSM and soil were closely related to the curing time of the CLSM and the gradation effect of the soils.

5. Conclusions

CLSMs are typically used for trench backfilling and void filling. However, the characteristics of the interface friction between the CLSM and natural soils had not been studied yet. Hence, the interface shear strength and behavior of the CLSM and soils based on the curing time, gradation, and normal stress were investigated in this study.

The CLSM was composed of fly ash, CSA cement, sand, silt, water, and an accelerator. Through flow and unconfined compressive strength tests, the high flowability and low strength of the CLSM were revealed. Poorly graded and well-graded sands were used to investigate the interface friction of the CLSM. These two sands had equal mean diameters but different gradations. By using the CLSM and soils, a series of direct shear tests were carried out to evaluate the interface friction characteristics. After mixing the CLSM, four different curing times were selected to carry out the direct shear test. In each test, three different normal stresses were applied to the CLSM–soil interface.

The direct shear tests carried out in this study provided the shear stress and normal displacement curves of the CLSM–soil specimens. The shear strength, maximum dilation, maximum contraction, and friction angle were analyzed to evaluate the effects of curing time, gradation, and normal stress on the interface friction of the CLSM. First, the shear strengths obtained within 1 day were higher than those obtained after 1 day, because the plowing of soil particles within 1 day was more significant. Second, the maximum dilation of the poorly graded sand–CLSM specimens under lower normal stresses generally increased with increasing curing time, because the CLSM was gradually hardened. Third, the maximum contraction of the poorly graded and well-graded sands generally increased with increasing normal stress, whereas the maximum contraction decreased with increasing curing time. In the early curing time, the maximum contraction of the well-graded sand–CLSM specimens was greater than that of the poorly graded sand–CLSM specimens. The results implied that the well-graded sands with a wide range of grain size distributions can more easily contract during shearing than the poorly graded sand. Fourth, the shear strength of the well-graded sand–CLSM interface was greater than that of the poorly graded sand–CLSM interface, because the contact area of the well-graded sand particles was greater. Finally, the friction angle for the CLSM– soil interface decreased as the curing time increased, indicating reliable trends for the variation in friction angles with the curing time. Regardless of the magnitude of the normal stress, the friction angles of the well-graded sand–CLSM interface were higher than those of the poorly graded sand–CLSM interface. Therefore, based on the shear mechanism, the characteristics of the interface friction between the CLSM and soils can be interpreted by considering the curing time, gradation, and normal stress.

Acknowledgments

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