

# SHEAR STRENGTH ENHANCEMENT OF COMPACTED SOILS USING HIGH-CALCIUM FLY ASH-BASED GEOPOLYMER

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**ABSTRACT:** The objective of this study is to experimentally assess the efficiency of geopolymer for the strengthening of soil material. Geopolymer used in the study is a utilizing of the high-calcium fly-ash (FA) mixed with sodium hydroxide (NaOH) and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) as an alkaline activator. The ratio of NaOH and  $\text{Na}_2\text{SiO}_3$  is 1:1. Three types of soils are used and each soil type is mixed with FA based geopolymer of 10% of dry soil by weight. Alkaline activator is fixed at 10% of optimum moisture content (OMC) of soil samples. Two conditions of soil sample were prepared for testing; soil samples mixed with fly-ash based geopolymer and mixed with tap water. They were compacted under the optimum moisture content then performed the direct shear test to determine the non-curing strength (at 0 days) and curing shear strength (at 7 days). The results indicate that OMC of silty sand and high plasticity silt (sludge) which mixed with fly-ash based geopolymer is slightly higher than those of sample mixed with tap water. OMC of a clayey soil is however slightly decreased when they were mixed with fly-ash based geopolymer. Soils mixed with fly-ash based geopolymer tend to give a higher state of the peak shear strength for curing sample about two times of soils mixed with tap water. This suggests that the fly-ash based geopolymer can be enhancing the shear strength of soils by increasing cohesion and friction angle. Soil improvement techniques using geopolymer can be applied for strengthening the soil embankment, soil slope, and earth dam foundation.

*Keywords: Geopolymer, Curing Period, Cohesion, Friction Angle, Soil Improvement*

## 1. INTRODUCTION

The shear strength is a challenging aspect of soil engineering works as soil slope stability in dam construction (tailing dam and earth fill dam) and retaining structure in the foundation. To be stable the soil slope, shear strength is essential to resist overburden pressure of soil strata. Cohesion and friction are main parameters for shear strength of soil. Ground improvement techniques are used to improve these parameters in term of by mechanical, hydraulic, chemical and physical modifications [1].

Compaction is a mechanical modification for improving the strength of soil. The compaction of soils is an important parameter for building roads, foundations, and all ground structures to improve mechanically. The amount of water will not be changed through soil compaction process and intergranular soil empty space reduced by removing the air, large pores will be changed to small one and water moved into the soil. The purpose of compaction is to improve shear strength and bearing capacity of the soil. Also, compaction caused by the reduction of shrinkage potential, subsidence, and permeability. So, shearing various parameters of compressed soil with geotechnical issues are so important such as foundation bearing capacity, soil lateral pressure and slopes stability. Moisture and compaction rates of shear strength parameters (cohesion and angle of internal friction) are

obtained through some tests on soil specimens [2].

Many researchers have extensively been studied on various materials to improve soil strength by chemical modification. Geopolymer is one of the popular chemicals to increase the strength of soil in ground improvement techniques as a green material with many advantages, such as low cost, high strength, the durability of weathering and friendly environment. The production of ordinary Portland cement (OPC) is an energy-intensive process and emits a very large amount of greenhouse gas, carbon dioxide into the atmosphere and the production of one ton of OPC releases about one ton of  $\text{CO}_2$  [3]. In soil engineering works, it is simplified that the geopolymer becomes an alternative and sustainable material to OPC.

In this study, the soil strengths are mechanically and chemically enhanced through the compaction and geopolymer. The shear stresses of compacted soils are experimentally developed by using geopolymer based on non-curing and curing condition. This reveals changes of cohesion and friction angle that indicate how the shear strength can be improved by using geopolymer at the same moisture content rather than by using water only. All test specimens are conducted in the laboratory at an ambient temperature which is to closely simulate the natural field condition.

## 2. TEST MATERIALS

### 2.1 Soil, Fly Ash, and Liquid Alkaline Activators

Three soil types are used in this study. They are collected from Ban Nong Bong, Muang district and Dan Keen, Chok Chai district, Nakhon Ratchasima and Bang Khen water treatment sludge, Metropolitan Waterworks Authority of Thailand (MWA). Their basic physical properties (specific gravity [4], grain-sized distribution [5] and Atterberg’s limits [6] are examined. Based on the Unified Soil Classification System [7], they can be classified as silty sand (SM), high plasticity silt (MH) and high plasticity clay (CH) for soil, which are collecting from Ban Nong Bong, Dan Keen and Bang Khen, respectively. Fig. 1 shows the particle size distribution of the soils. Index properties of soils used in this study are summarized in Table 1.

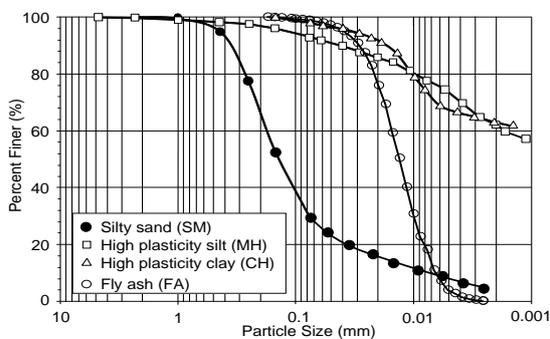


Fig. 1 Grain size distribution of three soil samples and fly ash.

Fly ash (FA) is a by-product of a waste material of thermal power plants in a process of combustion of pulverized coal in the furnaces. The amount of FA is annually produced about one billion tons worldwide in coal-fired power plants [8-10]. FA can regularly replace cement content up to 30% and 50-70% in the high volume of FA concrete [11]. FA used in this study is obtained from Mae Moh power plant in Northern Thailand. The chemical compositions of FA are shown in Table 2. FA particles are generally fine and spherical shape [12]. The specific gravity can be determined as 2.45.

Liquid alkaline activator is formulated by blending different proportions of commercial sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) solution and sodium hydroxide (NaOH). Sodium silicate is composed of 15.5 wt%  $\text{Na}_2\text{O}$ , 32.75 wt%  $\text{SiO}_2$  and 51.75 wt%  $\text{H}_2\text{O}$  and sodium hydroxide (NaOH) is 5 molar in solution. Both of chemicals are ready at liquid state. In this study, the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is one.

### 2.2 Soil Geopolymer

Soil-fly ash geopolymer is a mixture of liquid alkaline activator ( $\text{Na}_2\text{SiO}_3$  and NaOH), fly ash and soil. In this study fly, ash to soil ratio is fixed at 0.1.

The  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is 1.0. After blending soil, fly ash and liquid alkaline activator then they are used as testing material. The schematic mix design process is as shown in Fig. 2.

Table 1 Properties and classification of soil samples.

Locations	SG	LL (%)	PI (%)	Soil Types
Ban Nong Bong, Muang district, Nakhon Ratchasima	2.68	12.7	0.60	Silty sand (SM)
Dan Keen, Chok Chai district, Nakhon Ratchasima	2.67	68.0	29.20	High plasticity clay (CH)
Bang Khen water treatment plant, Bangkok	2.56	55.0	23.00	High plasticity silt (MH)

Table 2 Chemical composition of fly ash [12].

Chemical Composition (%)	Fly Ash (FA)
$\text{SiO}_2$	36.00
$\text{Al}_2\text{O}_3$	16.80
$\text{Fe}_2\text{O}_3$	17.64
CaO	26.73
$\text{SO}_3$	-
$\text{K}_2\text{O}$	1.83
$\text{TiO}_2$	0.48
$\text{MnO}_2$	0.15
$\text{Br}_2\text{O}$	-

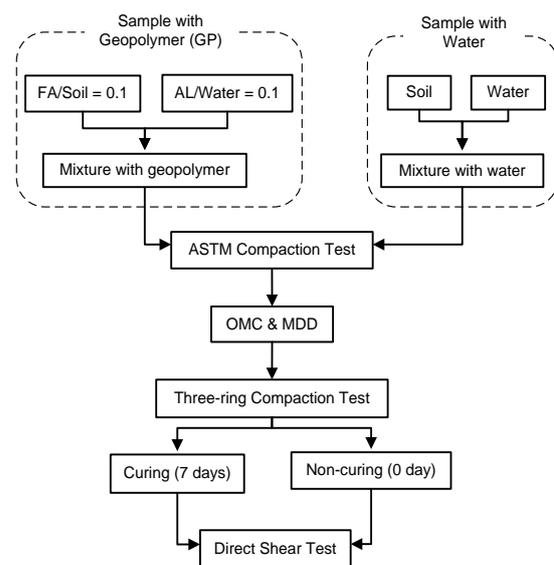


Fig. 2 Schematic representation of the mix design process for geopolymer compacted soils.

### 3. COMPACTION TEST

#### 3.1 Compaction with Water

The proper amount of oven dry soil is blended with tap water of various percentages as a conventional procedure of compaction test in a mixer for ten minutes to be homogenous. The soil mixture is routinely compacted in 4 inches mold according to ASTM D 1557 [13].

The compaction curve is obtained by drawing third-order polynomial curve through the measured data. The peak point on the compaction curve (Fig. 3) refers to the maximum dry density (MDD) and the corresponding water content to the MDD is the optimum moisture contents (OMC). The OMC and MDD of each soil type are as shown in Table 3.

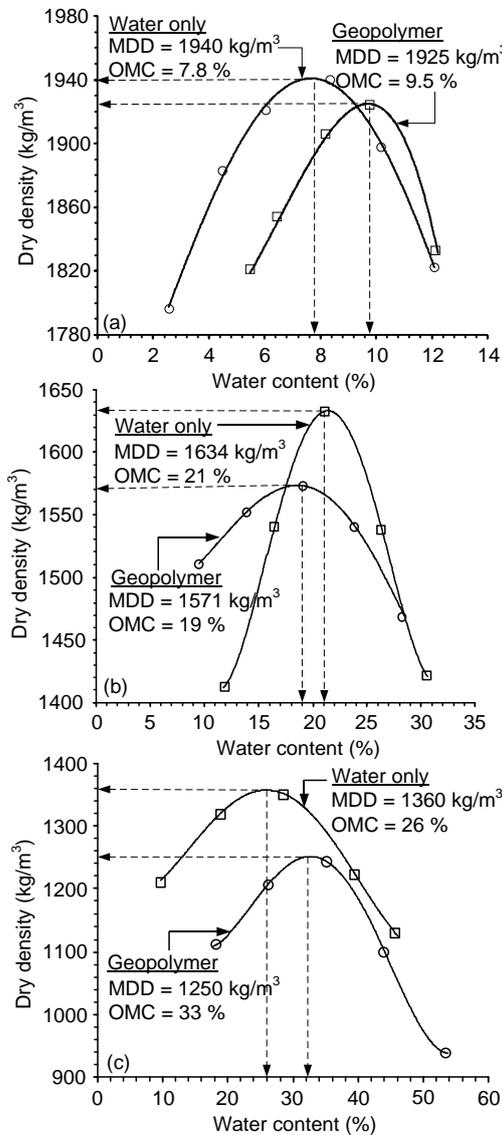


Fig. 3 Compaction curves using water and geopolymer for silty sand (a), high plasticity clay (b) and high plasticity silt (c).

Table 3 Shear parameters of three soil types between non-curing (0 days) and curing (7 days) condition.

Soil Type	Compaction Characteristic	OMC (%)	MDD (kg/m³)
SM	Water	7.8	1,940
	Geopolymer	9.5	1,925
CH	Water	21	1,634
	Geopolymer	19	1,573
MH	Water	26	1,360
	Geopolymer	32	1,250

The standard compaction mold consists of top ring and bottom rings as the diameter of 10.16 cm and height of 11.64 cm. The three-ring mold consists of a top, middle and bottom rings (Fig. 4). The inside diameter is 10.16 cm, outer diameter is 10.76 cm and combined height is 15.19 cm. The three rings are secured to the base plate using steel bolts and two steel clamps [11]. The soil sample in the three-ring mold is dynamically compacted with a release of steel hammer weight of 10 pounds and 27 blows per each of six layers. The energy of compaction is the same with ASTM modified proctor test [13]. Between three-ring mold and ASTM standard mold, the MDDs and OMCs obtained are very similar [14].

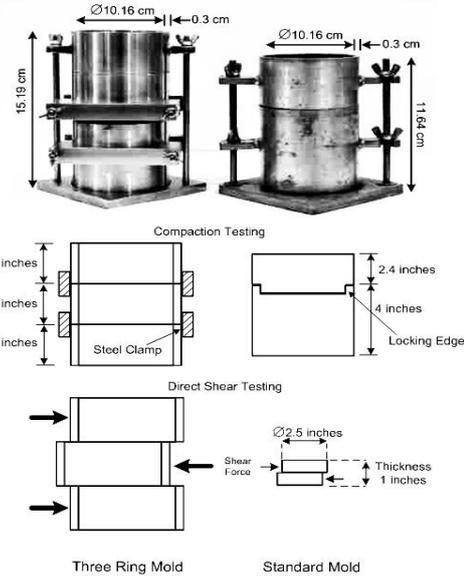


Fig. 4 Three-ring compaction mold (left) and ASTM standard mold (right).

The OMCs of soil from ASTM standard mold is prepared as moisture contents for three-ring compaction samples to be installed in the direct shear device (Table 4). The densities of compacted samples in three-ring molds are checked to be MDD condition corresponding to OMCs of ASTM standard mold before installing into the direct shear device (Table 5).

Table 4 Moisture contents variations from the direct shear test specimens under normal stresses of 0.4, 0.6, 0.8 and 1.0 MPa.

Soil Type	Curing Time (days)	Tested Samples with	OMC (%)	Moisture Content (%)			
				@0.4 MPa	@0.6 MPa	@0.8 MPa	@1.0 MPa
SM	0	Water	7.8	7.5	7.6	7.6	7.6
		Geopolymer	9.5	7.4	7.5	7.5	7.9
	7	Water	7.8	7.6	7.7	7.5	7.6
		Geopolymer	9.5	7.7	7.7	7.9	7.9
CH	0	Water	21	19.8	18.1	19.0	18.4
		Geopolymer	19	19.3	19.6	18.6	18.3
	7	Water	21	22.6	22.5	22.0	21.6
		Geopolymer	19	17.3	18.2	17.1	18.3
MH	0	Water	26	27.9	27.6	28.4	27.3
		Geopolymer	32	32.1	32.0	32.7	31.6
	7	Water	26	28.6	28.4	28.6	28.5
		Geopolymer	32	32.4	33.3	32.3	32.4

Table 5 Dry densities obtained from the direct shear test specimens under normal stresses of 0.4, 0.6, 0.8 and 1.0 MPa.

Soil Type	Curing Time (days)	Tested Samples with	MDD (kg/m <sup>3</sup> )	Density (kg/m <sup>3</sup> )			
				@0.4 MPa	@0.6 MPa	@0.8 MPa	@1.0 MPa
SM	0	Water	1,940	1,937	1,941	1,940	1,941
		Geopolymer	1,925	1,926	1,925	1,925	1,924
	7	Water	1,940	1,940	1,943	1,939	1,939
		Geopolymer	1,925	1,926	1,926	1,924	1,926
CH	0	Water	1,634	1,653	1,635	1,615	1,650
		Geopolymer	1,573	1,589	1,607	1,614	1,619
	7	Water	1,634	1,625	1,635	1,636	1,628
		Geopolymer	1,573	1,598	1,597	1,592	1,655
MH	0	Water	1,360	1,360	1,360	1,360	1,359
		Geopolymer	1,250	1,249	1,250	1,250	1,250
	7	Water	1,360	1,360	1,360	1,359	1,359
		Geopolymer	1,250	1,249	1,249	1,250	1,250

### 3.2 Compaction with Geopolymer (GP)

The proper amount of dry soil is mixed with FA as a ratio of 0.1 by weight. Liquid alkaline activator and water (with a ratio of 0.1 by weight) is added into the mixture of dry soil and FA and then blended for fifteen minutes. The modified compaction test is performed in 4 inches' mold of ASTM standard. Likewise, in the previous compaction with water, the MDDs of ASTM mold is prepared for three-ring samples of the direct shear device. The densities of three-ring molds are checked before conducting the direct shear test in the three-ring shear device, as shown in Table 5.

### 3.3 Test Results

The compaction results on soils and soil-fly ash geopolymers are compared on the same graphs with a function of dry densities and moisture contents. In silty sand, MDDs are 1,940 kg/m<sup>3</sup> for water only and 1,925 kg/m<sup>3</sup> for geopolymer, and OMCs are 9.5% for water only and 7.8% for geopolymer, as shown in Fig. 3(a). For other two types of soils, OMCs and MDDs are as shown in Fig. 3(b) and

3(c). All of the soil types behave that the maximum dry densities of soil samples mixed with geopolymer are less than the soil samples mixed with water. This is due to the low specific gravity of FA material (SG = 2.45). Moreover, the compaction with geopolymer gave a higher OMC than those compactions with pure water, when the samples are dried in an oven, they will give a lower MDD.

## 4. DIRECT SHEAR TEST

The direct shear test is the oldest and simplest form of shear test arrangement. It is commonly used to measure the shear strength of soil because the time taken for the test is fast and the sample preparation is easy [15]. In ASTM D 3080 [16], the test method and equipment have a disadvantage that the compacted soil samples are required to be removed from the 100-mm diameter compaction mold, trimmed and installed into a smaller shear mold (60-mm diameter). The process could disturb the samples physical properties [17]. The small shear test mold limits the maximum particle size of the soil sample [18].

#### 4.1 Test Device

The three-ring shear testing device is used to measure the shear strength of compacted soils for actual field conditions. This testing device is developed and proposed by Sonsakul et al. [14]. It serves as both compaction mold and shear box without sample disturbance of ASTM standard mold. The direct shear load frame fabricated for the three-ring mold can maintain a true vertical load on the sample during shearing. The vertical load frame for commercially available direct shear devices will slightly tilt as the shear force applies on one of the shear boxes. The three-ring mold can allow the maximum grain size of up to 10 mm. Soils with larger grain sizes demonstrate the higher shear strength than smaller grain sizes. For slope stability of compacted soil, the higher shear strength results are more reliable to approach the actual field condition.

#### 4.2 Sample Preparing and Curing Period

The soil samples after compacting in the three-ring mold are performed the direct shear test based on curing period. Horizontal normal stress and lateral shear force are applied from a 20-tons hydraulic hand pump to all compacted soil samples in the shear device. Normal stresses are 0.4, 0.6, 0.8 and 1.0 MPa, and shear displacement rate is about 0.02 mm/s to be significant and distinct shear behaviors.

Shear strengths of soils are measured for non-curing (at 0 days) and curing (at 7 days) of the compacted sample under ambient temperature. After the soil mixtures are compacted in the three-ring mold, the compacted sample for non-curing (0 days) condition is directly installed in the three-ring shear testing device as shown in Fig. 5. For curing strength, the compacted sample is kept in an airtight plastic bag under ambient temperature to outcome shear strength development of soil on curing time for 7 days. When reached the seventh day, the sample is taken out of the plastic bag to perform the three-ring direct shear test.

#### 4.3 Test Results

The shear test data are plotted on a graph with the relationship between shear stress and shear displacement. Under different four normal loads, the peak shear stress and residual shear stress are attained. In silty sand and high plasticity silt, the shear stresses of the non-curing state are slightly different between water and geopolymer (Fig. 6(a) and 6(c)). The shear stresses of curing condition are almost double different (Fig. 6(b) and 6(d)). The shear stresses of high plasticity silt are shown in Fig. 7(a)-7(d). Likewise, in high plasticity clay, the

behaviors of shear stresses are same as previous two soils (Fig. 8(a)-8(d)).

The peak shear stresses are related to shear strength and normal stress. According to the graphs, peak and residual shear strength vary with the curing period. Silty sand and high plasticity silt are same in behaviors. All of the peak and residual strengths are display as the curing period increases the shear strength of compacted samples with geopolymer, expect of clay sample in cured residual shear strength (Fig. 9). In addition, the shear strengths of each soil samples are arranged in Table 6. The test results show that the manners of peak and residual shear strength are depended on soil type.

For silty sand, the peak shear strength of samples is reached at around 2.5 mm except 7 days cured sample with geopolymer occurred around 1 mm. For high plasticity silt, peak shear strengths occur within 3 to 4 mm until 7 day's strength of sample with geopolymer occurred around 2 mm. In high plasticity clay, the shear strengths are diverse from previous two soil samples. The peak shear strengths are taken place around 1 mm.

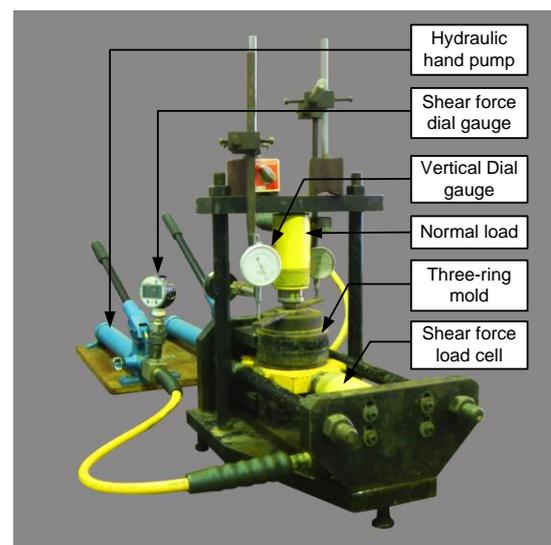
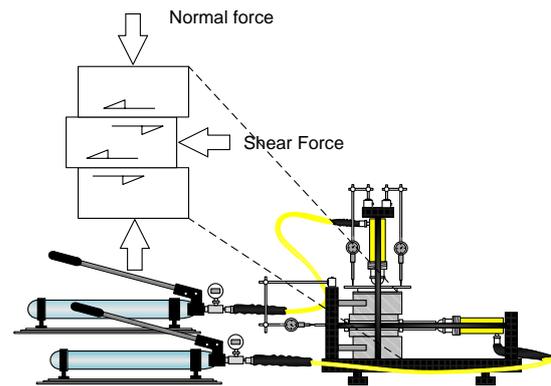


Fig. 5 Cross-section of Three-ring mold installation (top) and direct shear testing device (bottom) after Sonsakul, et al. [14].

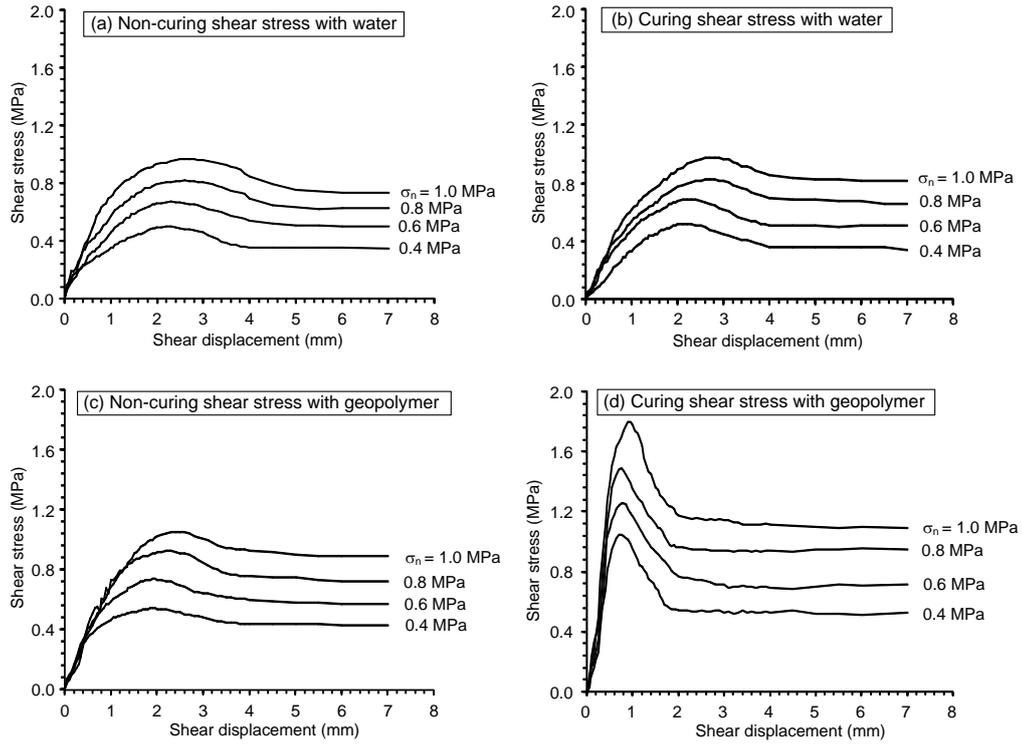


Fig. 6 Shear stresses related to shear displacement obtained for silty sand (SM).

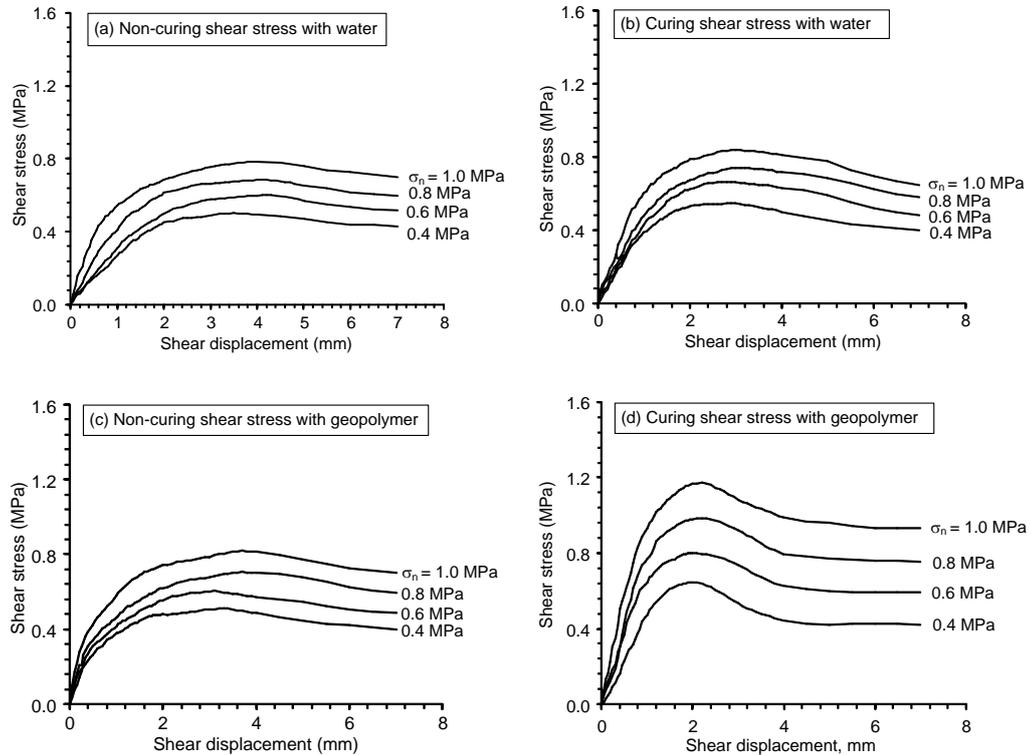


Fig. 7 Shear stresses related to shear displacement obtained for high plasticity silt (MH).

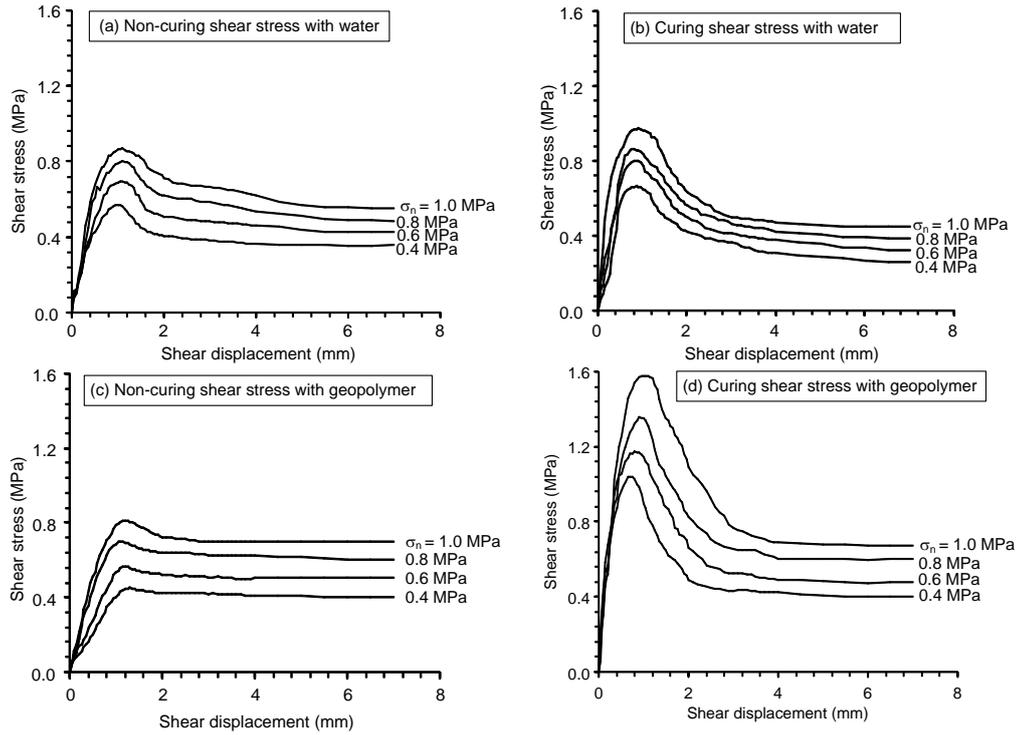


Fig. 8 Shear stresses related to shear displacement obtained for high plasticity clay (CH).

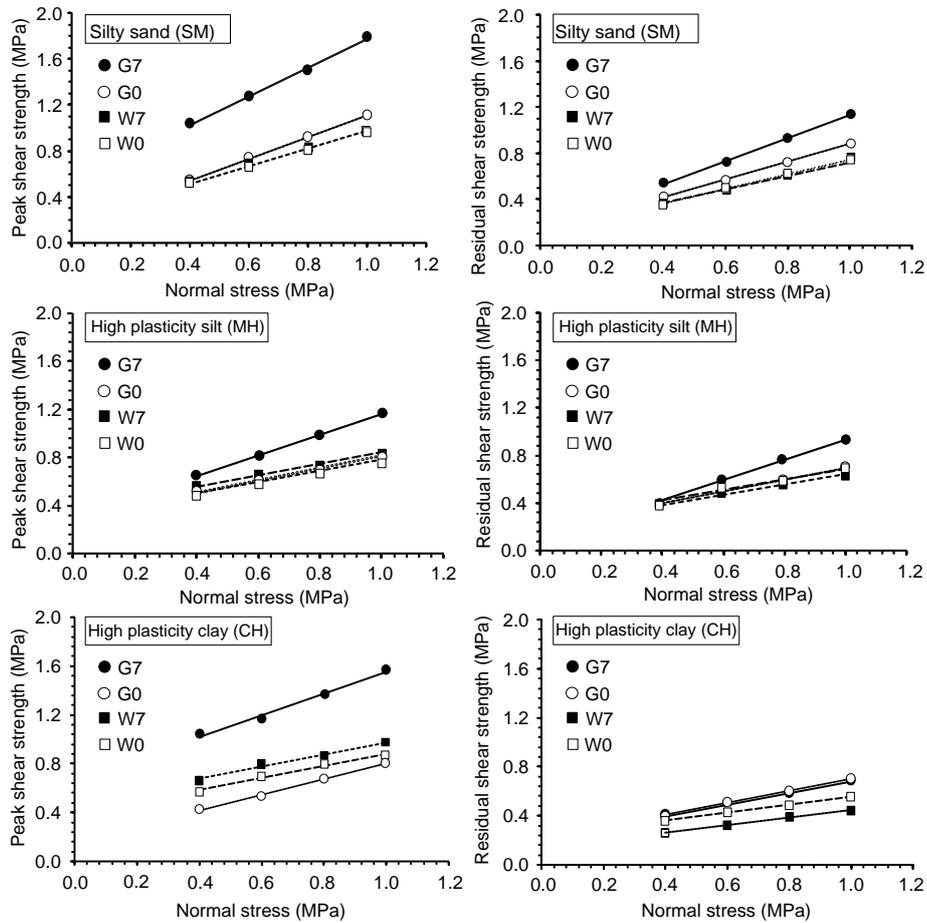


Fig. 9 Peak (left) and residual (right) shear strength for curing (7 days) and non-curing (0 days) samples.

Table 6 Shear parameters of three soil types between non-curing (0 days) and curing (7 days) conditions.

Soil Type	Curing Time (days)	Tested Samples with	Peak		Residual	
			$c_p$ (MPa)	$\phi_p$ (degrees)	$c_r$ (MPa)	$\phi_r$ (degrees)
SM	0	Water	0.20	37.8	0.11	32.5
		Geopolymer	0.22	43.3	0.12	37.3
	7	Water	0.23	36.7	0.11	32.4
		Geopolymer	0.59	51.4	0.13	45.1
CH	0	Water	0.38	26.5	0.23	18.0
		Geopolymer	0.17	32.4	0.21	26.2
	7	Water	0.48	26.2	0.14	17.4
		Geopolymer	0.66	41.8	0.24	25.2
MH	0	Water	0.32	25.0	0.25	23.8
		Geopolymer	0.30	27.2	0.19	26.8
	7	Water	0.37	25.4	0.21	23.3
		Geopolymer	0.29	41.3	0.08	40.5

### 5. DISCUSSIONS AND CONCLUSIONS

The standard compaction test and three-ring direct shear test have been performed in the laboratory to assess the enhancing shear strength of compacted soils with geopolymer. The study is of importance when the local soils need to be strengthening to meet the design requirements in field conditions, such as soil embankment, soil slope, and earth dam foundation. Three soil types (silty sand, high plasticity silt, and high plasticity clay) are compacted in a three-ring mold under optimum moisture content (OMC) before the shearing process in the direct shear device. The test specimens are based on curing (7 days) and non-curing (0 days) state under ambient temperature (27°C to 30°C). The ambient temperature is feasible as field conditions. For curing state, the specimens in the three-ring mold are kept in airtight plastic bags to control the moisture loss. For the non-curing state, the specimens are immediately sheared in the three-ring direct shear testing device. Curing and non-curing are to approach the strength after construction. Otherwise, the most of chemicals need time interval to take place chemical reaction inside their phase together with raw materials like local soils. While shearing, the horizontal displacement rate (shear displacement rate) is reasonable in 1 mm/min to be obvious strain softening of typical soils in shear behaviors. All specimens have been sheared with the dry state without submerging into water.

For silty sand and high plasticity silt, these soils samples with fly ash based geopolymer are increased in the optimum moisture content and a decrease in the maximum dry. In contrast, high plasticity soil with fly ash based geopolymer is acting differently in increasing of optimum moisture content corresponding with increasing of maximum dry density. It is like to be that fine particles of fly ash come inside of soil grains and closer between soil

grains with a more lubricating agent, alkaline liquid. They absorb more water, and then the moisture content is increase than in the state of mixing with water. The compaction result point outs that fly ash based geopolymer cannot improve the maximum dry density of soils.

The result of three-ring direct shear tests gives higher strengths in shearing when the soil samples are mixed with geopolymer and those higher strengths increase more in all soil types through curing state. After compacting with fly ash based geopolymer, the soils are attained a harden state through time period as long as chemical reaction occurs between soil grains and geopolymer molecules. In fields, when the selected soils are instantly mixed with chemical substances, the blending process should not be longer to save time-consuming of the project. In the laboratory, the short time interval (almost 15 minutes) of mixing process of soil samples with geopolymer reflects the advantages on field condition that in-situ mixing process can be performed as fast as possible. Moreover, the more laboratory strengths based on curing period under ambient temperature (27°C to 30°C) also point out that the field strength can also be attained after construction because of a chemical reaction under ambient temperature in actual condition. Although the clay soil is normally low internal friction angle, the compacted condition with geopolymer makes a higher internal friction angle. Indeed, the compaction can increase the shear strength of soil mechanically. The soils mixed with geopolymer transform to more brittle behavior in strain softening. This notes that fly ash based geopolymer enhances the shear strength of soils by increasing the cohesion and friction angle. Soil improvement techniques using geopolymer can be applied for strengthening the soil embankment, soil slope and earth dam foundation.

## 6. ACKNOWLEDGEMENTS

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