Effectiveness of lowering saturation on residual shear strength of sand stabilized with fly-ash

M Simatupang

1Department of Civil Engineering, Halu Oleo University, Kendari, Indonesia 93232
E-mail: minson.simatupang@uho.ac.id

Abstract. The established cementitious compounds as the pozzolanic reaction product could significantly ameliorate the peak shear strength of stabilized sand with fly ash. However, the enhancement of its residual shear strength has not been known well. In this research, the effects of fly ash percentages, curing times, and saturations, on various compositions, on the shear strength of stabilized sand were observed through direct shear strength tests. The residual shear strength of stabilized sand with fly ash was compared with that of bare sand. The research found that stabilized sand's shear strength increased with fly ash and curing time and decreased with saturation, both at peak and residual state. There is a significant improvement in the residual friction angle, even in a small fly ash percentage, by reducing saturation during the specimen preparation. The useful effect of fly ash bonding remained in the friction angle after the shearing occurrence, showing that the sand stabilization approach with fly ash was effective during and after shearing.

1. Introduction
The utilization of binding agents in improving the mechanical properties of soils is currently an exciting area of development. Many binders, such as calcite precipitation, fly ash, lime, and cement, have been used extensively to enhance the ground's resistance to liquefaction due to earthquakes [1–7]. The effectiveness of binding material on the stabilization of soils is based on its ability to maintain the given soils' mechanical properties, both during and after the shearing occurrence. It was confirmed that the bonding given by the binder was easily destroyed during shearing. However, whether there is still a beneficial effect of the binder on the treated soil after shearing is unknown. There are two different kinds of resistance given by the binder on the stabilized soils against shear: bonding resistance and dilative nature. Bonding resistance is resistance added by the binder to soil particles, while dilative nature enhancement is due to relative angularity. That is the ratio between bond size provided by the binding agent itself and the soil's particle size [4,7].

Currently, mixing soil with fly ash as a binding agent is a prospective alternative for ground improvement technique thru chemical reaction [8–10], especially for cohesionless soils. With the presence of water, the lime contained in the fly ash is separated, and cementitious materials composed of hydrate gel of both calcium silicate and calcium aluminate are generated.

Since fly ash is an industrial waste material, stabilization of sand with fly ash can degrade environmental contamination and materials costs [11,12]. It was confirmed that stabilized sands with fly ash could significantly ameliorate the mechanical properties of sands. Many studies have been conducted on stabilized sands' mechanical properties with fly ash, such as shear strength, unconfined compressive strength, California bearing ratio, and modulus of resilient [7–9,12–15]. They found that fly ash addition to inorganic soils could upgrade those properties plausibly.

It has also been reported in detail those parameters of shear strength, cohesion “c” and angle of friction "θ" at crest failure condition increase with both fly ash percentage and curing time [7,15].
However, their alteration on residual shear strength of sand stabilized at various compositions of both fly ash percentage and curing time has not been known well. It is interesting to compare with bare sand if the shear strength of the stabilized sand remains after the shearing.

On the other side, the strength improvement of sand stabilized with fly ash depends not only on fly ash amount and curing time but also on moisture content. The reduction in the moisture of stabilized sand will improve the sand's mechanical properties [15–17]. The advantages of lowering saturation on strength improvement of stabilized sand have been noted by Cheng et al. (2013), and Simatupang and Okamura (2017). The binder will accumulate locally at low saturation at particle contact surfaces directly related to the strength amelioration. They claimed that the same amount of binder, specimen prepared at low saturation produced a higher strength than that at higher saturation. They also observed that the binder amount could be halved to provide a specific strength by lowering saturation from 100% to 30%. The scopes of the previous research on stabilized sands with fly ash were limited to the attempts to examine their strength in peak conditions. Little research has been conducted to obtain their strength at residual state under different saturation during the specimen preparation.

As mentioned above, a series of direct shear strength tests have been carried out on both stabilized sand and bare sand in the gap view. Testing parameters are fly ash percentages, curing times, and saturations at a sundry arrangement. The tests are conducted until the specimen failure, where the almost stable value of shear strength is obtained and is named in this study as residual shear strength. Typical stress-strain relationships at various combinations of parameters under three different vertical loadings are presented. Besides that, shear strength comparisons between stabilized sand and bare sand were evaluated. Additionally, residual shear strength properties at residual state were analyzed. Peak shear strength behaviors were also included as a comparison.

2. Material and methods

2.1. Materials

Materials used in this study consisted of fine sand taken from the Pohara river and fly ash from the Nii Tanasa electric steam power generation industrial waste. Both were located in the Konawe Regency, Southeast Sulawesi Province of Indonesia. Following is a brief explanation of their properties.

2.1.1. Fine sand

Fine sand with 0.075-0.25 mm in size had a grain size distribution, as shown in Figure 1. Other sand properties were: specific gravity of $G_s = 2.67$, mean grain size of $D_{50} = 0.18$ mm, and maximum and minimum void ratio were 1.23 and 0.88, respectively. The sand was categorized as poorly graded sand following the Unified Soil Classification System [19]. The sand's grain was almost uniform in size with a coefficient of uniformity $Cu = 2$ and had angular to subangular shape.

2.1.2. Fly ash

Fly ash utilized was the industrial waste from coal combustion, which had a relatively smooth gradation of less than 2 mm. The fly ash's mean grain size was $D_{50} = 0.037$ mm, far below that of fine sand. Based on the grain size distribution using sieve analysis shown in Figure 1, at least 50% of the fly ash minerals passed thru the sieve No. 200.

Nii Tanasa fly ash contained as high as 24.04% calcium oxide (CaO) and 19.88% silicon dioxide (SiO$_2$) [7]. That the ratio between CaO and SiO$_2$ (CaO/sizeof) is more than one denotes that the Nii Tanasa fly ash is the prospective cementation material [20]. On the other side, the loss on ignition (LOI), which indicates the sum of unburned coal in the ash, is around 1.134%. This LOI is less than the maximum boundary for class C ash of less than 6% [21]. Based on that information, fly ash originating from the industrial waste of Nii Tanasa electric steam power generation is classified as class C that can self-cement and have a great CaO content.
2.2. Methods
The dry sand and fly ash were mixed evenly in the plastic bag before the water was added, and then it mixed again evenly. The shear mold with a diameter of 6.5 mm and a height of 2.2 mm was then filled with the sand-fly ash-water mixture and tamped to a target relative density of around 50%. Before shearing tests, curing for 7, 14, 28, and 56 days were performed on specimens. In creating a failure line, a series of direct shear strength investigations were realized under three different vertical loadings on different samples, but at the same fly ash percentage, curing time, and saturation at a constant strain rate of 1%/second till specimens achieved a steady-state at failure. Each of their strengths at every peak or residual state was plotted at the stress-strain relationship to establish a failure line according to Mohr-Coulomb strength theory.

3. Test conditions
The careful design of test conditions consisting of fly ash (FA) percentage, curing time (CT), and saturation during the preparation of the specimen (S_r) were meant to study their effects, in combination, on the residual shear strength of stabilized sand with fly ash. This method was done to know the effectiveness of that approach on shear strength refinement after shearing. The FA percentages were in the ranges of 5-30% with 5% interval, and CTs were 7-56 days. Each ensuing CT was set by multiplying the previous one with 2. The saturation degrees during the preparation of specimen were 30% and 100%.

Three different specimens on the same FA, CT, and S_r were loaded vertically at a different scale, 4, 8, and 12 kg for each sample during the implementation of direct shear strength tests. The relative density of specimens investigated was targeted at 50% with ±2% tolerances. The total amount of material used at that density was around 95 gr for both fine dry sand and fly-ash, and close to 11.3 ml and 37.5 ml of water volume at 30% and 100% saturation, consecutively. A strain rate of circa 1%/s was applied to the specimens during shearing tests until the sample failed.

4. Results and discussions
4.1. The behavior of sand stabilized with fly ash under varying vertical loadings
A series of direct shear strength tests were conducted at various FAs, CTs, and S_r.s. At the same vertical loading, shown typically in Figure 2, shear strength increased with FA up to a specific strain where the peak stress was reached. At low percentages of FA, it went up and down gradually. In contrast, it rocketed to a higher FA till the peak stress but decreased sharply after that. The peak stress was achieved at a deficient strain of around 1.5% at low FA and 2% at a higher FA. It shows that the higher the FA in the specimen, the stronger the sample itself against shearing till a specific strain, as stated previously.
Figure 2. Stress-strain relationship of fine sand. a) at various vertical loading (VL) and FA cured along 56 days under S_r-100%, b) at various VL and CT cured at 30% FA and S_r-100%, c) at various VL and S_r cured along 56 days at 30% FA.

On the other side, amelioration in shear strength occurs along with an increase in CT and a decrease in S_r. This is due to self-cementing, self-hardening, and decreasing moisture during curing. That the improvement in the treated soil's mechanical properties using geopolymer and Portland cement is highly influenced by moisture content has also been reported by Ghadir and Ranjbar (2018). The decrease in moisture was also achieved by lowering S_r during the specimen preparation, reducing time to evaporate.

The peak of the shear strength curves depicted in Figure 2 is higher under bigger VL at the same FA, CT, and S_r. Bigger VL makes the specimen more compact and directly increases the number of interparticle contact among grains. Consequently, an increase in the sum of shear surfaces is obtained, which contributes directly to improving the specimen's shear resistance (Acar and El-tahir 1986; Chang and Woods 1992). At the same FA, CT, and S_r, however, specimens loaded at higher VL exhibit more brittle behavior on shear, where the shear strength curves of the specimens tend to move leftwards. In this case, a smaller strain is capable of destroying the FA bonding.

4.2. Parameters of shear strength of stabilized sand with fly ash
The relationship between residual shear stress (τ_r) and normal stress (σ) at various FA and S_r is depicted in Figure 3. This relationship on the peak shear stress (τ_p) of stabilized sand is also included as a comparison. Those shear stresses are determined based on the Mohr-Coulomb failure criteria. Both of them, peak and residual stresses, are specified when the shear strength's peak and steady-state strength were reached on the stress-strain relationship, respectively, as shown in Figure 2.
Based on the graphs in Figure 3, shear strength parameters of stabilized sand at peak and residual conditions are always higher than that of bare sand and increase with FA. However, in the residual state, the shear strength parameter of cohesion "c" of stabilized sand becomes zero, indicating that the destruction of the FA bonding has occurred. In terms of cohesion, the beneficial effect of FA bonding, which binds the sand grain, has been disappeared as strain proceeded. Fortunately, the residual friction angle "θ" of stabilized sand seems higher than that of bare sand. Although the FA bonding has been destroyed as the strain exceeded the turning point, the beneficial effect of the FA bonding at the friction angle seems to remain. As for this study, the residual shear strength of stabilized sand with fly ash is only contributed by the residual friction angle.

4.3. Residual friction angle of sand stabilized with fly ash.

The residual friction angles of stabilized sand at different FAs, CTs, and Sr values are presented in Figure 4. Along with the increase in FA percentage, the residual friction angle improvement takes place irrespective of CT. This is due to the FA bonding, binding grains of sand into bigger and stronger particles. Consequently, they produce a higher relative angularity contributed by FA, which directly relates to an increase in the residual friction angle [4,7,25–27].

The friction angle of stabilized sand observed in this study at residual state seemed to have less value than the one at peak condition, as shown in Figure 3. The destruction of the FA bonding occurring during shearing was predicted to reduce the observed peak angle. As the FA bonding was destructed, the size of the bond generated by the FA that bound the sand grain might reduce during the shearing, thereby decreasing the relative angularity, which contributed directly to the reduction in the friction angle. As shown in Figure 4(a), the residual friction angles of stabilized sands observed under Sr-100% were in the range of 27.59° – 30° smaller from the peak friction angle of 27.78° - 30.14°, which was above the bare sand friction angle of 27.41°. It means that the beneficial effect of the FA bonding remains in the specimen after shearing in the form of an increase in the friction angle. Based on the Mohr-Coulomb strength theory, the increase in the shear strength occurs along with the friction angle increase even though FA bonding has been destroyed. Those residual friction angles on the other side were slightly below the residual friction angles of the stabilized sand under Sr-30%, which were in the range of 27.97° - 34.55°, as shown in Figure 4(b).
The residual friction angle increased along with an increase in CT. However, under the CT of less than 28 days, the increase was relatively narrow and almost the same despite a higher percentage of FA. The research conducted by Singhi et al. (2017) on the stabilized clayey soil showed the same trend. Within this duration, weak bonds probably produced yielding in low strength as well. The strength improvement occurs over time because of the residual friction angle improvement, as shown in Figure 4. However, there is little improvement in the CT of less than 28 days, but the increase is significant after that. As the FA percentage increases, the strength, as well as the friction angle, also increases. Pozzolanic responses hold an essential role in this thing. It needs enough time to accomplish the reaction in generating cementitious materials that responsible for enhancing the strength of stabilized sand with fly ash.

At low $S_r$, the amount of FA can be reduced significantly to provide a certain residual friction angle. It is clearly shown in Figure 4 that at $S_r$-100%, the highest residual friction angle of around 30° was obtained at a higher CT-56 day and 30% FA [Figure 4(a)]. In order to provide the same residual friction angle of about 30%, the amount of FA could be turned down to 5% by reducing $S_r$ to 30% at a higher CT of 56 days [Figure 4(b)]. The same trend was obtained by Cheng et al. (2013), who conducted unconfined compressive strength tests on calcite precipitated silica sand at different saturations. They got that the strength and stiffness of calcite treated silica sand increase with the reduction in saturation. Simatupang and Okamura (2017) performed liquefaction resistance investigations on calcite treated sands (Keisha no.4 and Toyoura) at various saturations. They concluded that a higher liquefaction resistance was obtained in a specimen with a lower saturation during the curing. It was proved using SEM images performed on the samples treated at different $S_r$ of 30% and 97% during curing. The precipitated calcite was agglomerated in the contact points when the specimen was treated at 30% saturation. At 97% $S_r$ during curing, however, the calcite was precipitated on the grain's whole surface.

Based on the test results obtained in this investigation supported these findings. That is, the residual friction angle of stabilized sand with fly ash could be increased by decreasing saturation during the preparation of the specimen. The agglomerated fly ash bonding at the contact surface becomes the main factor for effectively binding sand particles. As fly ash will react with water, the existence of water, particularly on the contact surface at low saturation, would generate the fly ash bonding specifically at that point directly related to the strength enhancement. It was noted that its formation determined the binder's effectiveness in the contact surface between grains rather than its amount on the whole surface of the grain [3,18]. This fact was also remarked by Hataf et al. (2018) in their research on the utilization of chitosan biopolymer for soil stabilization [29].
5. Conclusion
Based on the test results and discussions prepared in the previous section, the main findings are presented below. Shear strength curves of sands stabilized with fly ash observed in this study move smoothly in all stages at low fly ash percentages but change drastically, increase and decrease sharply at higher fly ash. The sharp decrease in strength reveals the fragile behavior of sand stabilized with fly ash. A small strain can deteriorate fly ash bonding, which results in a drastic fall of the peak strength after the turning point. As strain proceeds to a higher value, the stress-strain relationship of stabilized sand approaches that of bare sand at residual state, named residual shear strength.

A higher fly ash percentage mixed in the specimen generates a stronger sample and a bigger particle of the stabilized sand, which is directly attributed to the strength amelioration. Stronger samples were also produced at higher curing time and lower saturation. A stronger specimen yields a higher both strength and strain at failure state.

The direct shear strength curve peak was higher in a bigger vertical loading applied to the specimen during shearing. This achievement was caused by an increase in the number of particle contact points producing an increase in the shearing surface area. As a result, more resistance against the shearing of the specimen was obtained. Unfortunately, at a higher vertical loading, fly ash bonding was more easily broken in a smaller strain.

In the residual state, cohesion disappears as the fly ash bonding is broken during shear. As the fly ash bonding is broken, the size of the bonds formed by the pozzolan's reaction that binds the grains of sand is probably diminished. Consequently, the formed relative angularity is reduced, producing in smaller friction angle. Fortunately, the beneficial effect of the fly ash bonding remains at the residual friction angle. It is proved that the stabilized sand's residual friction angle is higher than that of the bare sand and increases with fly ash. It indicates that sand stabilization with fly ash is effective during and after shearing. With the presence of water, fly ash generates a bond directly related to the relative angularity of sand grains contributing to an enhancement in the residual friction angle.

In other parameters, the residual friction angle improves along with curing time, even though it grows slowly in the early stage of curing. The pozzolanic backlash needs ample time to create a cementitious compound that is liable for strength amelioration of stabilized sand. The desired time for optimum performance seems more than 28 days as shear strength in the form of residual friction angle starts to increase significantly after this time. Self-hardening and moisture reduction occurred over time are the main causes of this improvement. The more interesting thing is that there is a significant improvement in the residual friction angle even in a small fly ash percentage by reducing saturation during the specimen preparation.

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