Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-431

Monotonic and cyclic shear behavior of incineration bottom ash under constant volume condition

Zhibo Zhang[1], Xunchang Fei [2] and Wei Wu[3]

[1]*Ph.D. candidate, Nanyang Technological University, Singapore, albert.zhangzb@ntu.edu.sg*

[2]*Assist.Prof., Nanyang Technological University, Singapore, xcfei@ntu.edu.sg*

[3]*Assoc.Prof., Nanyang Technological University, Singapore, wu.wei@ntu.edu.sg*

ABSTRACT

Incineration is becoming a popular treatment method of waste in the last several decades which makes the study of the mechanical properties of incineration ash more important. This study uses a cyclic simple shear device to test the monotonic and cyclic shear behavior of a type of incinerated bottom ash (IBA) produced in Singapore. It's found that the friction angle of IBA is 32 degrees with zero cohesion, and no clear peak strength is observed at a medium-dense condition. As shear strain increases, the shear stress normalized by current vertical stress is independent of consolidation vertical stress. Contract behavior shows first followed by continuous dilation. The cyclic shear ratio (CSR) under 100 kPa vertical stress has an almost logarithmic linear correlation with the number of cycles. The slope of shear stress-shear strain (τ-γ) curve under the cyclic shear condition also follows the ultimate state line determined from monotonic shear. During all the cyclic shear tests, IBA fails by reaching maximum double amplitude shear strain (7.5%) while pressure ratio equivalent to 1.0 cannot be reached.

Keywords: Incineration bottom ash, Monotonic shear, Cyclic simple shear, Shear strength, Liquefaction

1 INTRODUCTION

Incineration method is becoming popular in the last several decades worldwide, as it can reduce the volume of waste substantially. The World Bank reported that 11.1% of all the municipal solid waste is treated by incineration and this proportion increases to around 80% in land-scarce countries, like Singapore. Among all the by-products, incineration bottom ash (IBA) constitutes approximately 90% of the incineration residues. Thus, the research on the mechanical properties of IBA is of high interest, which can be used to guide the IBA landfill design and potential reuse methods.

Becquart et al. (2009) reported 58.9° and 55.8° friction angle of IBA under drained and undrained conditions namely using triaxial apparatus. While some other studies show that friction angle varies from 34.8° to 51.1° and 26.0° to 37.2° under dry and saturated conditions respectively (Weng et al., 2010). Zekkos et al. (2013) found the friction angle and cohesion are 42° and 20.1 kPa under the direct shear test while in triaxial test, they are 24-50° and 14-35 kPa. The authors also investigated the small strain shear modulus of IBA by measuring shear wave velocity on site. The influence of dry density and water content on the shear strength and friction angle has been discussed by Xie et al. (2016), in which they also noticed a strain hardening response for saturated bottom ash and a strain softening response of unsaturated bottom in contract by using triaxial device.

A limited studies can be found about cyclic shear test on IBA. Lan (2021) conducted cyclic triaxial tests to measure the resilient modulus of IBA. Considering the size and shape of particles of IBA, it might be reasonable to use cyclic tests on sand for reference. A lot of cyclic simple shear tests and cyclic triaxial tests have been done on different kind of sand (Hyodo et al., 2002; Wu, 2002), or the mixture of sand and gravels (Hubler et al., 2018), in which the cyclic shear stress ratio (CSR), number of cycles (N) and Pressure ratio (R_u) have been used to describe the cyclic behaviors.

Despite the considerable amount of research conducted on the mechanical properties of IBA, most studies have focused on the static shear tests with direct shear device or triaxial apparatus. Therefore, it's of high interest to address the dynamic shear properties of IBA. Direct shear test results often overestimate the shear strength of a material because the failure plane is predetermined and may not represent the weakest plane In triaxial test, the cyclic load can only be applied in the vertical direction and the test is conducted under cyclic strain control. Direct simple shear was firstly applied by Kjellman (1951) in 1950s which overcomes the shortages mentioned above. It allows the specimen to fail along any horizontal plane and makes it possible to apply cyclic shear stress control and cyclic shear strain control along horizontal directions. In this study, a cyclic simple shear device is employed to test the monotonic and cyclic shear behavior of a type of IBA produced in Singapore.

2 MATERIAL AND METHOD

2.1 Description of material used

IBA is sampled from a batch of incineration ash that has just been treated by a waste management plant in Singapore. The basic properties of it are listed in Table 1. The IBA is with dark grey color before drying and several large particles at the top as shown in Figure 1. However, Figure 2 shows that more than 90% content are with diameter less than 4.75 mm which reveals that it's mainly composed by "sand-like" particles.

Table 1. *Properties of incineration bottom ash*

Material	Water content (%)	Specific gravity	UCSC classification			e_{min}	e_{max}
			C_u	C_c	Type		
IBA	11.3	2.892	4.55	1.01	SP	0.731	1.551

Figure 1. *Appearance of incineration bottom ash used in this study before drying*

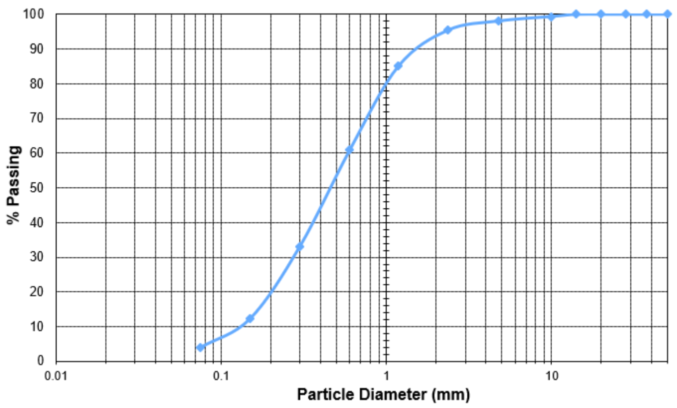

Figure 2. *Particle size distribution of incineration bottom ash*

2.2 Test apparatus and test program

The bi-directional cyclic direction simple shear device (BCDSS) (Figure 3) produced by Geocomp Corp. (Zehtab et al., 2019) has been used to conduct the monotonic and cyclic simple shear tests. It's a Norwegian Geotechnical Institute (NGI) type simple shear device (Bjerrum and Landva, 1966) which uses a stack of rigid rings to provide lateral confinement of the specimen. Thus, the constant volume condition can be reached by keeping the height of specimen constant after consolidation. In each direction, a Linear Variable Differential Transformer (LVDT) is used to control the behavior of the motor based on the setting parameters and the acquired force and displacement data from a low-profile load cell and the displacement sensor for all directions. The vertical motor has the capacity to provide 11 kN load with resolution of 0.36 N while two horizontal motors have a capacity of 4.5 kN with resolution of 0.18 N. In this research, all the tests have been conducted with passive control (PC) method to control the vertical strain and make the results comparable. The vertical axis is locked by a piston after the consolidation phase to keep the height of specimen with mechanical resistance.

All the tests were conducted under fully dry condition and the reduction of vertical stress was treated as virtual excess pore pressure, which was recognized as pressure ratio (R_u) in this study (Dyvik et al., 1987). Although some had recommended to use 6% double amplitude shear strain (γ_{DA}) (Wu, 2002), there is no difference or only one cycle difference on the number of cycles to trigger liquefaction based on this study. To observe the whole process and confirm the specimen is fully failed, 7.5% γ_{DA} is selected as the mobility failure criterion while liquefaction failure is recognized when Ru equals to 1.0.

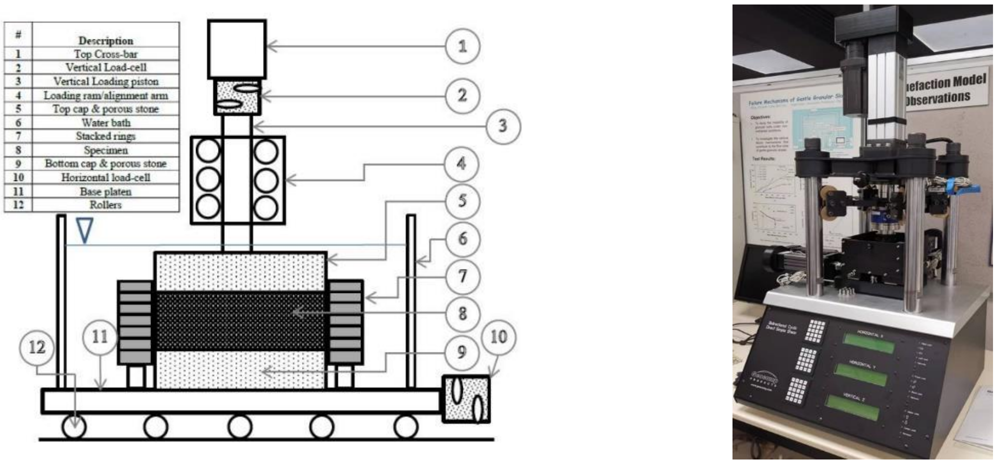

Figure 3. *Schematics of Bi-directional cyclic direction simple shear device (BCDSS) (Zehtab et al., 2019) (left). Physical picture of BCDSS (right)*

Test program (Table 2) includes 3 groups of monotonic shear tests under different consolidation stress and 4 groups of uni-directional cyclic simple shear tests with different cyclic stress ratio (CSR). In consolidation phase, vertical stress was increased until the predetermined value by three steps (for example, 10 to 50 to 100, to reach 100 kPa stress) and maintain the status for at least 120 mins according to ASTM D8296-19. A shear rate of 0.005 mm/s was chosen to allow the shear behavior fully developed during the test procedure. As for cyclic simple shear test, 4 seconds cyclic period and 5.5 as horizontal tunning parameter are selected to accurately control the horizontal shear stress to achieve the peak value and vary smoothly.

Table 2. *Testing program under constant volume condition*

Test type	Consolidation period	Vertical pressure (kPa)	Vertical strain control	Test speed (mm/s)	Cyclic stress ratio
Monotonic shear	≥120 mins	50,100,200	Passive control	0.005	-
Uni-directional cyclic simple shear	≥120 mins	100	Passive control	-	0.05,0.08,0.12,0.15

2.3 Specimen preparation method

The reconstituted specimens are with 101.4 mm (4 inches) diameter and 32 mm height. IBA sample was firstly dried with oven under 105 ℃ for more than 6 hours and then sieved to take out particles with diameter larger than 3.2 mm as required by ASTM D8296-19 for undrained cyclic direct simple shear test. Dry air pluviation method (Figure 4) has been used to constitute medium dense specimens (40-

50% relative density). The remaining part of IBA will be poured into split mold by using a funnel to minimize the dropping height. The negative suction pressure has been applied to force the latex membrane to cling to the inner surface of the Teflon coated stacked rigid rings. After taking out the funnel, the surface of the specimen was levelled.

Figure 4. *Dry air pluviation specimen preparation (left). Reconstituted specimen (right)*

3 Results and Discussion

3.1 Monotonic shear test results

The monotonic shear tests were conducted under 50, 100, 200 kPa consolidation stress with 0.005 mm/s constant shear displacement speed along the X direction. As the stack rings are considered rigid enough, the diameter of specimen is treated as constant. Therefore, the volume strain is controlled by passive height control method within 0.05% range according to ASTM D8296-19.

The shear stress – shear strain behavior is presented in Figure 5 until 18.75% maximum shear strain (namely 6 mm maximum horizontal displacement). Under the same shear strain, the shear stress is always higher for the test under higher consolidation stress. In all the three tests, shear stress increased sharply at initial stage, and then increase steadily and continuously with no peak value observed.

In Figure 5, monotonic shear test results under 50,100 and 200 kPa consolidation stress are plotted in shear stress versus vertical stress domain. A phase transformation (PT) point (shown as the intersection points between phase transformation line and each data curve) can be found for all the three curves. Before this PT point, shear stress increases as vertical stress decreases. After this PT point, shear stress increases linearly with vertical stress following the same ultimate state line (USL). The friction angle and cohesion of IBA are namely 32 degrees and 0 N, which can be easily determined with the assumption and equation as below:

The horizontal plane was the plane of maximum shear stress.

$$\varphi = sin^{-1}\frac{\tau}{\sigma v'}$$

where τ= shear stress; σ_v'= vertical effective stress at the corresponding status.

Comparing those two plots in Figure 6, it's obvious that the shear stress of IBA is more dependent on the real-time vertical stress rather than the consolidation stress. The shear stress normalized by the real-time vertical stress σ_v' increases until a stable value of 0.62 when the shear strain is larger than 10% for all the three tests. The virtual pore pressure in Figure 7 is recognized as the reduction of vertical stress during the shear test. The pore pressure normalized by the initial consolidation stress σ_{v0}' increases firstly and then decreases continuously since achieving 2% shear strain. It reveals that the IBA performs contractive behavior at early stage and then starts to swell from 2% shear strain. This behavior is same as the mid-dense Ottawa sand.

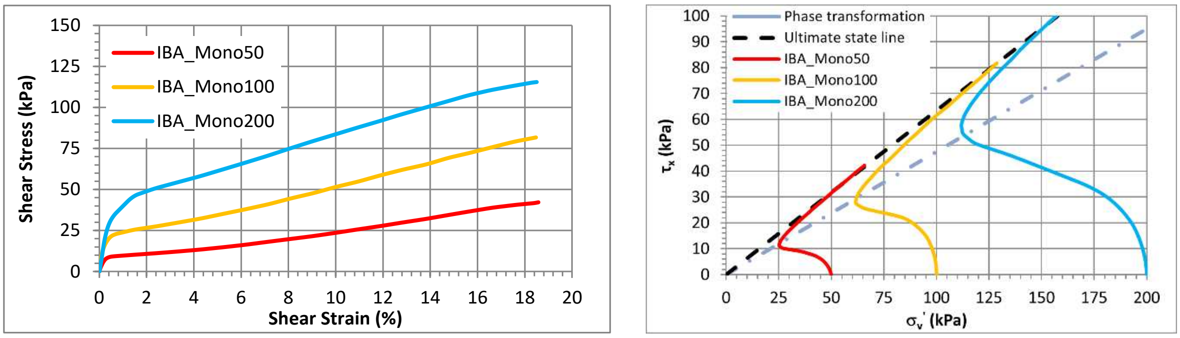

Figure 5. *Shear stress-shear strain (left). Shear stress – Vertical stress (right)*

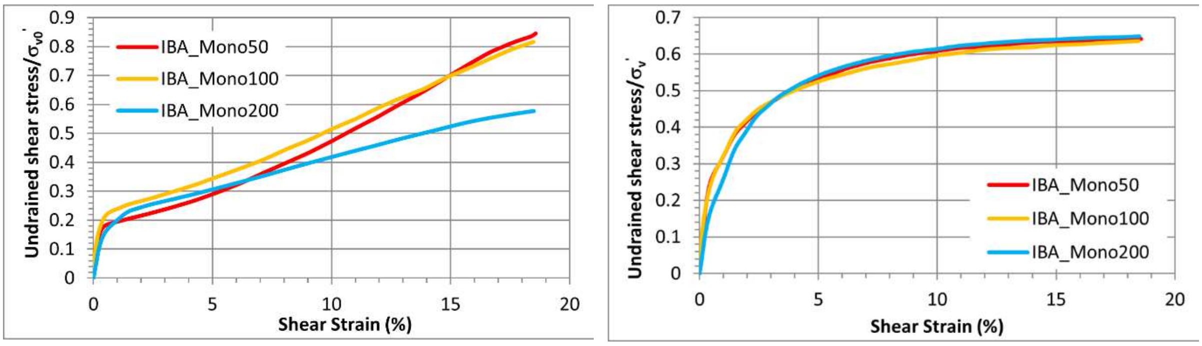

Figure 6. *Shear stress normalized by consolidation stress – Shear strain (left). Shear stress – Vertical stress (right)*

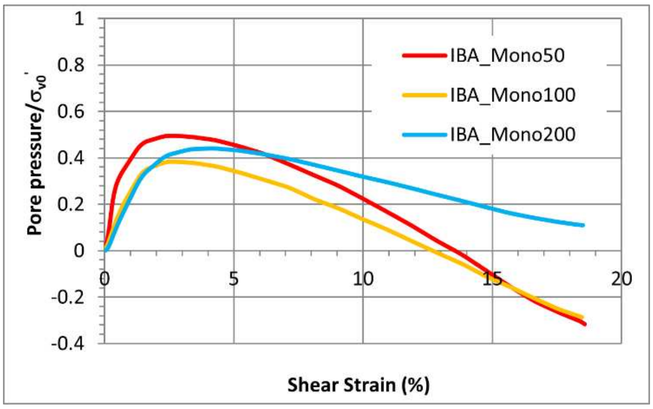

Figure 7. *N*ormalized pressure ratio – Shear strain

3.2 Uni-directional cyclic simple shear test results

The uni-directional cyclic simple shear tests were conducted under the same consolidation stress of 100 kPa with different CSR along X direction. During the consolidation phase, both X and Y direction have been activated to minimize the lateral shear stress by small displacement and this part of displacement will be eliminated from the shear strain calculation during cyclic simple shear phase.

Figure 8 presents the shear stress – vertical stress plot of uni-directional cyclic simple shear test under 100 kPa consolidation stress with CSR = 0.12 as an example. The peak of shear stress is always at -12 and 12 kPa which indicates a good quality of horizontal shear stress control. The vertical stress decreases from 100 kPa when the shear stress varies from -12 kPa to 12kPa periodically. Starting from a certain pressure, the behavior gradually changes to an arrow type in which vertical stress will not simply decrease continuously but increase and decrease periodically with the middle state keeping decreasing until a value close to zero. When the specimen is almost liquified, the slope of the butterfly-shaped loop is consistent with the USL line determined from the monotonic shear test results.

The relationships of shear stress normalized by consolidation stress and shear strain under different CSR are summarized in Figure 8. The IBA specimens were not liquified under CSR = 0.05 and CSR = 0.08 after 500 cycles. Thus, the shear strains of these two tests are always within a very small range.

The shear strain of test under CSR = 0.12 increases gradually while that of test under CSR = 0.15 increases quickly but they both reach the maximum double amplitude shear strain (7.5%) during a certain cycle. Figure 9 compares the number of cycles needed to achieve liquefaction for different CSR values in cyclic simple shear tests with constant volume condition under 100 kPa consolidation stress. The variation of pressure ratio (N) during each cycle keeps expanding as cycle increases, which reveals that the IBA specimen keeps weakening as the vertical stress reduces. It's noticed that the specimens are considered to be failed according to the maximum double amplitude shear strain criterion rather than pressure ratio reaching 1.0. The pressure ratios of shear tests under CSR = 0.12 and 0.15 in the last cycle are namely 0.95 and 0.97 which means that the vertical effective stress still exists.

In the plot of the number of cycles and shear strain as shown in Figure 9, the shear strain is always larger when the CSR is higher during the stable stage. And maximum double amplitude shear strain is also achieved earlier in the test with higher CSR value. For test with CSR ≤ 0.08, the shear strain is quite small and almost generated in the first several cycles. The shear strain keeps stable for a long period and the specimen will not fail in 500 cycles (the maximum cycle we set for the test). For test with CSR = 0.12, the shear strain increases slowly during most cycles while it increases sharply for the last 10-20 cycles until it failed. The total number of cycles to failure (N) also decrease a lot which is only 94 cycles. As for test with CSR = 0.15, the shear strain developed quickly, and it failed in 8 cycles. It's obvious that N is insensitive to CSR when CSR is very small (less than 0.08) while N depends heavily on CSR when CSR is large (more than 0.08).

As the failure under CSR =0.05 and 0.08 has not been observed after 500 cycles, the number of cycles to failure is estimated based on the gradient of the N – R_u curve in the stable part after 100 cycles. By plotting these N values into logarithmic scale, a logarithmic linear relationship can be noticed. The relationship can be fitted by an equation with the R^2 = 0.9989 (Figure 10). The cyclic resistance ratio (CRR) defined by the CSR at which the specimen is liquified in 10 cycles can be calculated based on this equation and the value is 0.147.

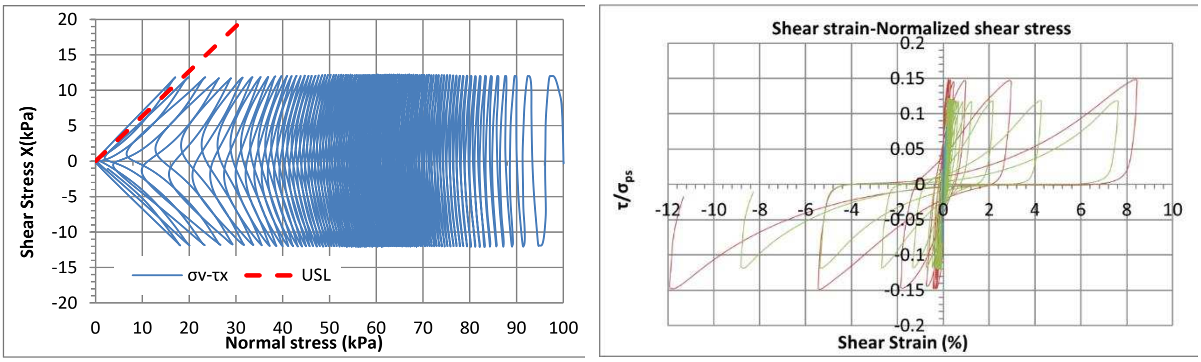

Figure 8. *USL determined from monotonic shear & Cyclic simple shear under 100 kPa vertical stress with CSR=0.12 (left). Normalized shear stress – shear strain (right)*

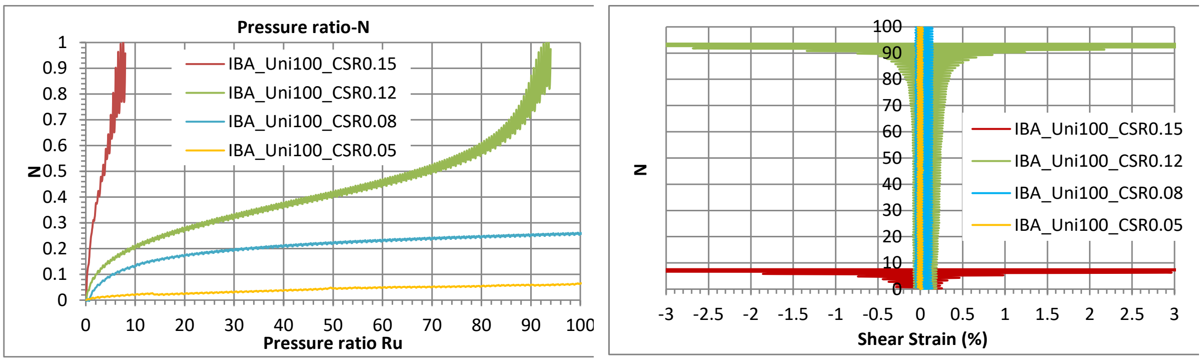

Figure 9. *Number of cycles to pressure ratio (N – R_u) (left). Number of cycles to shear strain (right)*

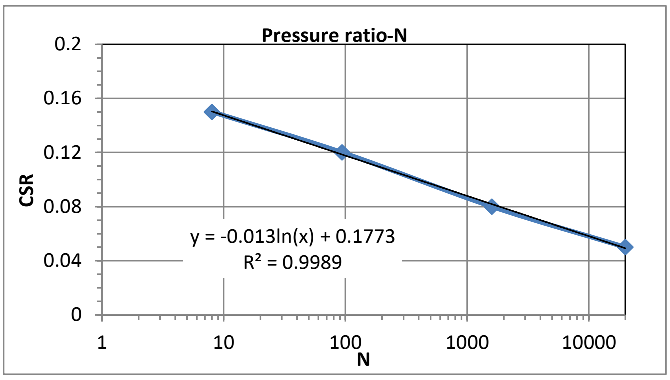

Figure 10. *CSR* – N under logarithmic scale (40-50% relative density)

4 CONCLUSIONS

1) The friction angle of medium dense IBA is 32 degrees with zero cohesion, and no clear peak strength is observed under constant volume condition.
2) As shear strain increases, the shear stress normalized by current vertical stress is independent of consolidation vertical stress. Contractive behavior shows firstly followed by continuous dilation.
3) The cyclic shear ratio (CSR) under 100 kPa vertical stress has almost logarithmic linear correlation with the number of cycles. The slope of shear stress-shear strain (τ-γ) curve under cyclic shear condition also follows the ultimate state line determined from monotonic shear.
4) During all the cyclic shear tests, IBA is failed by reaching maximum double amplitude shear strain (10%) while pressure ratio equivalent to 1.0 cannot be achieved.

5 ACKNOWLEDGEMENTS

The authors appreciate the support of National Environmental Agency of Singapore and Nanyang Technological University.

REFERENCES

Becquart, F., Bernard, F., Abriak, N. E., & Zentar, R. (2009). Monotonic aspects of the mechanical behaviour of bottom ash from municipal solid waste incineration and its potential use for road construction. Waste Management, 29(4), 1320-1329. doi:10.1016/j.wasman.2008.08.019

Bjerrum, L., & Landva, A. (1966). Direct simple-shear tests on a Norwegian quick clay. Géotechnique, 16(1), 1-20.

Dyvik, R., Berre, T., Lacasse, S., & Raadim, B. (1987). Comparison of truly undrained and constant volume direct simple shear tests. Géotechnique, 37(1), 3-10.

Hubler, J. F., Athanasopoulos-Zekkos, A., & Zekkos, D. (2018). Monotonic and cyclic simple shear response of gravel-sand mixtures. Soil Dynamics and Earthquake Engineering, 115, 291-304.

Hyodo, M., Hyde, A. F., Aramaki, N., & Nakata, Y. (2002). Undrained monotonic and cyclic shear behaviour of sand under low and high confining stresses. Soils and Foundations, 42(3), 63-76.

Kjellman, W. (1951). Testing the shear strength of clay in Sweden. Géotechnique, 2(3), 225-232.

Lan, N. C. (2021). Static and Cyclic Properties of Municipal Solid Bottom Ash in Vietnam. International Journal of GEOMATE, 20(80). doi:10.21660/2021.80.j2066

Weng, M. C., Lin, C. L., & Ho, C. I. (2010). Mechanical properties of incineration bottom ash: the influence of composite species. Waste Manag, 30(7), 1303-1309. doi:10.1016/j.wasman.2009.11.010

Wu, J. (2002). Liquefaction triggering and post-liquefaction deformation of Monterey 0/30 sand under unidirectional cyclic simple shear loading: University of California, Berkeley.

Xie, R., Xu, Y., Huang, M., Zhu, H., & Chu, F. (2016). Assessment of municipal solid waste incineration bottom ash as a potential road material. Road Materials and Pavement Design, 18(4), 992-998. doi:10.1080/14680629.2016.1206483

Zehtab, K., Gokyer, S., Werden, S. K., Marr, W. A., & Apostolov, A. (2019). On the effects of inadequate height control in constant volume monotonic and cyclic direct simple shear test. Paper presented at the Geo-Congress 2019: Earthquake Engineering and Soil Dynamics.

Zekkos, D., Kabalan, M., Syal, S. M., Hambright, M., & Sahadewa, A. (2013). Geotechnical characterization of a Municipal Solid Waste Incineration Ash from a Michigan monofill. Waste Manag, 33(6), 1442-1450. doi:10.1016/j.wasman.2013.02.009