Effect of Crushing on Stress-Strain Behavior of Fly Ash under Monotonic Compression and Repeated Loading-Unloading Conditions

Aparna Shrivastava[1], Ankit Ghanghas[2] and Ajanta Sachan[3]

[1] M. Tech Student, Civil Engineering, Indian Institute of Technology Gandhinagar, India
E-mail: aparna.shrivastava@iitgn.ac.in

[2] U. G. Student, Civil Engineering, Indian Institute of Technology Gandhinagar, India
E-mail: ankit.ghanghas@iitgn.ac.in

[3]Associate Professor, Civil Engineering, Indian Institute of Technology Gandhinagar, India
E-mail: ajanta@iitgn.ac.in

Abstract. Use of fly ash in various geotechnical structures has increased instead of using conventional geomaterials. Million tons of fly ash is produced every year and its safe disposal is an issue as it creates health hazards if exposed to air directly. Fly ash is largely used as structural fill material in highway, railway embankments and as a backfill material in Geosynthetic reinforced structures. Fly ash is a by-product generated on coal combustion. It contains spherical, hollow particles (cenospheres) and particles filled with smaller particles (plerospheres). Due to presence of air voids in cenospheres, specific gravity of fly ash is obtained to be lower as compared to soil. Due to the hollow nature of fly ash particles they undergo crushing and deformation when subjected to external loading. The present study evaluates the effect of crushing on stress-strain behavior under monotonic compression and repeated loading-unloading UU triaxial testing conditions. A successive cycles of standard proctor tests were performed on fly ash to induce different degrees of crushing. Specimens with different degrees of crushing (50 mm diameter and 100 mm height) were prepared at maximum dry density (MDD) of uncrushed fly ash. Stress-stain response under monotonic compression loading exhibited significant decrease in peak deviatoric stress with the increase in crushing of fly ash particles. There was significant reduction in accumulated axial strain with the increase in crushing under repeated loading-unloading conditions.

Keywords: Fly ash, Cenospheres, Plerospheres, Crushing, UU triaxial.

1 Introduction

Fly ash is a by product generated by coal combustion from thermal power plant. Large amount of production of fly ash by coal combustion has raised the need for its safe disposal every year. Fly ash is health hazardous when exposed to air freely. It contains two types of particles: cenospheres and plerospheres. Cenospheres are the spherical particles which are hollow from inside and plerospheres are the particles filled with small spheres (Gupta and Sachan [13]). Fly ash particles are majorly spherical containing silicon, aluminium and iron oxide (Martin et al. [1]). Fly ash is largely used as a structural fill in highway and railway embankments. Also, fly ash is used as landfill covers and pavement subgrade material. Some of the researchers [1], [2], [3] and [4] studied the basic geotechnical properties of fly ash and its strength characteristics. Researchers [5] and [6] have studied the morphological characteristics of fly ash. Kim et al. [7] studied the suitability of fly ash and bottom ash mixtures in highway embankment as construction material. Fly ash particles being hollow in nature are highly susceptible to breakage and crushing on application of external loading. Researchers [8] and [9] studied the breakage of various soils due to external loading. Lade et al. [10] proposed particle breakage factor B_{10} based on effective particle size D_{10}. Hattamleh et al. [11] studied the effect of particle crushing on natural sand by performing direct shear test. Some of the researchers [12] and [13] reported that impact loading can crush the fly ash significantly. Gupta and Sachan [13] also reported that both microscopic and macroscopic (compactability, compressibility, and shear behavior) properties vary with the crushing of fly ash particles. Crushing of fly ash can significantly alter its shear strength parameters [13]. The current study mainly focuses on effect of particle crushing of fly ash on shear behavior under monotonic compression and repeated loading-unloading UU triaxial testing conditions.

2 Material Properties

Fly ash was collected from Gandhinagar thermal power plant and its basic geotechnical properties were determined by performing specific gravity, grain size analysis and standard proctor test. Basic geotechnical properties of fly ash (uncrushed) are shown in Table 1. The specific gravity was found to be 2.11, which was obtained to be much lesser than soil due to presence of air voids in hollow cenospheres [1] of fly ash particles. The optimum moisture content (OMC) and maximum dry density (MDD) of Gandhinagar fly ash were obtained to be 29% and 1.21 g/cc respectively. Grain size analysis showed 20.5% sand and 79.5% silt content. Fly ash particles were predominantly of silt size range and non-plastic in nature.

Table 1. Basic geotechnical properties of fly ash (uncrushed)

Properties	Values
Specific Gravity	2.11
Sand	20.5%
Silt	79.5%
Optimum Moisture Content (OMC)	29%
Maximum Dry Density (MDD)	1.21 g/cc
Visual appearance	Grey
Nature	Non-plastic

3 Experimental Program

In the present study a series of UU (unconsolidated undrained) triaxial tests under monotonic compression and repeated loading-unloading conditions were performed at confining pressure of 100 kPa on fly ash specimens with different degrees of crushing. The tests were conducted at strain rate of 0.4 %/min. In order to prepare samples with different degrees of crushing, fly ash was subjected to impact loading by conducting standard proctor tests as per the procedure mentioned in [IS 2720-7 (1980)]. The uncrushed sample (S0) was obtained from Gandhinagar thermal power plant. Fly ash was compacted in three layers of equal mass by providing 25 blows using 2.6 kg hammer with a free fall height of 310 mm. In order to prepare S1, 13 such rounds were conducted on S0 thus Imparting a total of 7702 kJ/m^3 energy in crushing. The sample was then oven dried for 24 hours and was used to prepare S2. In order to prepare S2, S1 was subjected to above mentioned energy. The same procedure was followed to prepare samples S3, S4 and S5. All the specimens were prepared at 1.21 g/cc of MDD (Maximum Dry Density) of uncrushed fly ash. Also, the saturation level was kept constant for testing of specimens with different degrees of crushing i.e. 55%. The soils were compacted in equal layers and after compacting each layer of soil scratching with knife was done to ensure proper bonding between the layers. The specimens of 50 mm diameter and 100 mm height were prepared by moist tamping method using three-piece mould supported by collar at the top and base plate at the bottom. For repeated loading-unloading tests, the specimens were initially loaded at 0.4 %/min till 40% of the peak deviatoric stress (obtained during monotonic compression tests) and then unloaded till 5% of the peak deviatoric stress. The test was continued upto 50 minute to acquire 20% axial strain failure criteria. All the UU triaxial tests were performed as per IS 2720-11(1993), which gives c and ϕ parameters of material having inclined failure envelope UU tests were chosen to perform for analysis of the stress-strain response of fly ash under loading-unloading conditions to understand the degradation in stiffness response of fly ash. It was not dynamic loading rather it was monotonic compression strain-controlled loading-unloading condition at constant strain rate.

Results and discussions

3.1 UU triaxial tests under monotonic compression conditions

The stress-strain of fly ash specimens with different degrees of crushing at confining pressure of 100 kPa under UU triaxial monotonic compression conditions is presented in Fig. 1. It was observed that the peak deviatoric stress decreased significantly with the crushing of fly ash from 968 kPa for S0 specimen to 425 kPa for S3 (Table 1).

There was a significant decrease in peak deviatoric stress from S0 to S1 while it again increased for S2 and further decreased for S4. Specimen S5 exhibited similar response same as S1. Specimen S0 exhibited brittle behavior with well-defined post peak softening response. However, the specimens S3, S4 and S5 indicated ductile behavior such that the deviatoric stress was more or less constant after achieving peak deviatoric stress. As per Gupta and Sachan [13], it was found that the particles in its uncrushed state were spherical in nature; either cenosphere or plerosphere. On application of impact loading, hollow cenospheres got crushed and crumbled. With the increase in crushing energy, the solid spheres (plerospheres) got ruptured and deformed. Such crushing of particles led the increased percentage of fines at higher crushing cycles. The fly ash specimens prepared at same dry density (1.21 g/cc) for specimens at higher crushing cycle will have more tendency to rearrange themselves during shearing, which resulted into ductile behavior of specimens at higher crushing cycles (S3-S5). At higher crushing cycles, the crushing of cenospheres and rupturing of plerosphere resulted into the increased percentage of fines leading to the greater void spaces. It caused reduction in peak deviatoric stress at higher crushing cycles.

Table 1. Shear behavior of fly ash specimens with different degrees of crushing under UU triaxial condition

Specimens	Peak deviatoric stress (kPa)	Axial strain at failure (%)
S0	968	2.13
S1	556	2.01
S2	788	2.05
S3	425	2.56
S4	458	1.8
S5	560	1.85

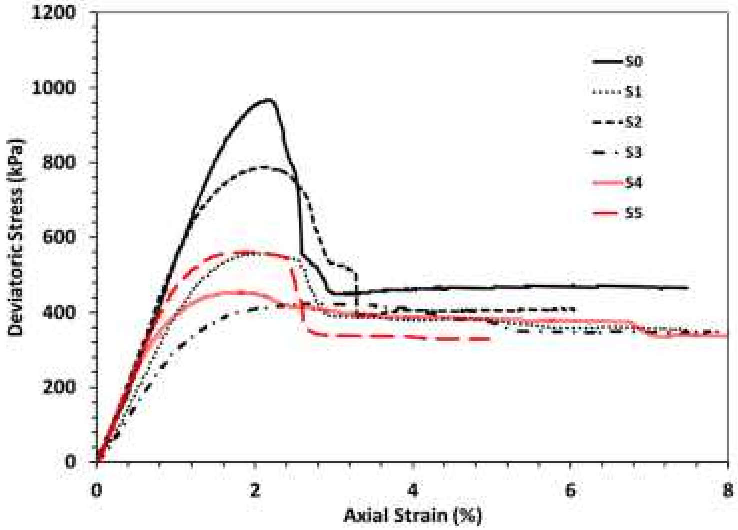

Fig. 1. Stress-strain response of fly ash specimens with different degrees of crushing under monotonic compression UU triaxial condition

3.2 UU triaxial tests under repeated loading-unloading tests

The stress-strain behavior of fly ash specimens with different degrees of crushing at confining pressure of 100 kPa under repeated loading-unloading UU triaxial conditions is shown in Fig. 2. As per journal paper [14], three criteria were used to evaluate the effect of degrees of crushing of micaceous soil under repeated loading-unloading conditions: (1) total number of loading-unloading cycles completed in a particular time, (2) number of loading-unloading cycles completed in 2.5% axial strain, and (3) time required for completion of given loading-unloading cycle. Since none of the specimens could reach to even 2% axial strain, the specimens were compared based on the two criteria: total number of loading-unloading cycles completed in 50 minutes (N_t), and time required to complete 1st loading-unloading cycle (T_1).

It was observed that the total number of loading-unloading cycles completed reduced from S0 to S2 (N_t = 135 for S0 and 71 for S2) in the duration of 50 minutes. The number of loading-unloading cycles were then increased (N_t = 97 for S5) for S3 to S5 specimens (Table 2). Total accumulated strain for the uncrushed fly ash specimen (S0) was obtained to be 1.1% and for specimen S5 to be 0.3% (Fig. 2). Looking into another criterion, it was found that time required to complete first loading-unloading cycle decreased with the crushing of fly ash.

As per previous literature [15], the behavior under repeated loading-unloading can be explained through dissipated energy concept (difference between the total strain energy stored during loading and the recovered elastic strain energy during unloading). According to [16], the dissipation of energy during any loading-unloading cycle was reported to be the cause of plastic strains that physically referred to the rearrangement of the particles and breakage of bonding and other part of energy stored as internal energy. For specimen S0, the accumulation of plastic strain would be more due to the rearrangement of cenospheres and plerospheres even at higher axial strain. The hollow air voids in the cenospheres would cause high probability of crushing during shear deformation itself leading to the rearrangement of the particles. This resulted into large shear deformation for the specimen S0 (1.1%) at given loading. Fig. 2 also indicated that the recovery of strains decreased with the increase in crushing levels of fly ash. For specimen S0, the recovered elastic strain for the first loading-unloading cycle was obtained to be 0.15% and for highly crushed specimen S5 to be 0.07%. Lesser recovery of elastic strains would lead to the higher plastic strains for the crushed specimen S5 and resulted into higher dissipated energy. Greater plastic strains for the higher crushed specimens could occur with the greater rearrangement of the crushed cenospheres and ruptured plerospheres at higher crushing levels.

Table 2. Shear behavior of fly ash specimens with different degrees of crushing under UU triaxial repeated loading-unloading condition

Specimens	Number of loading-unloading cycles completed in 50 minutes (N_t)	Time to complete first loading-unloading cycle (seconds)
S0	135	157
S1	76	72
S2	71	129
S3	86	110
S4	91	89
S5	97	67

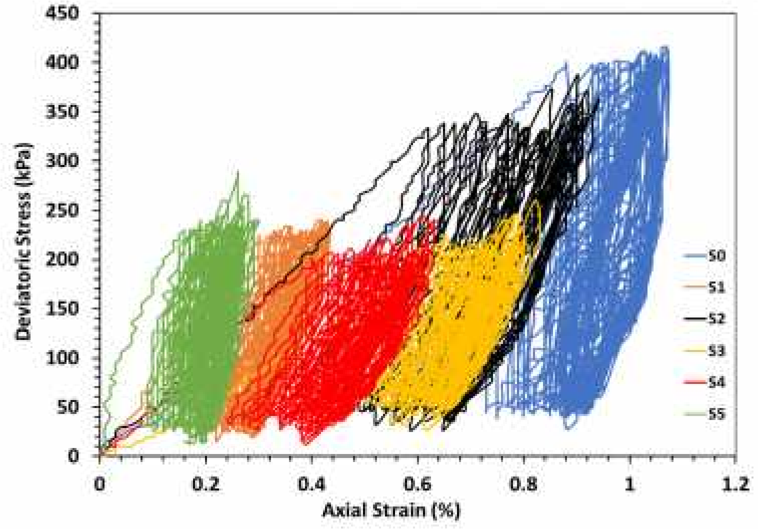

Fig. 2. Stress-strain response of fly ash specimens with different degrees of crushing under repeated loading-unloading UU triaxial condition

Conclusions

A series of UU triaxial tests under monotonic compression and repeated loading-unloading conditions were performed on fly ash specimens with varying degrees of crushing. The results are summarized as follows:

- The UU triaxial tests under monotonic compression conditions exhibited the significant reduction in peak deviatoric stress with the increase in crushing of fly ash particles. The uncrushed specimen S0 indicated brittle failure, whereas the higher crushed specimens indicated ductile failure.
- The UU triaxial tests under repeated loading-unloading conditions, total number of loading-unloading cycles completed in 50 minutes reduced with the particle crushing. Also, it was noted that time required to complete first loading-unloading cycle decreased with the crushing of fly ash.
- Total accumulated strain for the uncrushed fly ash specimen S0 was obtained to be 1.1% and for highly crushed specimen S5 to be 0.3%.
- For uncrushed specimen S0, the accumulation of plastic strain would be more due to the rearrangement of cenospheres and plerospheres. This resulted into the large shear deformation for the uncrushed specimen S0 (1.1%) at given loading.
- It was observed that the recovery of strains decreased with the increase in particle crushing of fly ash.

References

1. Martin, J. P., Collins, R. A., Browning, J. S., & Biehl, F. J. (1990). Properties and use of fly ashes for embankments. Journal of energy engineering, 116(2), 71-86.
2. Kim, B., & Prezzi, M. (2008). Evaluation of the mechanical properties of class-F fly ash. Waste management, 28(3), 649-659.
3. Pandian, N. S. (2013). Fly ash characterization with reference to geotechnical applications. Journal of the Indian Institute of Science, 84(6), 189.
4. Jakka, R. S., Ramana, G. V., & Datta, M. (2010). Shear behaviour of loose and compacted pond ash. Geotechnical and Geological Engineering, 28(6), 763-778.
5. Fisher, G. L., Prentice, B. A., Silberman, D., Ondov, J. M., Biermann, A. H., Ragaini, R. C., & McFarland, A. R. (1978). Physical and morphological studies of size-classified coal fly ash. Environmental Science & Technology, 12(4), 447-451.
6. Kutchko, B. G., & Kim, A. G. (2006). Fly ash characterization by SEM–EDS. Fuel, 85(17), 2537-2544.
7. Kim, B., Prezzi, M., & Salgado, R. (2005). Geotechnical properties of fly and bottom ash mixtures for use in highway embankments. Journal of Geotechnical and Geoenvironmental Engineering, 131(7), 914-924.
8. Hardin, B. O. (1985). Crushing of soil particles. Journal of Geotechnical Engineering, 111(10), 1177-1192.
9. Hagerty, M. M., Hite, D. R., Ullrich, C. R., & Hagerty, D. J. (1993). One-dimensional high-pressure compression of granular media. Journal of Geotechnical Engineering, 119(1), 1-18.
10. Lade, P. V., Yamamuro, J. A., & Bopp, P. A. (1996). Significance of particle crushing in granular materials. Journal of Geotechnical Engineering, 122(4), 309-316.

11. Al Hattamleh, O. H., Al-Deeky, H. H., & Akhtar, M. N. (2013). The consequence of particle crushing in engineering properties of granular materials. International Journal of Geosciences, 4(07), 1055.
12. Choi, W., Son, Y., Park, J., Noh, S., & Bong, T. (2013, April). Changes in crushing and granularity characteristics of bottom ash as compaction energy. In World of Coal Ash (WOCA) Conference, Lexington (pp. 22-25).
13. Gupta, K., & Sachan, A. (2018). Effect of crushing and strain rate on mechanical behavior of type-F fly ash. Transportation Infrastructure Geotechnology, 5(1), 4-23.
14. Sachan, A., Seethalakshmi, P., & Mishra, M. C. Effect of Crushing on Stress–Strain and Pore Pressure Behavior of Micaceous Kutch Soil Under Monotonic Compression and Repeated Loading–Unloading Conditions. Geotechnical and Geological Engineering, 1-15.
15. Polito, C., Green, R. A., Dillon, E., and Sohn, C. (2013). “Effect of load shape on relationship between dissipated energy and residual excess pore pressure generation in cyclic triaxial tests.” Canadian Geotechnical Journal, 50(11), 1118-1128.
16. Voznesensky, E. A., & Nordal, S. (1999). Dynamic instability of clays: an energy approach. Soil dynamics and earthquake engineering, 18(2), 125-133.
17. IS 2720-7 (1980): Methods of tests for soils, Determination of dry densty-water content relation using light compaction. Bureao of Indian Standards, New Delhi, India.
18. IS 2720-11 (1993): Methods of tests for soils, Determination of the shear strength parameters of a specimen tested in unconsolidated undrained triaxial compression without the measurement of pore water pressure. Bureao of Indian Standards, New Delhi, India.