# Shear Strength and Pore Pressure Response of Coal Ash under Undrained Shearing at Isotropic and $K_0$ Consolidation

Aparna Shrivastava[1] and Ajanta Sachan[2]

[1] PhD Scholar, Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Gandhinagar, Gujarat, 382355
E-mail: aparna.shrivastava@iitgn.ac.in
[2] Associate professor, Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Gandhinagar, Gujarat, 382355
E-mail: ajanta@iitgn.ac.in

**Abstract.** Coal ash is utilized as structural fill material in highway and railway construction. Shear strength tests are commonly conducted on specimens consolidated under isotopic conditions (IC); however, stress conditions in the field are anisotropic (horizontal and vertical stresses are not equal). The current study focuses on evaluation of shear strength and pore pressure response of coal ash consolidated under $K_0$ conditions simulating field conditions more accurately. Two series of CU triaxial testing were conducted on coal ash under IC and $K_0$ conditions at different mean effective stresses (at the end of consolidation) ranging from $p'_0$ = 50, 100, 150, 200 and 300 kPa. Peak stresses for $K_0$50 and $K_0$100 tests were observed to be less as compared to IC50 and IC100, respectively. For IC specimens, pore pressure was obtained to be less dilative with increasing $p'_0$; however, the behaviour was in contrast for the $K_0$ specimens. For the higher range of mean effective stresses ($p'_0$ = 100, 200 and 300 kPa), peak deviatoric stress showed a large increase for both IC and $K_0$ specimens with increasing $p'_0$. For the same $p'_0$, the $K_0$ specimen exhibited lower peak stress as compared to IC specimen although a smaller difference for higher $p'_0$ was observed. The contractive pore pressure response was observed to increase with increasing $p'_0$ for IC specimens. However, $K_0$ specimens exhibited a significant increase in dilative pore pressure response with increasing $p'_0$.

**Keywords:** Coal ash, Isotropic, $K_0$, Shear strength, Pore pressure.

## 1 Introduction

Coal ash is used in the field of geotechnical engineering being an excellent and emerging geomaterial. It is used as fill material on highways and railways. In all these structures, the anisotropic conditions (vertical and horizontal stress are unequal) prevail in the field. However, due to the unavailability of the equipment and tedious procedure; usually, the shear strength parameters are determined under isotropic conditions. Past research has indicated that the geotechnical parameters under isotropic and anisotropic conditions could make a large difference. Many studies are available related to the effect of isotropic and anisotropic consolidation on clays (Ladd CC 1965, Donaghe and

Townsend 1978 and Shi et al. 2015, Mayne 1985, Rowshanzamir and Askari 2010 and Kantesaria and Sachan 2019). Ladd CC (1965) compared the behaviour of isotropically and $K_0$ consolidated NC clay specimens under CU conditions. The shear strength ratio remained unchanged in the case of $K_0$ consolidation compared to isotropic conditions. However, $\varphi$' and A parameter at failure ($A_f$) decreased for $K_0$ specimens at failure. Donaghe and Townsend (1978) and Shi et al. (2015) investigated the effect of anisotropic and isotropic consolidation of clays under CU conditions. They concluded that volume change during consolidation was not the unique function of vertical effective consolidation stress rather it depends on the deviatoric stress and mean effective stress at consolidation. The undrained strength of anisotropically consolidated specimens was found to be lower than the isotropic case at the same vertical effective consolidation stress. Mayne (1985) concluded that normalized undrained shear strength ($S_u/\sigma_v'$) for both anisotropically NC and OC clay under compression was 87% of isotropic specimen. Also, $\varphi'$ for CAU was obtained to be 97% of CIU tests. Lim et al. (2018) concluded that the residual soil behaviour under CAU and CIU conditions behaved similarly to the dense and loose sand, respectively. Kato et al. (2001) studied the effect of anisotropic consolidation on the undrained behaviour of Toyoura sand. It was reported that the behaviour became independent of the stress state at consolidation at a steady and quasi-steady state.

There are many studies available on the effect of stress-induced anisotropy on clays and sands. However, coal ash as an emerging geomaterial also requires to understand its shear response considering the effect of anisotropic consolidation, which exists in the field. Hence, the present work elucidates the shear and pore pressure response of coal ash under isotropic and $K_0$ consolidation by performing consolidated undrained testing.

## 2 Material Properties

Coal ash used for the current study was collected from the Gandhinagar thermal power plant, Gujrat, India. The grain size analysis indicated that the material possesses 86% silt and 14% sand-size particles. The specific gravity was obtained to be 2.27. The maximum dry density and optimum moisture content were found to be 1.46 g/cm$^3$ and 18.9%, respectively. The liquid limit was obtained as 28% through cone penetrometer test. Plastic limit test could not be performed due to its non-plastic nature. The permeability was determined by performing falling head permeability test and was obtained to be 3*10$^{-5}$ cm/sec.

## 3 Experimental Program and Specimen Preparation

For the current study, two series of tests were conducted on coal ash specimens at different mean effective stress, $p'_0$ (at end of consolidation) under isotropic and $K_0$ consolidated conditions, respectively. The $p'_0$ was chosen to be 50, 100, 150, 200 and 300 kPa. The testing was done in a stress path triaxial testing system having 16 kN capacity of load cell and displacement transducer of 50 mm capacity. The specimens were prepared at 95% MDD and OMC of coal ash obtained through a standard proctor test using a moist tamping technique. The specimens were remoulded in 4 layers of equal height with the approximately same energy at each level. The tests were conducted on specimens with 50 mm diameter and 100 mm height. The specimen was firstly saturated by using $CO_2$ flushing, water flushing and back pressure saturation before the consolidation and shearing phase of the testing. The Skempton's B vale was ensured to be 0.95 before the consolidation phase of the test. The loading rate was kept as 0.05%/min for the shear deformation. The value of $K_0$ was obtained to be 0.42 using the $K_0$ consolidation module given in the triaxial setup. The $K_0$ value was calculated by back volume measurement which used the volume change to calculate the new initial height to maintain radial strain to be zero. The test IDs were defined by the mode of consolidation i.e., isotropic (IC) or $K_0$ and mean effective stress at the end of consolidation ($p'_0$). For example, $K_0$100 denoted the specimen consolidated under $K_0$ conditions till the mean effective stress at the end of consolidation reached 100 kPa.

# 4 Results and Discussion

## 4.1 Compressibility response of coal ash during consolidation process in the triaxial device

Fig. 1 shows the *e*-log *p*' response of coal ash specimens during the consolidation process under both the isotropic and $K_0$ conditions. The specimens exhibited the initial void ratio of 0.636, which decreased while consolidation. With increase of the $p'_0$ under both IC and $K_0$ conditions, the void ratio decreased from the initial value, though the change was very small. However, it was observed that at the same $p'_0$, the void ratio was found to be the same under IC and $K_0$ conditions. At $p'_0$=200 and 300 kPa, the IC and $K_0$ specimens indicated similar changes in the void ratio. This might be due the low compressibility of the coal ash material.

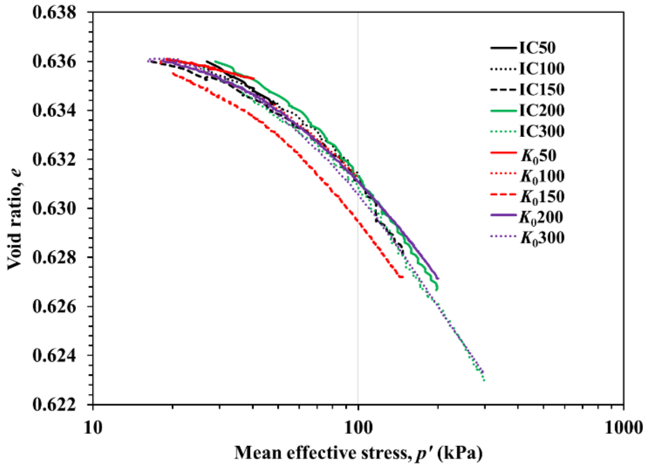

**Fig. 1.** *e*-log *p*' response of compacted fly ash for isotropically and $K_0$ consolidated specimens in triaxial device

### 4.2 Shear behavior of coal ash under isotropic and $K_0$ consolidated conditions under a lower range of mean effective stresses ($p'_0$)

Fig. 2 depicts the effect of stress-induced anisotropy on the undrained shear behavior of coal ash at a lower range of $p'_0$ (50, 100 and 150 kPa) under IC and $K_0$ conditions. Peak deviatoric stress for $K_0$50 and $K_0$100 were seen to be very less as compared to IC50 and IC100, respectively. However, the difference in peak stresses was observed to be small in the case of $K_0$150 compared to IC150 (Fig. 2a). At the same $p'_0$, the axial strain at failure ($\varepsilon_f$) was found to be lesser for $K_0$ consolidated specimen as compared to the IC specimen. For instance, $\varepsilon_f$ for $K_0$50 and IC50 was found to be 1.13% and 1.63%, respectively. For IC specimens, the stress-strain patterns were such that the deviatoric stress was found to reduce after achieving the peak stress. Very similar behavior was reflected for $K_0$150 specimen. However, $K_0$50 and $K_0$100 specimens exhibited reduced deviatoric stress after achieving peak, which then again increased with continued shearing until the peak stress. The IC100 indicated more peak strain than IC50 specimen, which might be due to the low effect of confining pressure when increased from 50 kPa to 100 kPa. The effect of stress-induced anisotropy on the evolution of excess pore water pressure is presented in Fig. 2b. All the specimens were found to develop negative excess pore water pressure after an initial positive pore water pressure. For IC specimens, the excess pore water pressure was observed to be less dilative with an increase of $p'_0$; however, the behavior was in contrast in the case of $K_0$ consolidated specimen. The effective stress path moved towards the origin initially due to the generation of positive pore water pressure, which then moved away from the origin due to the development of negative pore water pressure (Fig. 2c).

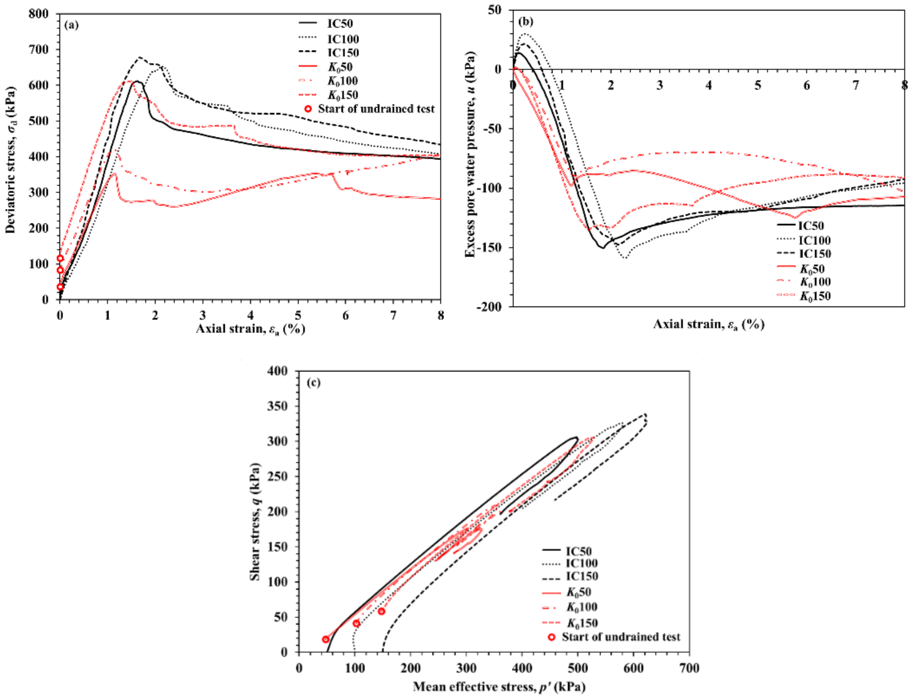


**Fig. 2.** Effect of stress induced anisotropy on shear response of compacted fly ash at 50, 100 and 150 kPa of mean effective stresses: (a) Stress-strain response, (b) Excess pore water pressure response, and (c) Effective stress path

### 4.3 Shear behaviour of coal ash under isotropic and $K_0$ consolidated conditions under higher range of mean effective stresses ($p'_0$)

Fig. 3 shows the effect of stress-induced anisotropy at a higher range of $p'_0$ (100, 200 and 300 kPa) on undrained shear behaviour of coal ash under IC and $K_0$ conditions. With the increase in $p'_0$, peak deviatoric stress increased for both IC and $K_0$ specimens (Fig. 3a). For the same $p'_0$, the $K_0$ specimen exhibited lower peak stress as compared to IC specimens. However, the difference was observed to be very small at higher $p'_0$. The peak stress for IC300 and $K_0$300 was found to be 897 kPa and 970 kPa; whereas peak stress for IC100 and $K_0$100 was obtained as 652 kPa and 417 kPa, respectively. The higher mean effective stress might have provided higher shear resistance to the coal specimen, which lead to higher peak stress of $K_0$300 specimens as compared to the IC300 specimens. The excess pore water pressure response depicted the increased positive pore water pressure with an increase in $p'_0$; however, the dilative response was observed to be more with an increase in $p'_0$. The effective stress path was observed to move towards origin due to positive pore pressure evolution at the beginning and then was found to move away from origin due to negative pore water pressure generation (Fig. 3c).

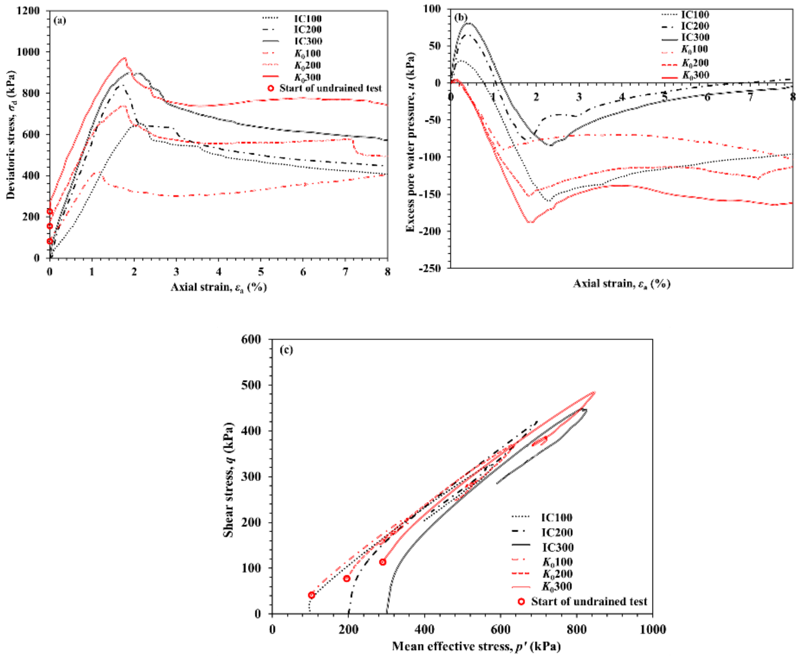


**Fig. 3.** Effect of stress-induced anisotropy on shear response of compacted fly ash at 100 kPa, 200 kPa and 300 kPa of mean effective stresses: (a) Stress-strain response, (b) Excess pore water pressure response, and (c) Effective stress path

## 5 Conclusion

The current study evaluated the strength and pore pressure response of coal ash consolidated under isotropic and $K_0$ conditions. It was concluded that the change in void ratio was found to be very small during the consolidation phases under both conditions. However, significant difference in stress-strain response was observed for $K_0$ specimens as compared to IC specimens at same mean effective stress ($p'_0$). The excess pore water pressure was observed to be less dilative with the increase in $p'_0$ for IC specimens. However, it was found to be more dilative with the increase in $p'_0$ for $K_0$ specimens.

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