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Geotechnical behavior of fiber reinforced fly ash

Shenbaga R. Kaniraj & V. Gayathri
Department of Civil Engineering, Indian Institute of Technology, New Delhi, India

ABSTRACT: The influence of randomly oriented fiber inclusions on the geotechnical behavior of two Indian fly ashes was studied. Polyester fibers and a constant fiber content of 1 % (by dry weight) were used in the experiments. The paper presents the results of the compaction tests, triaxial shear tests, and other geotechnical characterization tests on the raw and fiber reinforced fly ashes. The fiber inclusions increased the strength of the fly ashes and changed their behavior from brittle to ductile.

1 INTRODUCTION AND SCOPE

Gray (1970), Brown & Sheu (1975), Wu & Erb (1988), Wu *et al* (1988) observed that the presence of plant roots improved the strength of the soils and the stability of natural slopes. This led to more detailed studies on soils reinforced with artificial and natural fibers. While Gray & Ohashi (1983), and Shewbridge & Sitar (1989), carried out laboratory tests on soils in which the fibers were oriented in particular directions, Hoare (1979), Hoover *et al* (1982), Maher (1988), Gray & Maher (1989), Maher & Gray (1990), Maher & Ho (1994), Nataraj & McManis (1996), Gopal Ranjan *et al* (1996), Michalowski & Zhao (1996), and Consoli *et al* (1998) carried out tests with the fibers oriented randomly in the soils.

Fly ash is a silt-size residual waste produced from burning of coal in thermal power stations. The main geotechnical applications of fly ash are in building highway embankments, fills, landfill liners, and covers. The effect of fiber inclusions on the geotechnical characteristics of fly ashes have not been studied in as much detail as that of soils. Chakraborty & Dasgupta (1996), and Kaniraj & Havanagi (2001) have carried out experimental studies on some Indian fly ashes reinforced with randomly oriented fibers. The type and composition of coal, the method of burning and other factors affect the characteristics of fly ashes. Therefore, fly ashes can vary from plant to plant or even within the same plant over time. Similarly, the characteristics of fibers such as their type, diameter, length, tensile strength, and tensile modulus also vary widely. Therefore, in order to comprehend the influence of fiber inclusions it is necessary to compare the behaviors of fly ash-fiber mixtures of different combinations. The paper presents the results of an experimental study carried out with this as the objective.

2 MATERIALS USED

Two Indian fly ashes were used in the present study. They were collected in dry state from the electrostatic precipitators of the Dadri and Rajghat thermal power stations. The Rajghat fly ash was the same as that used by Kaniraj & Havanagi (2001) in their study. Polyester fibers were mixed with the fly ashes. The properties of the polyester fibers used in the present study and in the experiments of Kaniraj & Havanagi (2001) are given in Table 1.

Table 1. Properties of fibers used in different studies.**

Study	Type & Color	Diameter mm	Length mm	Aspect ratio	Specific gravity	Tensile strength MPa	Tensile modulus Mpa
Present study	Polyester Black	0.0203*	6	313	1.38	510	-
Kaniraj & Havanagi (2001)	Polyester Grey	0.075*	20	267	1.3	80-170	1450-2500

*Approximate values, as the fibers tend to split. **Values as given by the manufacturers HI-TECH FIBERS, South Carolina, U.S.A.

3 TEST PROGRAM

3.1 *Test program*

The test program consisted of experiments for the determination of: a) the physical, chemical, and geotechnical characteristics of the Dadri fly ash, and b) the geotechnical characteristics of the Dadri and Rajghat fly ashes mixed with randomly oriented 6 mm long polyester fibers.

3.2 *Fly ash-fiber mixture preparation*

The fly ash was first dried under heating lamps at approximately 40° C. The total dry weight of the mixture required to prepare a specimen, W, is known from the specimen's dimensions and dry unit weight, γ_d. W is also expressed as, $W = W_s + W_f$, where W_s and W_f are the weights of the dry fly ash and fibers, respectively. W_f is expressed as, $W_f = f_c W_s$, where f_c is the fiber content. Since a constant fiber content of 1 % was used the weight of dry fly ash is given by, $W_s = (W/.01) \approx 0.99\ W$. First, the required amounts of fly ash and fibers were measured and mixed together in the dry state. As the fibers tended to lump together, it required considerable care and time to separate them to get an even distribution of the fibers in the mixture. The dry fiy ash-fiber mixture was then mixed with the required amount of water. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. Kaniraj & Havanagi (2001), however, found that the fibers could be mixed with the fly ash more efficiently in the moist state than in the dry state. Therefore, they first mixed the dry fly ash with water and then mixed the moist fly ash with the fibers. This method of mixing was not satisfactory with the fibers used in the present study.

3.3 *Fly ash-fiber specimen preparation*

For triaxial shear tests, cylindrical specimens were prepared by static compaction of the fly ash-fiber mixture at the standard Proctor *MDD-OMC* of the raw fly ash. A 37.7 mm inner diameter and 73.5 mm long mould with additional detachable collars at both ends was used. To ensure uniform compaction, the entire required quantity of material was placed inside the mould-collars assembly and compressed in three steps alternately from the two ends till the specimen reached the dimensions of the mould.

4 FLY ASH CHARACTERISTICS

4.1 *Physical properties*

The physical properties of the Dadri and Rajghat fly ashes are summarized in Table 2.

Table 2. Physical properties of fly ashes.

Property	Dadri fly ash	Rajghat fly ash*
Specific gravity, G	2.2	2.19
Loss on ignition, %	0.4	1.4
Specific surface area, cm^2/g	3520	4020

*All results in the paper for Rajghat fly ash raw and 20mm fly ash fiber mixtures are from Kaniraj & Havanagi (2001)

4.2 *Chemical composition*

The chemical compositions of the Dadri and Rajghat fly ashes are summarized in Table 3. Both the fly ashes are classified as class F and pozzolanic materials as per ASTM C 618 (1993) specifications.

4.3 *Geotechnical classification*

The results of the experiments for grain size distribution and Atterberg limits are summarized in Table 4. Both the fly ashes can be classified as ML type belonging to the non-plastic silt category.

5 FIBER REINFORCED FLY ASH

The effect of fibers on the geotechnical characteristics of fly ashes was investigated by conducting standard Proctor compaction tests, unconfined compression tests, unconsolidated undrained and drained triaxial shear tests on raw fly ashes and fly ashes blended with 1 % polyester fibers by weight.

Table 3. Chemical compositions (%) of fly ashes.

Composition	Dadri fly ash	Rajghat fly ash
Silica (SiO_2)	60.12	61.21
Alumina (Al_2O_3)	30.16	30.07
Iron oxide (Fe_2O_3)	6.36	4.17
Lime (CaO)	1.00	0.10
Magnesia (MgO)	0.53	0.40
Titania (TiO_2)	---	2.60
Soda (Na_2O)	0.06	< 0.01
Potash (K_2O)	0.007	0.02
Sulphates (SO_3)	0.10	< 0.01

Table 4. Geotechnical classification test results.

Properties	Fly ash	
	Dadri	Rajghat
Grain size distribution		
Fine sand, 0.475-0.075 mm, %	5	20
Silt size, 0.075-0.002 mm, %	82	77
Clay size. < 0.002 mm, %	13	3
Uniformity coefficient, C_u	4.82	5.65
Coefficient of curvature, C_c	1.01	0.9
Atterberg limits		
Liquid limit, w_P, %	30.5	48-50
Plastic limit. w_l, %	NP	NP

5.1 *Compaction tests*

Figure 1 shows the compaction curves of the fly ashes with and without fiber inclusions. The values of maximum dry unit weight *(MDD)* and optimum moisture content *(OMC)* are summarized in Table 5. The results show that the Dadri and Rajghat fly ashes are distinctly different in their compaction characteristics. The small fiber content has not affected the *MDD* and *OMC* of the Dadri fly ash appreciably. In Rajghat fly ash, however, the effect was a little more marked; the fiber inclusions increased the *MDD* and decreased the *OMC*. All the specimens for the shear tests were prepared at the *MDD-OMC* of the raw fly ashes. The effects due to differences in the unit weight and water content of the raw and reinforced fly ash specimens were thus avoided. The differences in the behavior will be only due to the fiber inclusions.

5.2 *Unconfined compression tests*

A minimum of three specimens of the fly ash-fiber mixtures were prepared and tested at a deformation rate of 0.4064 mm/min. Figure 2 shows the stress-strain curves of the raw and fly ash-fiber specimens. The fiber inclusions had a significant effect on the stress-strain behavior. In raw fly ash specimens, a distinct failure axial stress was reached at an axial strain of about 1.5%-2.5% following which the specimens collapsed. Whereas, the fiber reinforced specimens exhibited more ductile behavior. After reaching a peak axial stress at a small strain, the specimens continued to deform under declining axial stress. Kaniraj & Havanagi (2001) observed that with the 20 mm fiber inclusions in the Rajghat fly ash there was no distinct reduction in axial stress even at 15% axial strain. The unconfined compressive strength *(UCS)* also increased. Table 6 summarizes the *UCS* and failure strain, ε_f, of the unreinforced and fiber reinforced fly ash specimens. The 6 mm long fiber inclusions have increased the *UCS* of the Dadri and Rajghat fly ash specimens by 55% and 174%, respectively. The increase in *UCS* is, therefore, more significant in the Rajghat fly ash-fiber specimens than in the Dadri fly ash-fiber specimens. Kaniraj & Havanagi (2001) reported that the increase in *UCS* depends on the *UCS* of the unreinforced specimen. Lower the *UCS* of the unreinforced specimen higher is the increase in *UCS* due to the fiber inclusion. The results of the present study confirm to this observation. Further, the increase in the *UCS* of the Rajghat fly ash specimens is more due to the shorter (6 mm) fiber inclusions than due to the longer (20 mm) ones.

Table 5. *MDD & OMC* of fly ash-fiber mixtures.

		Fiber	*MDD*, kN/m³ *(OMC %)*	
			raw fly ash	fiber reinforced
Dadri	1	6	13.8 (21)	13.8 (22)
Rajghat	1	6	10.5 (37)	10.7 (34)
Rajghat	1	20	10.5 (37)	11.0 (33)
Rajghat	½	20	10.5 (37)	11.0 (32)

Table 6. *UCS* of fly ash-fiber specimens *(fc= 1 %)*.

Fly ash	Fiber	*UCS*, kPa (ε_f, %)	
		raw fly ash	Fiber reinforced
Dadri	6	116.7 (≈ 2)	181 (2-5)
Rajghat	6	65.7 (≈ 2.5)	180.2 (3-5)
Rajghat	20	65.7 (≈ 2.5)	157.9 (15)

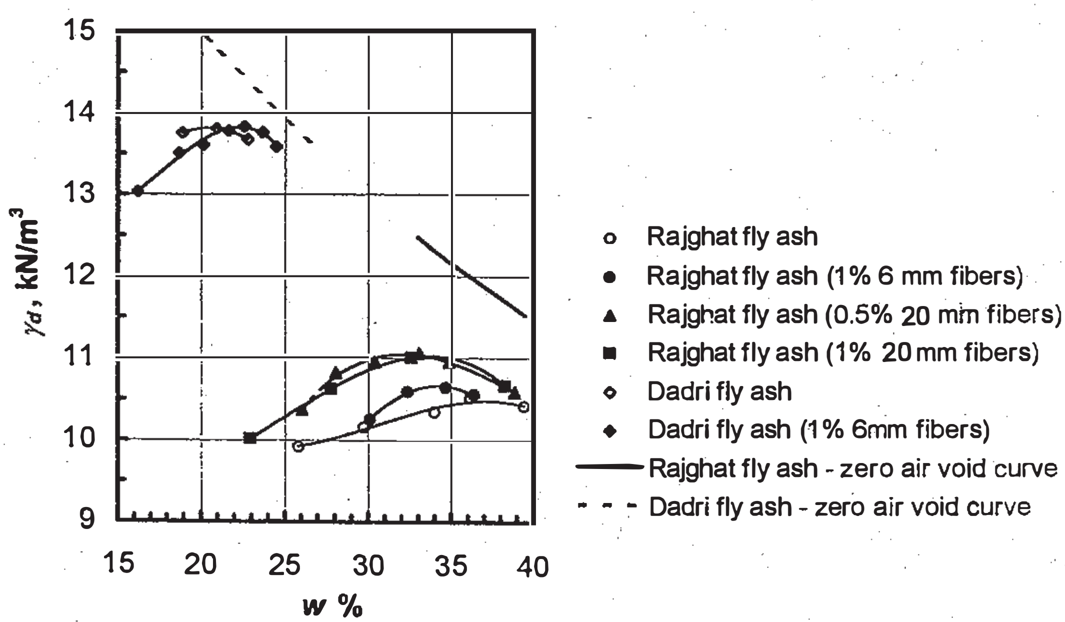

Figure 1. Compaction curves for fly ashes and fly-ash fiber mixtures.

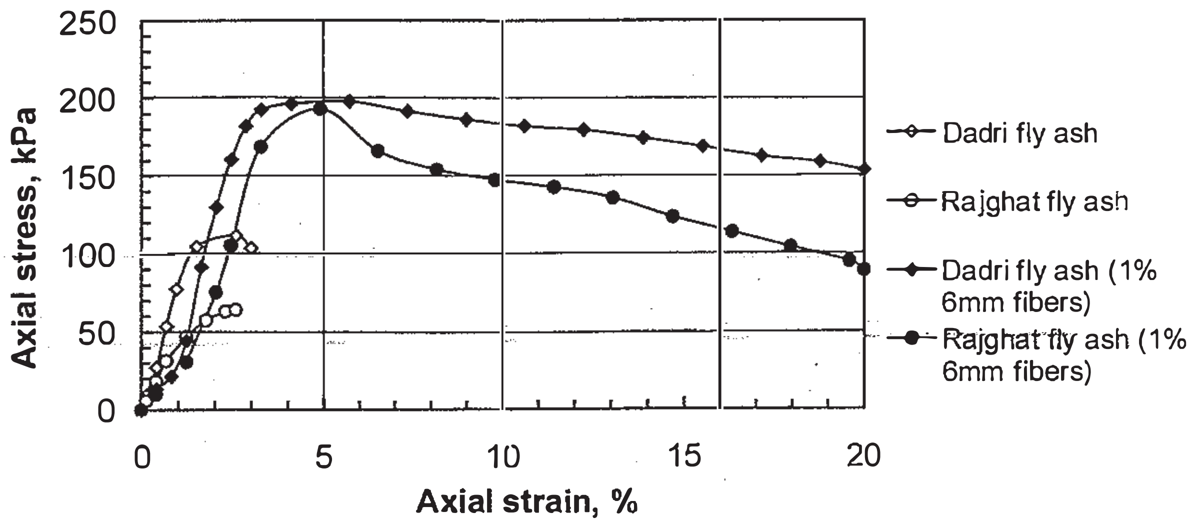

Figure 2. Stress-strain curves for specimens in unconfined compression tests.

5.3 *Unconsolidated undrained (UU) tests*

Unconsolidated undrained triaxial shear tests were carried out at confining stresses in the range of 98.1 to 490.5 kPa. In raw fly ash specimens, the deviator stress attained a peak value and thereafter remained almost constant. In Dadri fly ash the strain to attain the peak deviator stress varied between 11-14%. In fiber-reinforced specimens, no peak deviator stress was reached even at 15% axial strain. This may be a manifestation of the ductile behavior induced by the fiber inclusions. For determination of total stress shear strength parameters c_{uu} and ϕ_{uu}, the failure deviator stress, $(\sigma_1-\sigma_3)_f$, was taken as the peak deviator stress for raw fly ash specimens and as the deviator stress at 15% axial strain for fly ash-fiber specimens. Figure 3 shows the *p-q* [$p = (\sigma_1+\sigma_3)_f/2$, $q = (\sigma_1-\sigma_3)_f/2$] plots for the UU tests. The values of c_{uu} and ϕ_{uu} are summarized in Table 7. There is an increase in both c_{uu} and ϕ_{uu} due to fiber inclusions. Both the short and long fibers have caused an increase in the c_{uu} and ϕ_{uu} of the Rajghat fly ash specimens.

5.4 *Drained triaxial shear (CD) tests*

Drained triaxial shear tests were carried out only on the combinations of Dadri fly ash and 1 % fiber content of 6 mm long fibers. Prior to consolidation, the specimen was saturated in the following way. A small confining stress of about 20 kPa was applied and water was allowed to flow from a burette through the specimen, from bottom to top, for 24 hours. The CD tests were conducted at confining stresses in the range of 98.1 to 490.5kPa.

The deviator stress-axial strain behavior in CD tests was also found to be the same as in the UU tests. Using the same procedure as for the UU tests, the values of c' and ϕ' were determined. Figure 4 shows the p'-q' plots. The fiber inclusions increased the c' of the Dadri fly ash specimens from 0 to 55.9 kPa and the ϕ' from 29.3° to 33.6°.

Table 7. UU test results (f_c= 1%)

Fly ash	Fiber length mm	c_{uu} kPa (ϕ_{uu}) raw fly ash	c_{uu} kPa (ϕ_{uu}) fiber reinforced
Dadri	6	12.6 (31°)	93.7 (32.5°)
Rajghat	6	43.2 (30.1°)	102.8 (36°)
Rajghat	20	43.2 (30.1°)	128.6 (36°)

6 CONCLUSIONS

Laboratory experiments were carried out to study the influence of randomly oriented fiber inclusions on the geotechnical characteristics of two Indian fly ashes. Polyester fibers and a constant fiber content of 1% (by dry weight) were used in the experiments. The following are the main conclusions from the present experimental study and the comparison of the results with the previous studies.

1. The small amount of 1% fiber content in the form of randomly oriented fiber inclusions improved the stress-strain response of the fly ash specimens in all triaxial shear tests and changed their behavior from brittle to ductile.
2. The 6 mm long fiber inclusions increased the unconfined compressive strength of the Rajghat fly ash-fiber specimens more significantly than the *UCS* of the Dadri fly ash-fiber specimens. The effect of longer (20mm) fibers on the *UCS* of Rajghat fly ash is less than that of the shorter fibers.
3. The fiber inclusions also increased the total stress shear strength parameters c_{uu} and ϕ_{uu}, in the UUtests and the effective stress parameters c' and ϕ' in the drained triaxial shear tests.

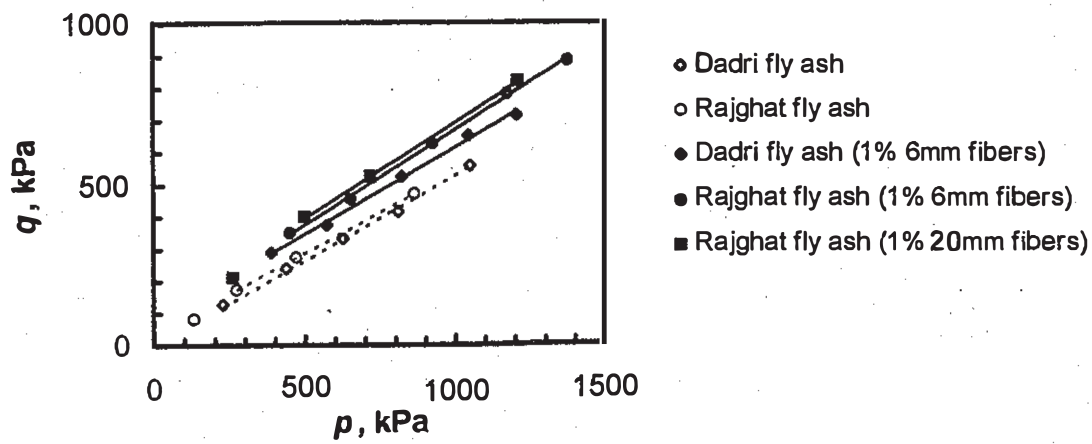

Figure 3. p-q plots for unconsolidated undrained tests.

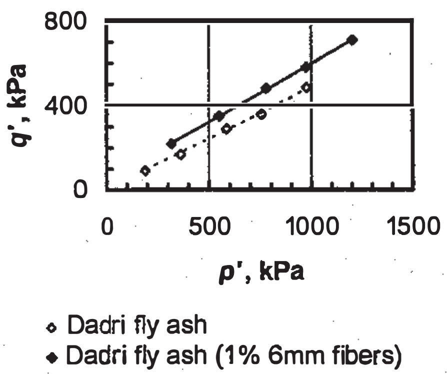

Figure 4. p'-q' plots for consolidated drained tests.

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