Strength Characteristics of Fiber Reinforced Cement Stabilized Fly ash

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Abstract — **In the present research work, a series of triaxial compression tests were carried out to study influence of fiber reinforcement and cement stabilization on the shear strength characteristics of fly ash. The varying parameters used are cement content, fiber content and curing period. Addition of cement to plain fly ash increases the cohesion and angle of internal friction and the optimum percentage of cement can be considered as 6%. The increase in cohesion is due to the cementation process where as the increase in angle of internal friction is due to the change in texture caused by flocculation-agglomeration mechanism of cement stabilization. Addition of fiber increases the cohesion and angle of internal friction of the fly ash and maximum percentage improvement was observed at 0.2% fiber content. Increase in shear strength parameters of fly ash due to inclusion of fiber is due to the fact that randomly oriented discrete inclusions incorporated into fly ash mass improves its load deformation behavior by interacting with the fly ash particles mechanically through surface friction and also by interlocking. Addition of fiber to cement stabilized fly ash further improves both the shear strength parameters of fly ash. Under the stress imposed, the fiber deforms and thereby interlocks the fly ash-cement mix. Besides, it mobilizes the frictional resistance at cement-fly ash-fiber interface and thereby improves the performance of the mix.**

Keywords—Fly ash, fiber, cement, shear strength

I. INTRODUCTION

As a result of heavy industrialization, the demand for power is increasing day by day. In India, most of the thermal power plants are coal based which results in the generation of large quantity of fly ash. This will create several environmental problems like leaching and dusting and it requires large areas for disposal causing huge capital loss to power plants. As per estimates, the annual fly ash generation in India during 2009-10 was about 200 million tonnes and the amount of fly ash recycled was about 30% only, ie 60 million tonnes. Expected generation of fly ash till 2015 would be 300 million tonnes which would pose a severe problem of disposal. Due to the abundance of fly ash, it is beneficial to recognize practical uses for fly ash instead of disposing it in landfills at a substantial cost. Several uses have been recognized for fly ash in construction including soil stabilization, Portland cement supplementation. Evidently, there is a major possibility for improvement regarding the utilization of fly ash and it is advantageous to find uses in which fly ash is the primary constituent rather than an additive to accelerate its consumption. For increasing use of fly ash as a construction material, it is required to enhance some properties of fly ash. Fly ash has become an attractive construction material because of its self-hardening property which depends on the amount of free lime in it. Engineering performance of fly ash can potentially be improved by mixing with cementing agents like Portland cement, quicklime and hydrated lime. Its performance can also be improved by mixing with randomly oriented fibers. The present study aims at investigating the performance evaluation of fly ash when amended with cement and fiber.

Kim et al. (2007) investigated the mechanical properties such as compaction response, compressibility and shear strength of fly ash. Kaniraj and Havanagi (1999) conducted studies on the compressive strength of cement stabilized fly ash-soil mixtures. Lav, A. and Lav, M. (2000) studied the effects of cement and lime stabilization in terms of chemical composition, crystalline structures, and hydration products. Singh (2013) studied the influence of coir fibers on shear strength parameters and stiffness modulus of fly ash. Tests results indicate that on inclusion of coir fiber, the shear strength parameters and stiffness modulus of fly ash increases. Kaniraj and Havanagi (2001) conducted a study to investigate the individual and combined effects of randomly oriented fiber inclusions and cement stabilization on the geotechnical characteristics of fly ash – soil mixture.

II. MATERIALS AND METHODOLOGY

A. *Materials used*

1) *Fly Ash*

The fly ash used in this study was collected from Kolaghat Thermal Power Plant (KTPP). The particle morphology was analyzed from the micrographs obtained by JEOL JSM-5800 Scanning Electron Microscope (SEM). These micrographs reveal that the fly ash particles of KTPP are almost spherical in shape and porous in nature with varying sizes. The spherical ash particles with much brighter surface are identified as cenospheres.

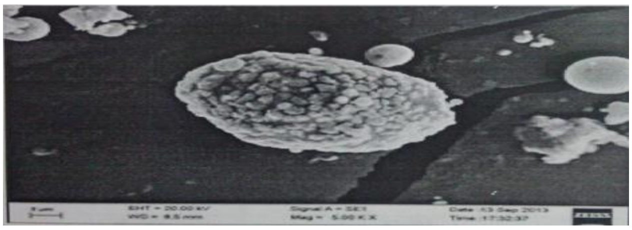

Fig.1. Scanning electron micrographs of KTPP fly ash sample at ×5000 magnifications

The elemental composition and chemical composition (element oxides) of fly ash sample are determined from EDXS presented in Table 1 and 2 respectively. The particle size distribution curve is shown in Fig.2. and the associated properties are presented in Table 3.

TABLE 1. ELEMENTAL COMPOSITION OF KTPP FLY ASH

Element	*Quantity (% by mass)*
Na	0
Al	13.44
Si	29.08
K	3.15
Ca	0
Fe	6.68
Cu	0
Zn	0
O	47.64

TABLE 2. CHEMICAL COMPOSITION OF KTPP FLY ASH

Compound	*Quantity (% by mass)*
Na_2O	0
Al_2O_3	31.31
Si_2O	60.2
K_2O	2.1
CaO	0
FeO	4.29
CuO	0
Fe_2O_3	2.1

From the data presented in Table 2, it can be seen that the percentage of lime present in the fly ash is less than 20% by mass and hence the fly ash is classified as Class F (ASTM C-618).

TABLE 3. PROPERTIES OF FLY ASH

Properties	*Description*
Gravel content(%)	0
Sand content(%)	28
Fines content(%)	72
D_{10}(mm)	0.018
D_{30}(mm)	0.027
D_{60}(mm)	0.04
C_u	2.22
Cc	1.01

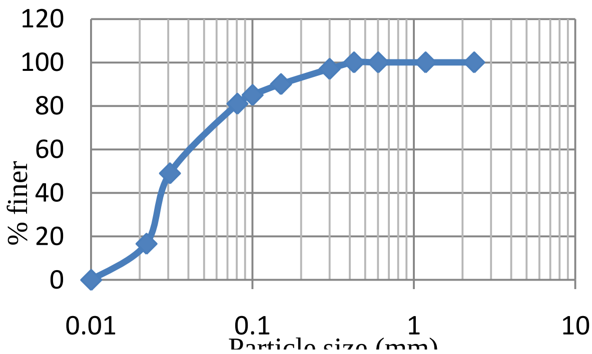

Fig.2. Particle size distribution curve of fly ash

2) Cement

The cement used in this study was Portland Slag Cement. Its physical properties were investigated and listed below in Table 4.

TABLE 4. PROPERTIES OF CEMENT

Properties	*Description*
Fineness (cm^2/gm)	2544
Standard consistency (%)	32
Initial setting time (min)	150
Final setting time (min)	280
Specific gravity	3.06
Soundness (mm)	2
3 days compressive strength (N/mm^2)	19.95
7 days compressive strength (N/mm^2)	29.63
28 days compressive strength (N/mm^2)	43.24

3) Fibre

The fiber used in this study is commercially available polypropylene fiber of length 24 mm. Polypropylene fibers are hydrophobic, non-corrosive and resistant to alkalis, chemicals and chlorides. These fibers are having higher tensile strength and are resistant to sea water. These are also having higher melting point, i.e 164˚C. SEM of typical polypropylene fiber in magnification ×1500 is depicted in Fig. 3.4. The properties of fiber, as provided by the manufacturer, is summarized in Table 5.

Fig.3. Scanning electron micrograph of polypropylene fiber

TABLE 5. PROPERTIES OF FIBER

Properties	*Description*
Polymer type	Virgin Polypropylene Homo-polymer
Diameter	30.3 µm
Elongation	20-22 %
Strength	550-600 MPa

B. *Methodology*

All the tests in this investigation are carried out using a standard triaxial apparatus. This test was conducted according to ASTM D 2850-03a (2007) for the determination of shear strength parameters (c and ϕ) of fly ash mixed with different percentages of cement and fiber cured for 0, 7, 14 and 28 days. Three identical samples were prepared for the test in cylindrical split mould having diameter 38.1 mm and height 76.2 mm for each type of mix, at their respective OMC and MDD.

III. RESULTS AND DISCUSSIONS

The results obtained from the studies on strength characteristics of fly ash stabilized with cement, polypropylene fibers and with both cement and fibers are presented and influence of parameters such as cement content, fiber content and curing time are discussed.

A. *Plain fly ash*

In order to understand the influence of cement and fiber addition on the performance improvement of fly ash, reference tests were carried out with plain fly ash at 0,7, 14 and 28 days curing. From the stress-strain response, it is observed that the fly ash specimens exhibited a brittle behavior and from the failure patterns, it is clear that plain fly ash specimens exhibited general shear failure. Influence of curing period on the stress-strain response of plain fly ash is shown in Fig.4. It is observed that peak deviator stress increases with increase in curing period. The strength envelopes (p-q plots) for peak stresses corresponding to various curing periods are depicted in Fig.5. Correspondingly, the peak shear parameters obtained are summerized in Table 6.

It is observed that the plain fly ash exhibited lower values of shear strength parameters (both c and ϕ). Also, with increase in curing period, there is not much improvement in the value of cohesion. The result is in conformity with the chemical composition and classification of fly ash, which was classified as Class F and the CaO content in the present fly ash is very low (< 10%) which is primarily responsible for gaining strength in presence of water along with silica and alumina. The EDX of plain fly ash shows that oxides of alumina and silica are more than the oxides of calcium present in the fly ash. The deficiency of CaO in fly ash resulted lower strength in presence of water.

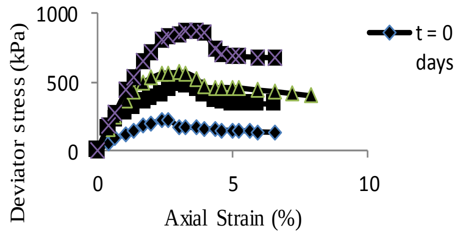

Fig.4. Stress-strain response of plain fly ash

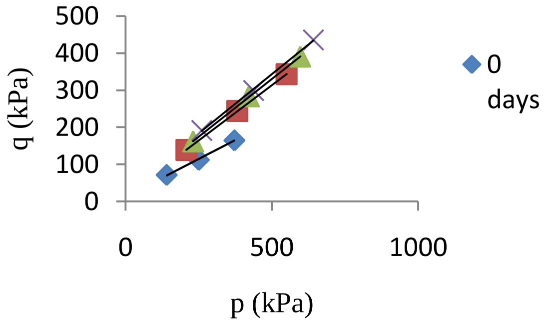

Fig.5. p-q diagram for plain fly ash

TABLE 6. PEAK SHEAR STRENGTH PARAMETERS OF PLAIN FLY ASH

		curing time (days)			
		0	7	14	28
Shear parameters	c (kPa)	15.01	18.98	24.1	30.22
	φ (˚)	23.81	36.66	38.6	39.73

B. *Cement Stabilized Fly ash*

A series of triaxial compression tests were carried out to investigate the behavior of cement stabilized fly ash specimens. Typical stress-strain responses of fly ash with varying cement content (3%, 6% and 9%) for different curing periods are illustrated below. It is revealed that, with the addition of cement, the deviatoric stresses at failure (q) had increased for all the cement contents. Also, there was an increase in deviatoric stress with increase in curing period for cement stabilized fly ash.

1) Effect of cement content

From the stress-strain relationship (Fig.6.) and failure patterns obtained, it is observed that the specimens stabilized with cement showed a sharp peak in the stress–strain curve and immediately after attaining the peak deviatoric stress, there was a rapid reduction in the deviatoric stress with increase in strain for different curing periods. i.e, the cement stabilized fly ash specimens showed more brittle behaviour compared to plain fly ash. In this type of specimens, distinct failure planes were developed and with increase in cement content, the inclination of the failure planes with vertical axis of the specimens decreased. At higher curing period (28 days), specimens with high cement contents were observed to split nearly along vertical plane. Fig.7. shows the stress-strain response of both plain fly ash and cement stabilized fly ash (c_c = 3%) for a particular curing period of 28 days.

TABLE 7. PEAK SHEAR STRENGTH PARAMETERS OF CEMENT STABILIZED FLY ASH

Cement content in % (c_c)	*Shear parameters*				
		Curing time (days)			
		0	7	14	28
3	c(kPa)	21.06	26.66	42.79	84.03
	φ (˚)	37.95	41.25	43.21	41.53
6	c(kPa)	36.58	90.48	188.54	241
	φ (˚)	40.51	45.96	48.37	46.91
9	c(kPa)	61.07	285.35	380.76	436.1
	φ (˚)	42.15	49.37	49.79	48.98

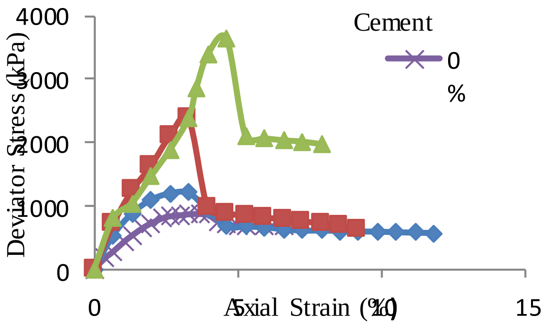

Fig.6. Stress-strain response of cement stabilized fly ash (28 days curing and 207 kPa confining pressure)

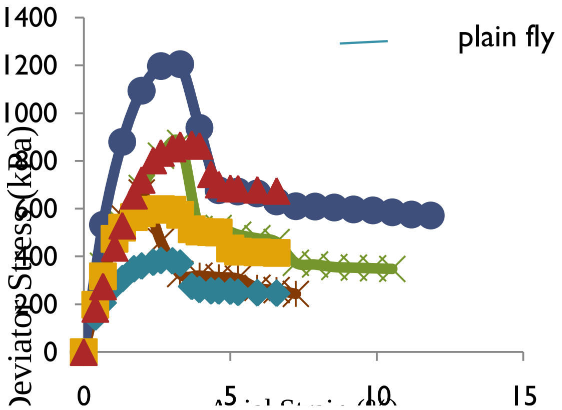

Fig.7. Stress-strain response of plain fly ash and cement stabilized fly ash (c_c = 3%, 28 days curing)

It is observed that the peak deviatoric stress and stiffness were dramatically increased, while residual strength remained almost the same and the post peak behaviour becomes strongly brittle for cemented fly ash. Fig.8. shows the p-q response of cement stabilized fly ash for different cement contents at 28 days curing.

From the p-q responses, it is found that the shear strength parameters, c and ϕ increased with the addition of cement to fly ash. This is attributed to the increase in the availability of alkali (which is by-product of hydration of cement) for pozzolanic reaction. The increase in shear strength for cement stabilized fly ash is due to the development of more cementitious products in the stabilized matrix as a result of fly ash–cement interaction. The values of cohesion (c) and angle of internal friction (ϕ) obtained for cement stabilized fly ash at curing periods are presented in Table 7.

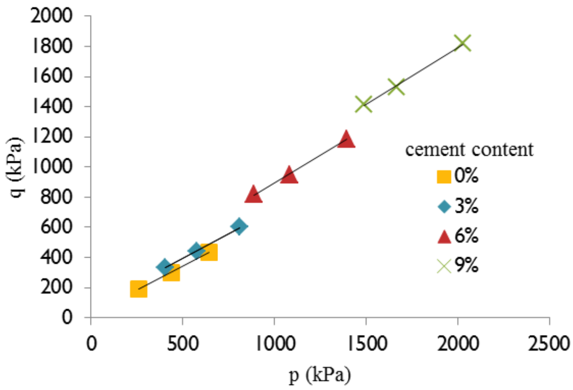

Fig.8. p-q diagram of cement stabilized fly ash (28 days curing)

Addition of cement increased the cohesion and angle of internal friction of the fly ash. On increasing the cement percentage, shear strength of fly ash-cement mix increases, however, the significant increase in cohesion was observed at 6% cement after 28 days curing (186% increase), while at 9% cement, the percentage increase was observed as only 80%. Also, the angle of internal friction increases by 13% at 6% cement content and at 9% cement, the improvement is only 4.4%. Therefore, for economic considerations, the optimum percentage of cement can be considered as 6%.

The increase in cohesion part of the shear strength of stabilized fly ash is more significant due to development of bonding between the particles on stabilization. The increase in cohesion is due to the cementation process where as the increase in angle of internal friction is due to the change in texture caused by flocculation-agglomeration mechanism of cement stabilization. When cement is added to fly ash, it is mainly utilized for the hydration reaction. During the hydration of cement, C_3S and C_2S present in cement react with water forming complex calcium silicate hydrates (C–S–H). The C–S–H gel thus formed fills the void space and binds the particles together imparting strength to the mass. With increase in cement content in the mixture, the quantity of gel formation increases, which binds the particles more effectively.

2) Effect of curing period

It is observed that the values of both c and ϕ of all mixes increased with increase in curing period. But this increase is more prominent upto 14 days curing. At 28 days, the increase in strength parameters is not much noticeable as that from 7 to 14 days. In the earlier stages of cement stabilization, fly ash particles served as nucleation sites for hydration and pozzolanic reaction products. In the later stages, further formation of C-S-H gel surrounded the fly ash particles and filled the space between the fly ash particles and thus increases the strength of cement-fly ash mix. Fig.9. shows the influence of curing period on the stress-strain response of cement stabilized fly ash.

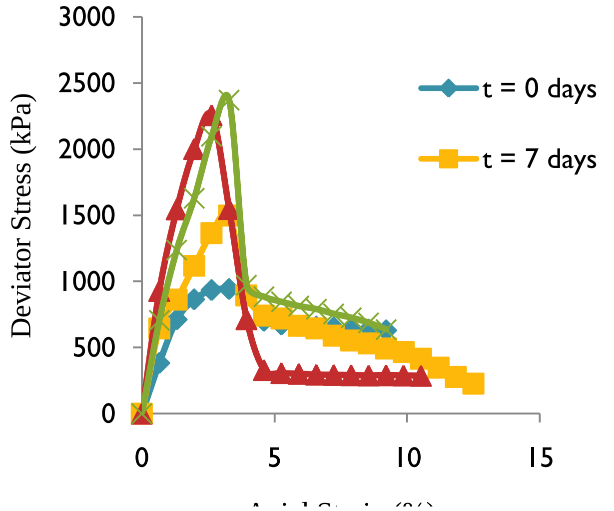

Fig.9. Stress-strain response of cement stabilized fly ash (c_c = 6 %, σ_3 = 207 kPa)

C. Fiber Reinforced Fly ash

A number of stress- strain curves were plotted from the tests results of triaxial compression test performed on fly ash reinforced with different fiber contents (0.1%, 0.2%).

1) Effect of fiber content

It is found that deviator stress at failure increased with increase in percentage fiber content at a particular cell pressure as shown in Fig.10. The increase in peak deviator stress may be due to the shear transfer mechanism which has been induced by the inclusion of fibers. Fiber inclusion enhanced the peak stress of fly ash specimens. It can also be seen that fiber reinforced uncemented fly ash exhibited more ductile behavior and smaller loss of post peak strength than uncemented and cemented fly ash. From the test results, it is clear that the most significant effect of the fibers was on the stress-strain behavior of the fly ashes. It is observed that the stress-strain responses of fiber reinforced fly ash had exhibited relatively less pronounced peak indicating that the fly ash with fiber had turned relatively ductile. The failure patterns indicated a more localized failure that the fiber reinforcement prevented a general mode of failure as observed in case of plain fly ash. The fibers changed the brittle behavior of the raw fly ashes to ductile behavior. Also, the stiffness of reinforced fly ash increased with the increase in confining pressure and fiber content. This is due to the fact that under higher confining pressures, fly ash samples are more confined and more resistant to deformation which results in higher deviator stress at failure. Fig.11. shows the stress-strain response of both cemented fly ash and fiber reinforced fly ash (c_c = 3%) after a curing period of 28 days.

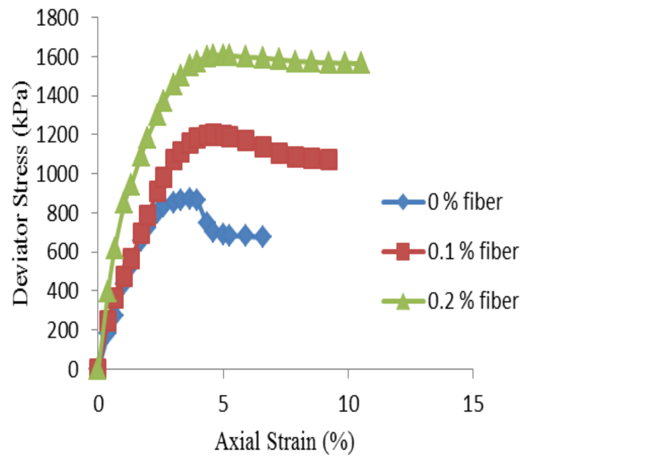

Fig.10. Stress-strain response of fiber reinforced fly ash (28 days curing and 207 kPa confining pressure)

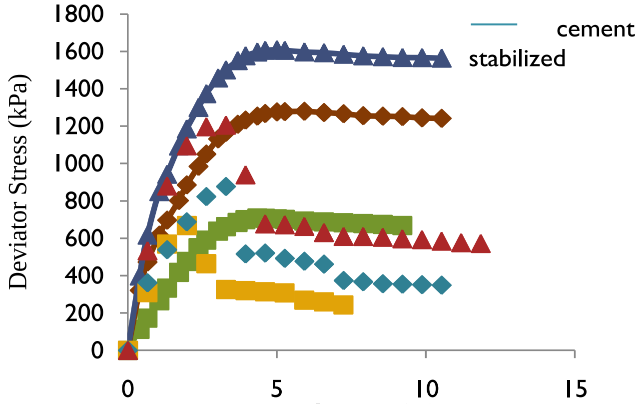

Fig.11. Stress-strain response of cemented and fiber reinforced fly ash (f_c = 0.2%, c_c = 3%) after 28 days curing.

Fiber reinforced fly ash specimens exhibited a higher value of peak deviator stress compared to cement stabilized fly ash. It can also be seen that fiber reinforced fly ash exhibited more ductile behavior and smaller loss of post peak strength than uncemented and cemented fly ash. In order to determine the values of shear strength parameters (c and ϕ) of reinforced fly ash for various fiber contents, failure envelopes were drawn and shear strength parameters (c and ϕ) were measured from the modified failure envelopes. Fig.12. shows the p-q response of fiber reinforced fly ash for different fiber contents at 28 days curing.

It is observed that for reinforced fly ash, there was a significant increase in cohesion and angle of internal friction over the unreinforced fly ash. Table 8 shows the values of cohesion (c) and angle of internal friction (ϕ) of reinforced fly ash. Addition of fiber increases the cohesion and angle of internal friction of the fly ash. The results presented in table 8 shows that on increasing the fiber percentage from 0.1% to 0.2%, cohesion of fly ash-fiber mix increases by 6.6% at 28 days curing. Also, the angle of internal friction increases by 13.6% at 0.2% fiber content and hence the optimum percentage of fiber can be considered as 0.2%.

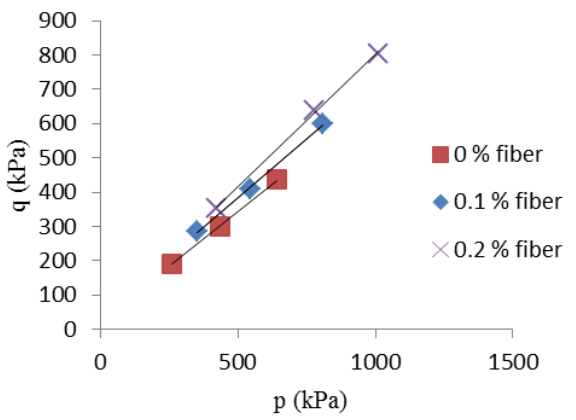

Fig.12. p-q diagram of fiber reinforced fly ash (28 days curing)

TABLE 8. PEAK SHEAR STRENGTH PARAMETERS OF FIBER REINFORCED FLY ASH

Fiber content in %(f_c)	*Shear parameters*				
		Curing time (days)			
		0	7	14	28
0.1	c (kPa)	20.57	32.5	43.4	47.63
	φ (˚)	36.98	42.89	43.24	44.23
0.2	c (kPa)	23.85	39.87	43.07	50.76
	φ (˚)	46.58	49.05	49.96	50.25

Fiber inclusion has more effect on the friction part of the shear strength than on the cohesion part. The significant increase in shear strength parameters of fly ash due to addition of fiber will improve the load carrying capacity of fly ash. The increase in shear strength parameters of fly ash due to inclusion of fiber is due to the fact that randomly oriented discrete inclusions incorporated into fly ash mass improves its load deformation behavior by interacting with the fly ash particles mechanically through surface friction and also by interlocking. The function of bond or interlock is to transfer the stress from fly ash to the discrete inclusion by mobilizing the tensile strength of discrete inclusion. Thus, fiber reinforcement works as frictional and tension resistance element. Further, addition of fiber makes the fly ash a composite material whose strength is greater than that of unreinforced fly ash.

2) Effect of curing period

With increase in curing period, both the peak deviatoric stress and the shear strength parameters increased and the effect was more significant upto 14 days curing. Beyond this period, there was only a slight increase in strength parameters.

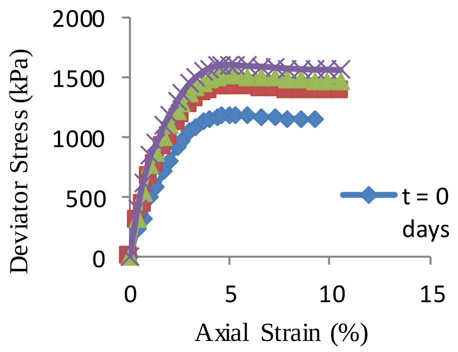

Fig.13. Stress-strain response of fiber reinforced fly ash (f_c = 0.2 %, σ_3 = 207 kPa)

D. Fiber Reinforced Cement Stabilized Fly ash

The influence of cement and fiber addition on the performance of fly ash can be observed through the stress-strain curves plotted from the tests results of triaxial compression test.

1) Effect of fiber content on cemented fly ash

The combined effect of fiber and cement inclusions on the stress–strain response is shown in Fig.14. It is readily observed that the peak deviator stresses increased with increase in fiber content.Inclusion of fibers within the cemented fly ash reduced the brittleness of the response and increased the failure strain. The deviatoric stress increases with an increase in axial strain until the peak value is reached, followed by a sudden drop in cemented fly ash, but the reduction of post-peak stress is gradual when fibers are included. Furthermore, the residual strength of cement–fiber fly ash specimens increases with increased fiber content. Undoubtedly, one of the main advantages of fiber reinforcement when applied to fly ash is the improvement in material ductility. Also, the fiber reinforced cemented fly ash is stiffer as compared to uncemented fly ash. From the failure patterns observed, it is observed that fiber reinforced fly ash with low cement content exhibited local shear failure whereas with higher cement content, it exhibited general type of shear failure. Fig.15. shows the stress-strain response of both cemented and fiber reinforced cemented fly ash (fc = 0.2 %, cc = 6%) after 28 days curing.

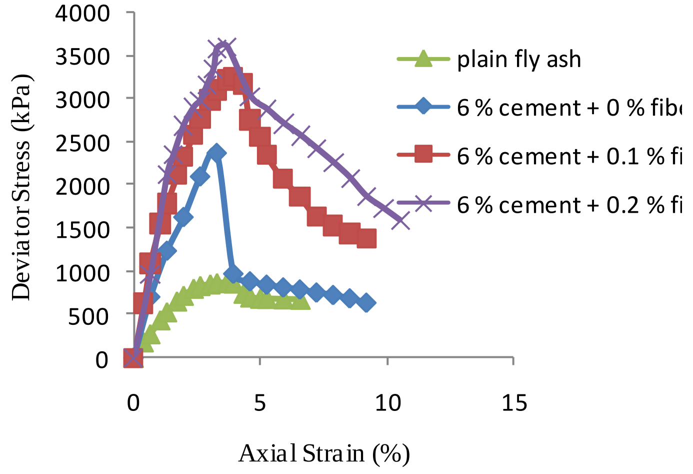

Fig.14. Stress-strain response of fiber reinforced cement stabilized fly ash (28 days curing and 207 kPa confining pressure)

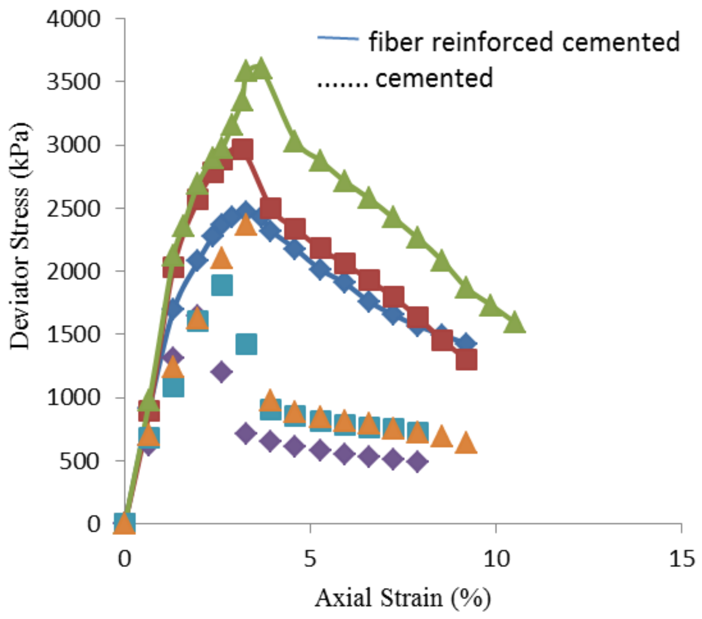

Fig.15. Stress-strain response of cemented and fiber reinforced fly ash (f_c = 0.2%, c_c = 6%, 28 days curing)

Fiber reinforced fly ash specimens exhibited a higher value of peak deviator stress compared to cement stabilized fly ash. It can also be seen that fiber reinforced fly ash exhibited more ductile behaviour and smaller loss of post peak strength than cemented fly ash specimens. In fiber-reinforced cemented fly ash, the interactions between the fiber surface and the hydrated products make main contribution to the strength at the interface. Fig.16. shows the p-q response of fiber reinforeced cement stabilized fly ash at different fiber contents after 28 days curing.

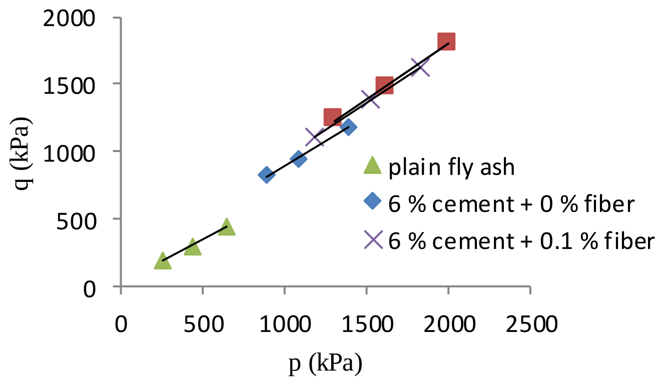

Fig.16. p-q diagram of fiber reinforced cement stabilized fly ash (28 days curing)

Percentage of fiber and cement content play an important role in the development of the shear strength parameters c and ϕ. The cohesion and internal friction angle of specimens of cemented soil increase with increasing fiber content. If the fiber content remains the same, cement inclusion significantly enhances the shear strength parameters. Shear parameters improved significantly with the addition of both cement and fiber to fly ash. Table 9 shows the values of cohesion (c) and angle of internal friction (ϕ) of fiber reinforced cement stabilized fly ash.

For both cohesion and friction, the maximum percentage increase is observed for FA+6C+0.2F mix. Percentage improvement for cohesion of this mix is found to be 155% and that for angle of internal friction is 45% at 28 days curing. Therefore, for economic considerations, the optimum percentage of cement and fiber can be considered as 6% and 0.2% respectively. Addition of cement to fly ash improves both cohesion and angle of internal friction since it provides the free lime needed for the pozzolanic reaction resulting in the improvement of shear strength. Cohesion (c) is more influenced by the addition of cement than angle of internal friction (ϕ). The effect of cement will increase with increase in curing period.

Addition of fiber to this cement stabilized fly ash further improves both the shear strength parameters. Under the stress imposed, the fiber deforms and thereby interlocks the fly ash-cement mix. Besides, it mobilizes the frictional resistance at cement-fly ash-fiber interface and thereby improves the performance of the mix. Shear strength parameters of fiber reinforced cement stabilized fly ash increases significantly with increase in curing days.

TABLE 9. PEAK SHEAR STRENGTH PARAMETERS OF FIBER REINFORCED CEMENT STABILIZED FLY ASH

Mix	*Shear strength parameters*							
	Curing days							
	0		7		14		28	
	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)
FA + 3C + 0.1F	52.2	45.076	70.4	46.13	84.86	46.89	112.25	47.75
FA + 6C + 0.1F	112.2	47.57	123.68	48.65	256.7	51.7	297.3	51.97
FA + 9C + 0.1F	200.96	48.152	326.88	53.76	412.8	54.09	450.43	54.14
FA + 3C + 0.2F	69.06	50.32	79.04	51.26	96.9	51.61	120.64	52.28
FA + 6C + 0.2F	121.5	51.03	150.69	51.44	267.3	54.29	307.9	53.6
FA + 9C + 0.2F	241.67	51.41	336.8	55.18	431.5	55.88	478.86	56

2) Effect of curing period

With increase in curing period, both the peak deviatoric stress and the shear strength parameters increased and the effect was more significant upto 14 days curing. Beyond this period, there was only a slight increase in strength parameters.

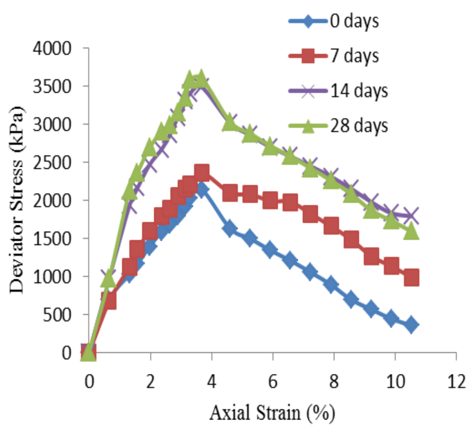

Fig.17. Stress-strain response of fiber reinforced cement stabilized fly ash (f_c = 0.2%, c_c = 6%, σ_3 = 207 kPa)

E. CONCLUSIONS

In the present research work, a series of triaxial compression tests were carried out to study influence of fiber reinforcement and cement stabilization on the shear strength characteristics of fly ash. The varying parameters used are cement content (cc), fiber content (fc) and curing period. The conclusions drawn from the present study are presented below.

1. The performance improvement of the fly ash continues to increase with increase in cement content until about 6% beyond which further improvement is marginal.
2. At optimum cement content (i.e. 6%), the increase in friction angle is in the range of 13% and cohesion is as high as 186%.
3. Increase in cohesion is due to the cementation process where as the increase in angle of internal friction is due to the change in texture caused by flocculation-agglomeration mechanism of cement stabilization.
4. With fiber reinforcement the performance of the cement stabilized fly ash is further enhanced. At optimum fiber content of 0.2% with 6% of cement, cohesion improvement is in the order of 155% and friction improvement is in the range of 45%.
5. The increase in strength of cemented fly ash due to fiber is attributed to the mechanical interaction of the reinforcement through interlocking and adhesion leading to a composite mass that takes enhanced loading.
6. Unreinforced cemented fly ash exhibits brittle behavior while with fiber reinforcement it is ductile in nature.

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