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ORIGINAL PAPER

Effect of fly ash and polypropylene fibres content on the soft soils

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Abstract Fly ash is a waste produced from the burning of coal in thermal power stations. The staggering increase in the production of fly ash and its disposal in an environmentally friendly manner is increasingly becoming a matter of global concern. Efforts are underway to improve the use of fly ash in several ways, with the geotechnical utilization also forming an important aspect of these efforts. An experimental program was undertaken to investigate the effects of multifilament and fibrillated polypropylene fibre on the compaction and strength behavior of CH class soil with fly ash in different proportions. The soil samples were prepared at two different percentages of fibre content (i.e. 0.5 and 1% by weight of soil) and two different percentages of fly ash (i.e. 10 and 15% by weight of soil). A series of tests were prepared including optimum moisture content and laboratory unconfined compression strength tests, compaction tests and Atterberg limits test. The fibre inclusions increased the strength of the fly ash specimens and changed their brittle behavior into ductile behavior.

Keywords Fibre-reinforced soil · Fly ash-soil · Polypropylene fibres

Résumé Les cendres volantes constituent un déchet issu de la combustion du charbon dans les centrales thermiques. L'augmentation vertigineuse de la production de cendres volantes et sa mise en dépôt dans des conditions respectueuses de l'environnement sont de plus en plus des sujets de préoccupation générale. Des efforts sont en cours pour améliorer l'utilisation des cendres volantes de plusieurs façons, l'utilisation de ces produits en géotechnique représentant un aspect important de ces efforts. Un programme expérimental a été entrepris pour étudier les effets, sur les caractéristiques de compactabilité et de résistance, de l'incorporation de fibres de polypropylène multi filament (M19) et fibrillated (E19) à des sols de classe CH comportant différentes proportions de cendres volantes. Les échantillons de sol ont été préparés avec deux teneurs différentes en fibres (i. e. 0,5 et 1% en poids de sol) et deux teneurs différentes en cendres volantes (i. e. 10 et 15% en poids de sol). Une série d'échantillons ont été préparés à la teneur eau optimum et des essais de compression simple et de compactage ainsi que des mesures de limites d'Atterberg ont été réalisés. L'incorporation de fibres a augmenté la résistance des échantillons contenant des cendres volantes et modifié leur comportement fragile en un comportement ductile.

Mots clés Sol renforcé par incorporation de fibres · Sol contenant des cendres volantes · Fibres de polypropylène

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Introduction

Various laboratory investigations have been conducted on fly ash/lime stabilization of soil and fibre reinforced soil. Fly ash is one of the most extensive waste materials from the manufacturing industry and is continuously being created due to the increase in energy, utilities and infrastructure in urban areas. Coal burning electric utilities worldwide annually produce millions of tons of fly ash as a waste/by-product and the environmentally acceptable disposal of this material has become an increasing concern.

Due to the high volume of material it requires, the construction industry is often looked upon as a potential consumer of fly ash and studies on the utilization of fly ash and lime for soil stabilization have been undertaken by many investigators, e.g. Mitchell and Katti (1981), Maher et al. (1993), Consoli et al. (2001). The physical and chemical mechanisms of both the short- and long-term reactions involved in the lime stabilization of soils or soil–fly ash mixtures have been extensively described by Ingles and Metcalf (1972) and Brown (1996). Edil et al. (2006) indicated the effectiveness of fly ash for the stabilization of fine grained soils.

Maher and Ho (1994) indicated that an increase in the strength and toughness of kaolinite fibre composite was a function of fibre length and content, and water content. They suggested the contribution of fibres to peak compressive strength was reduced and ductility increased with increasing fibre length. Consoli et al. (1998) reported that inclusion of fibre glass in silty sand effectively improves peak strength and Consoli et al. (2002) indicated that the inclusion of polyethylene terephthalate fibre in fine sand improves both peak and ultimate strength, which is dependent on fibre content. Kumar and Tabor (2003) studied the strength behavior of silty clay with nylon fibre for varying degrees of compaction.

The effect of the inclusion of polymer fibre in plain fly ash was studied by Chakraborty and Dasgupta (1996) who conducted tri-axial tests and found an increase in friction angle for fibre contents ranging from 0 to 4% by weight of fly ash with a constant fibre aspect ratio of 30. Kaniraj and Havanagi (2001) conducted a study on a soil–fly ash mixture reinforced with 1% polyester fibres (20 mm length) and demonstrated the combined effect of fly ash and fibre on the soil. Kaniraj and Gayatri (2003) indicated that 1% polyester fibres (6 mm length) increased the strength of raw fly ash and changed the mode of failure from brittle to ductile. Dhariwal (2003) carried out performance studies on the California bearing ratio values of fly ash reinforced with jute and non-woven geo fibres. Bearing in mind the gaps in the available literature and the limited studies on behavior of fibre reinforced soil–fly ash mixtures, the study was undertaken to identify and quantify the influence of fibre variables on the engineering behavior of soil–fly ash mixtures.

A number of research studies have demonstrated that the inclusion of fibre results in significant modifications and improvement in the engineering behaviour of soils. Typically, multifilament (MF19) and fibrillated (F19) polypropylene fibre are added and mixed with soil or fly ash. One of the primary advantages of fibres is the absence of potential planes of weakness that can develop parallel to oriented reinforcement.

Fibre inclusions cause significant modification and improvement in the engineering behavior of soils. A number of research studies on fibre-reinforced soils have recently been carried out using tri-axial, unconfined compression, CBR, direct shear and tensile and flexural strength tests (Andersland and Khattak 1979; Freitag 1986; Setty and Rao 1987; Maher and Gray 1990; Maher and Ho 1994; Michalowski and Zaho 1996; Ranjan et al. 1999; Consoli et al. 1998, 2002; Santoni et al. 2001; Kumar et al. 2006).

The literature cites various studies conducted to understand the behavior of soils modified by the addition of fibres and other components. Lima et al. (1996) observed a large increase in compressive strength with the addition of lime and cement to fibre-reinforced soils. Consoli et al. (1998) carried out drained triaxial compression tests to study the individual and combined effects of cement stabilization and randomly oriented fibre inclusions on the behavior of silty sand. Consoli et al. (2002) conducted unconfined compression tests, splitting tensile tests, and saturated drained triaxial compression tests to evaluate the benefit of utilizing randomly distributed polyethylene fibres obtained from plastic wastes, alone and combined with rapid hardening portland cement, to improve the engineering behavior of uniform sand. Kumar et al. (2006) found that UCS of highly compressible clay increases with the addition of fibres and further increases when fibres are mixed in clay sand mixtures.

Chakraborty and Dasgupta (1996) studied the strength characteristics of fibre-reinforced fly ash by carrying out laboratory triaxial shear tests. The fly ash was collected from the Kolaghat thermal power station in India. Kaniraj and Havanagi (2001) studied the behavior of cement-stabilized fibre-reinforced fly ash–soil mixtures. They mixed Indian fly ash with silt and sand in different proportions. The study showed that cement stabilization increases the strength of raw fly ash-soil specimens. The fibre inclusions increased the strength of raw fly ash–soil specimens as well as that of cement-stabilized specimens and changed their brittle behavior to ductile behavior. They further concluded that the combined action of cement and fibres is either more than or nearly equal to the sum of the increase caused by them individually (Kumar et al. 2007).

This study mixed fly ash with multifilament (MF19) and fibrillated (F19) polypropylene fibre to improve on such unfavorable properties of the soil as low strength, low bearing ratio and low compaction. The paper examines the effect of multifilament (MF19) and fibrillated (F19) polypropylene fibre content on the geotechnical behaviour of clayey soil–fly ash mixtures. The purpose of this investigation was to identify and quantify the influence of fibre variables on the performance of fibre-reinforced soil–fly ash specimens. The paper discusses the geotechnical laboratory tests carried out with varying polypropylene fibre content.

Materials

The soil samples used in the present experimental tests were obtained from Suşehri–Koyulhisar, northeast of Sivas, where there is a high risk of landslides (Fig. 1). The soil was air dried and broken into pieces in the laboratory.

A characteristic X-ray diffraction plot of the soil shown in Fig. 2 indicates that the soil was predominantly illite (with swelling potential) with lesser amounts of kaolin, quartz and feldspar. The physical properties of the soil used in the investigation are summarized in Table 1. The soils were classified as belonging to the high plasticity CH group (USCS classification). The grain size distribution of the fly ashes and soil samples is given in Fig. 3.

Fly ash is defined as the mineral matter extracted from the flue gases of a furnace fired with coal. Fly ash consists of often hollow spheres of silicon, aluminum and iron oxides, and unoxidized carbon. It can be regarded as non-plastic fine silt according to the unified soil classification system. The composition of fly ash varies considerably depending on the nature of the coal burned and the characteristics of the power plant (Cabrera and Woolley 1994). As fly ash is a pozzolanic material (siliceous or siliceous and aluminous) its engineering behavior can be improved by the addition of cement or lime.

In the study, the fly ash was obtained from the industrial waste from the Kangal thermal power station in Turkey

Fig. 1 Location map of the calyey soils used

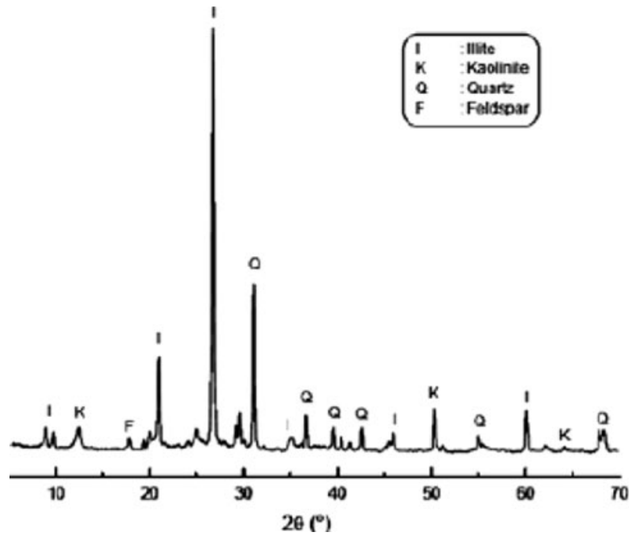

Fig. 2 Characteristic XRD graph of clayey soil used

Table 1 Engineering properties of clayey soil used in the study

Property	Clayey soil
Gravity	2.81
MDUW	1,320 kg/m^3
OWC	35.80%
USCS	CH
AASHTO	A-7-6
Gravel	2%
Sand	8%
Silt	11%
Clay	79%
Liquid limit	81.95%
Plastic limit	26.55%
Plasticity index	55.40%
Specific surface area, A_c	0.71

which produces some four million tons of fly ash from lignite coal each year. The physical and chemical properties of the Kangal fly ash are given in Table 2. It is a high calcium fly ash with a lime content of 16% and is classified as class C according to ASTM C61. Its self cementing characteristics make it an inexpensive source of high quality soil stabilizing agent.

Polypropylene fibre is the most common synthetic material used to reinforce concrete and soil. The primary attraction is that of low cost (Miller and Rifai 2004) and ease of mixing with soil. In this study, two types of fibres including fibrillated polypropylene fibre (F19) and multi-filament fibre (MF19) were used to evaluate their potential to enhance the CBR characteristics of clayey soil. The fibres were supplied by the polypropylene fibre industry in Istanbul, Northwest Turkey. Photographs are presented in

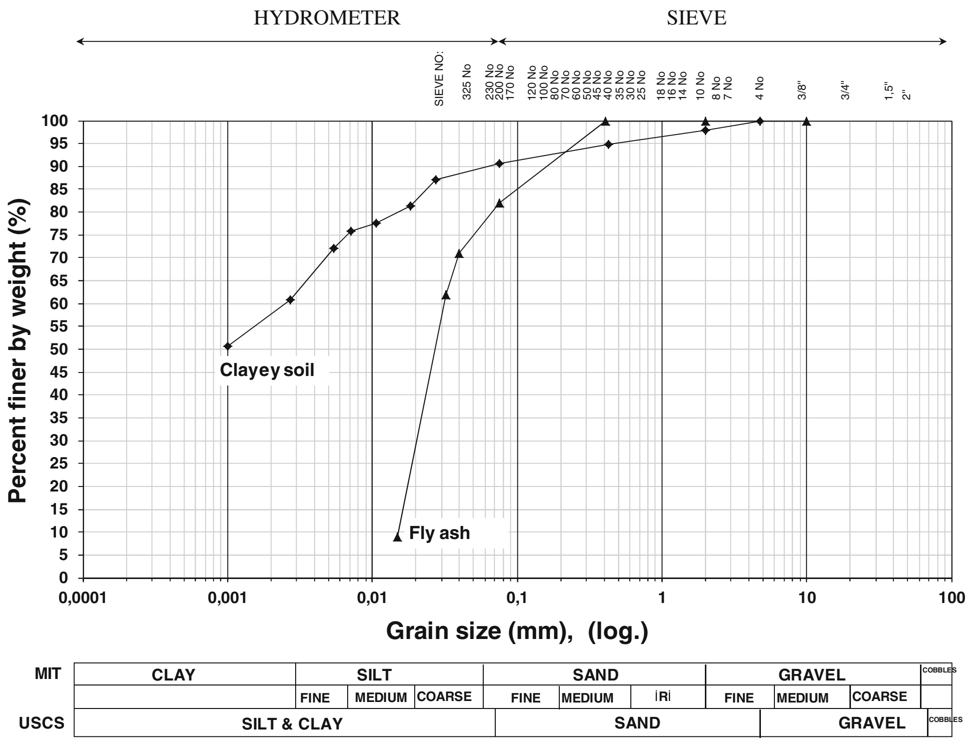

Fig. 3 Grain size distribution curves of fly ash, clay on the base of sieve and hydrometer analysis

Table 2 The physical and chemical properties of fly ash

Composition	Kangal fly ash	Composition	Kangal fly ash
Type	Class C or high lime fly ash	Loss of ignition	2.15
SiO_2 (S)	33.14	Free CaO	6.35
Al_2O_3 (A)	14.70	Reactive siliceous	28.85
Fe_2O_3 (F)	4.32	Reactive CaO	25.60
S + A + F	52.16	Density (g/cm^3)	2.24
CaO	35.18	Dry loose unit weight (g/cm^3)	0.81
MgO	1.18	Amount retained on 90 μm sieve (%)	28
SO_3	7.85	Amount retained on 45 μm sieve (%)	52
		Pozzolanic activity (TS EN 450 1998)	
K_2O	0.92	(%) 7D	72
Na_2O	0.58	(%) 28D	78
Na_2O equiv.	1.19		

Fig. 4 and their properties in Table 3. The fibre content used was 0.5, 1 and 1.5%, by dry weight of soil.

Investigation

The geotechnical characteristics of fly ash–soil specimens mixed with 0.5, 1 and 1.5%, by dry weight of soil oriented fibres were investigated. The mix proportions can be determined from the following equations:

$$\rho_u = \frac{w_{fly\,ash}}{w_{mix.}}, \quad \rho_f = \frac{w_{fibrilated\,fiber}}{w_{mix.}}, \quad \rho_{mf} = \frac{w_{multiflament\,fiber}}{w_{mix}} \tag{1}$$

where ρ_u, ρ_f, ρ_{mf} are proportions of fly ash and polypropylene fibre by dry weight of soil (respectively, M19 and F19) $w_{fly\ ash}$, $w_{fibrilated\ fibre}$, $w_{multiflament\ fibre}$; dry weight, w_{mix}; total weight.

The combination of fibre and fly ash in the clayey soil was as follows;

(a) Fly ash is added to the clayey soil in the proportion 0, 10 and 15% by dry weight of soil.
(b) Fibrillated fibre is added to the soil–fly ash mix in the proportions 0.5, 1.0 and 1.5% by dry weight.
(c) Multifilament fibre is added to the soil–fly ash mix in the proportions 0.5, 1.0 and 1.5% by dry weight.

More detail can be seen in the Table 4.

Compaction tests

The soils were compacted using the standard 2.5 kg proctor and the 4.5 kg heavy rammer (ASTM D698). The optimum moisture content (OMC) and maximum dry density (MDD) of the clayey soils are shown in Table 4. Figures 5 and 6 show the variation in MDD and OMC for the different proportions of fly ash–soil–fibre mixtures.

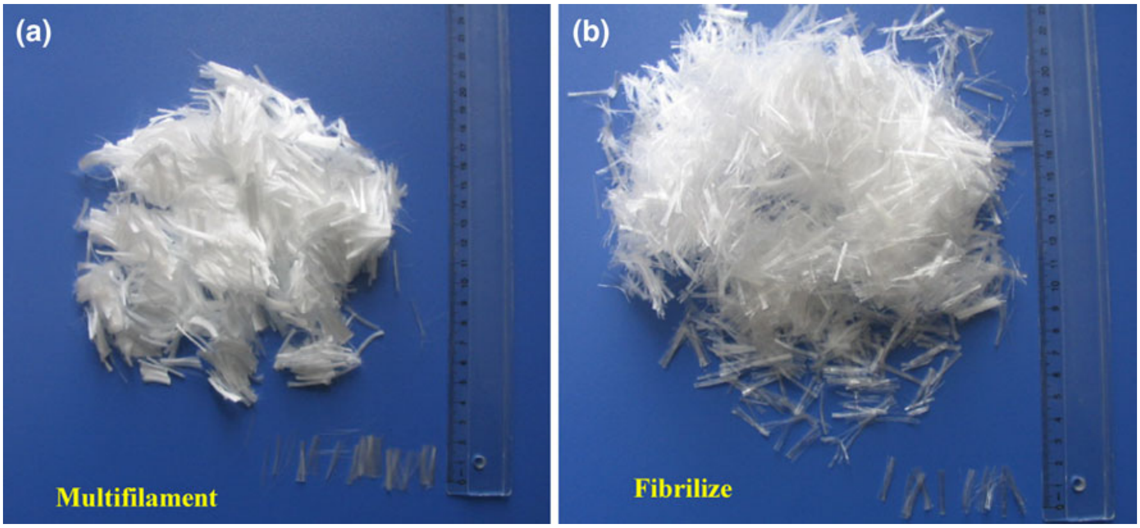

Fig. 4 Multifilament fiber (MF19) and fibrillated polypropylene (F19) used in this study (as supplied by the manufacturer)

Table 3 Properties of polypropylene fibers used (as supplied by the manufacturer)

Type and composition	Polypropylene fiber	
Fiber type	Multifilament (MF)	Fibrile (F)
Standard	ASTM C-1116-1997 type III	ASTM C-1116-1997 type III
Length	19 mm	19 mm
Tenacity	7.0 g/denier	6.0 g/denier
Tensile strength	700 N/mm^2	400 N/mm^2
Young's (elasticity) modulus	3.500 N/mm^2	2.600 N/mm^2
Breaking elongation	20%	15%
Density	0.91 g/cm^3	0.91 g/cm^3
Color	Transparent	Transparent
Softening point	150°C	150°C
Melting point	160°C	160°C
Acid resistance	Stable	Stable
Alcali resistant	Stable	Stable
Ultraviolet resistance	Optional	Optional

The results indicate that with an increase in fly ash, the MDD of the mixes decreases and the OMC increases. With the addition of fly ash, there is further decrease in MDD and increase in OMC. The presence of fly ash having a relatively low specific gravity may be the cause of this reduced dry density. The increase in OMC can be attributed to the increasing amount of fines which require more water content because of their larger surface area.

The results of compaction tests showed that fibres had a lowering effect on the MDD and OMC of fly ash–soil–fibre mixtures. This is somewhat different from the trend observed by Setty and Rao (1987) who reported that both MDD and OMC increase with increase in fibre content in silty sand mixed with polypropylene fibres. Some fibres, especially polypropylene, which absorb water and hence tend to increase the OMC have been used in the present study.

Unconfined compression tests

As discussed above, a minimum of three specimens were prepared for each combination of variables and tested at a deformation rate of 0.264 mm/min. Figure 7 shows typical stress–strain curves for the fly ash–soil–fibre specimens. The fibre with fly ash inclusions had a significant effect on the stress–strain behavior. The fly ash specimens attained a distinct axial failure stress at an axial strain of about 1.5–2.5% following which they collapsed; but, the fibre-reinforced specimens exhibited a highly ductile behavior. The specimens mixed with 19 mm fibres attained a peak axial stress at a relatively higher axial strain than the fly ash specimens and then they continued to deform under declining axial stress. Thus, inclusion of the fibres seems to have an important influence on the behavior of the specimens. The unconfined compressive strength (UCS) was taken as the peak stress or the axial stress corresponding to 15% axial strain if no peak stress was discernible.

California bearing ratio tests

California bearing ratio (CBR) tests were conducted using a cylindrical mould on specimens compacted in three layers at maximum dry unit weight and the OMC determined by conducting standard Proctor tests. The tests were conducted following AASHTO T193. According to AASHTO T193-63 and ASTM D1883-73, the soaking

Table 4 Detail of fly ash–soil–fiber mixtures for tests conducted

Combination		Soil (%)	Fly ash (%)	Fiber (%)	MDD (kg/m^3)	OMC (%)	$CBR_{average}$	$CBR_{rate\ of\ increase}$
SOIL	SOIL	100	0	0	1,320.00	35.80	0.47	1.00
SOFA10	SOIL + FLY ASH 10%	90	10	0	1,281.35	38.63	6.16	13.11
SOFA15	SOIL + FLY ASH 15%	85	15	0	1,238.05	40.85	13.47	28.65
SOF0.5	SOIL + FLY ASH 0% + FB 0.5%	99.5	0	0.5	1,287.70	34.88	2.86	6.09
SOF1	SOIL + FLY ASH 0% + FB 1%	99	0	1	1,288.10	35.30	2.81	5.98
SOF1.5	SOIL + FLY ASH 0% + FB 1.5%	98.5	0	1.5	1,265.97	34.45	2.41	5.12
SOMF0.5	SOIL + FLY ASH 0% + MF 0.5%	99.5	0	0.5	1,286.29	35.79	1.93	4.11
SOMF1	SOIL + FLY ASH 0% + MF 1%	99	0	1	1,292.50	36.31	2.01	4.28
SOMF1.5	SOIL + FLY ASH 0% + MF 1.5%	98.5	0	1.5	1,271.40	34.80	1.72	3.65
SOFA10F0.5	SOIL + FLY ASH 10% + FB 0.5%	89.5	10	0.5	1,283.14	37.91	19.39	41.25
SOFA10F1	SOIL + FLY ASH 10% + FB 1%	89	10	1	1,268.81	38.09	15.72	33.45
SOFA10F1.5	SOIL + FLY ASH 10% + FB 1.5%	88.5	10	1.5	1,248.00	37.55	13.14	27.96
SOFA10MF0.5	SOIL + FLY ASH 10% + MF 0.5%	89.5	10	0.5	1,272.42	37.83	20.81	44.28
SOFA10MF1	SOIL + FLY ASH 10% + MF 1%	89	10	1	1,262.63	37.67	18.89	40.19
SOFA10MF1.5	SOIL + FLY ASH 10% + MF 1.5%	88.5	10	1.5	1,245.12	37.11	16.03	34.10
SOFA15F0.5	SOIL + FLY ASH 15% + FB 0.5%	84.5	15	0.5	1,251.40	39.24	25.49	54.23
SOFA15F1	SOIL + FLY ASH 15% + FB 1%	84	15	1	1,245.65	38.91	23.93	50.91
SOFA15F1.5	SOIL + FLY ASH 15% + FB 1.5%	83.5	15	1.5	1,243.29	37.62	24.04	51.15
SOFA15MF0.5	SOIL + FLY ASH 15% + MF 0.5%	84.5	15	0.5	1,256.05	39.21	26.07	55.46
SOFA15MF1	SOIL + FLY ASH 15% + MF 1%	84	15	1	1,248.15	39.36	24.29	51.68
SOFA15MF1.5	SOIL + FLY ASH 15% + MF 1.5%	83.5	15	1.5	1,229.47	38.67	20.29	43.18

$CBR_{rate\ of\ increase} = CBR_{average}/CBR_{unreinforced}$

FB fibrillated polypropylene fiber, *MF* multifilament polypropylene fiber

period for CBR samples for normal soil is 96 h or 4 days (Bowles 1978).

The CBR samples prepared with different proportions of fly ash and polypropylene fibres (0, 10 and 15% fly ash with 0.5, 1.0 and 1.5% of polypropylene fibres) to soil at its optimum water content were compacted and then soaked in water. The CBR values obtained are tabulated in Table 4. It appears that the addition of 0.5% multifilament fibres (MF) gives the maximum percentage increase in CBR value (ratio of obtained CBR value/highest CBR value) after curing for 96 days; see Fig. 8.

Test results and discussion

Compaction characteristics

The addition of fly ash to the soil caused a significant reduction in MDD and an increase in OMC. However, with the addition of fibre both the MDD and OMC decrease. In the other soil–fly ash mixture, MDD decreases with increase in the fibres. Typical values of MDD and OMC for the different soil–fly ash mixtures with various fibre content are presented in Figs. 5 and 6.

Unconfined compression test values

A minimum of three specimens were prepared for each combination of variables and tested according to ASTM D 2166. As seen in Fig. 7, fibre inclusion enhanced the peak stress of unstabilized soil, although the proportion was less significant. It can also be seen that fibre-reinforced unstabilized soil exhibits more ductile behavior and smaller loss of post-peak strength than unstabilized soil, with the reduction in the loss of post-peak stress being more pronounced for higher fibre content.

Figure 7 also shows that the initial stiffness of the soil appears not to be affected by the addition of fibre, although the effect on the stabilized soil specimens is clear. The peak stress increases dramatically with an increase in fly ash content, and the stabilized soil exhibits a marked stiffness and brittleness. Its failure strain is 0.5–0.75%, which is much smaller than that for the unstabilized soil and fibre-reinforced unstabilized soil. It is also of note that the inclusion of fibres with the stabilized soil reduces the brittleness of the response. The failure strain increased, ranging from 1.5 to 2%. The axial stress increases with increase in axial strain until the peak value is reached, followed by a sudden drop to zero in stabilized soil, but the

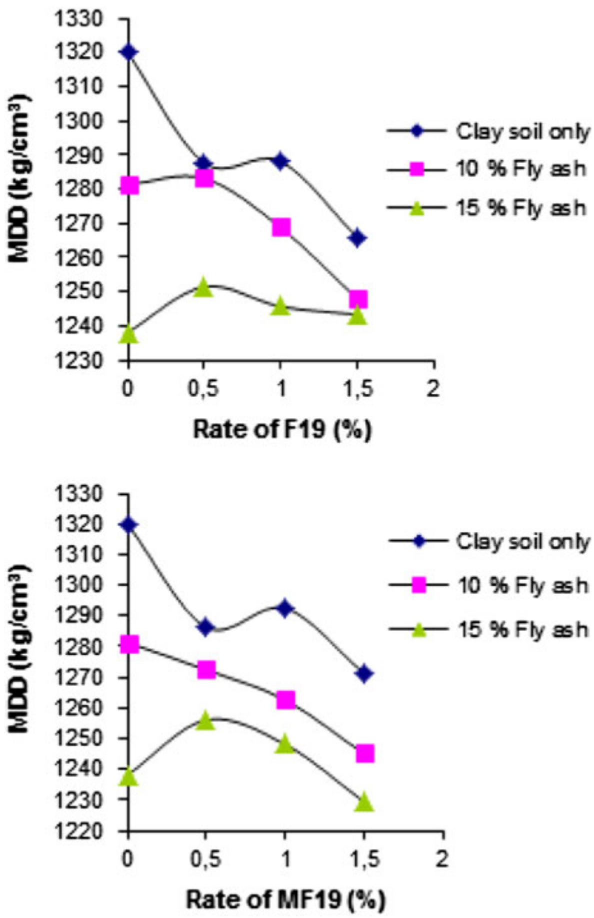

Fig. 5 The variation of maximum dry unit weight

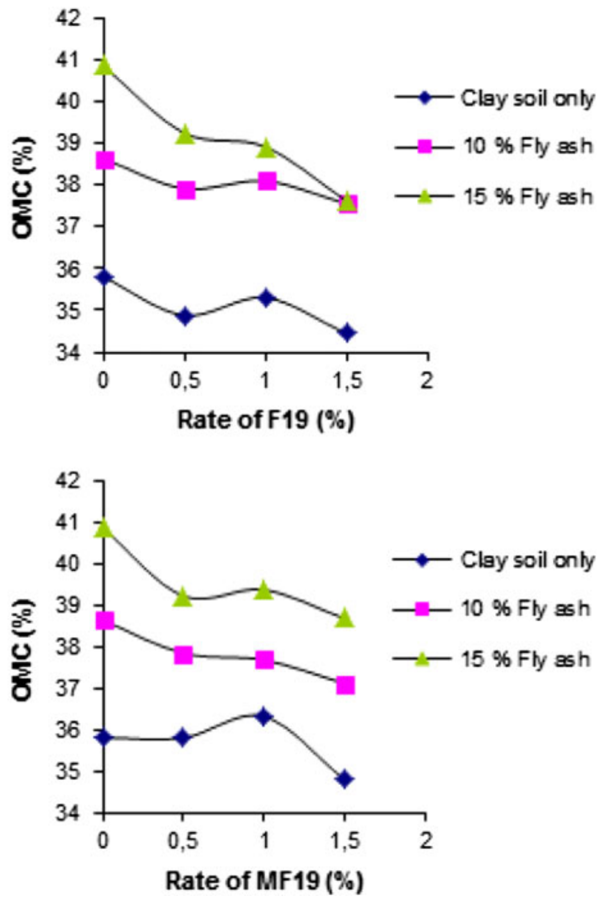

Fig. 6 The variation of optimum water content

reduction of post-peak stress is gradual when fibres are included. Furthermore, the residual strength of fly ash–fibre–soil specimens increases with increased fibre content. Undoubtedly, one of the main advantages of fibre-reinforcement when applied to soil is the improvement in material ductility.

California bearing ratio values

A minimum of three specimens were prepared for each combination of variables and tested according to AASHTO T193-63 and ASTM D1883-73. The results are shown in Table 4, which indicates.

(a) The addition of polypropylene fibres to the fly ash–soil mixtures resulted in a significant increase in the CBR values.

(b) The clayey soil samples stabilized with fly ash and polypropylene fibres show an increase in CBR values; for the soil +15% fly ash +0.5% MF this was by as much as 55% due to the fly ash acting as a binding agent.

(c) The maximum CBR value of the SOFA15MF1.5 sample was 26.07% while the minimum value of 1.72% was obtained for the SOFA10FB1 group.

(d) The CBR of the multifilament fibres (MF19) was a little higher than that for the polypropylene fibres (F19).

(e) All the results indicated that an increase in fly ash resulted in an increase in CBR values which was enhanced by the addition of polypropylene fibres.

Conclusions

An experimental program was undertaken to investigate the individual and combined effects of fibre inclusions and fly ash stabilization on the geotechnical characteristics of (1) unstabilized-unreinforced specimens; (2) fly ash-stabilized specimens; (3) fibre-reinforced specimens; and (4) fibre-reinforced fly ash-stabilized specimens. The main conclusions are follows.

1. Polypropylene fibres act a reinforcement to the soil and prevents the formation of cracks. With fly ash, it binds

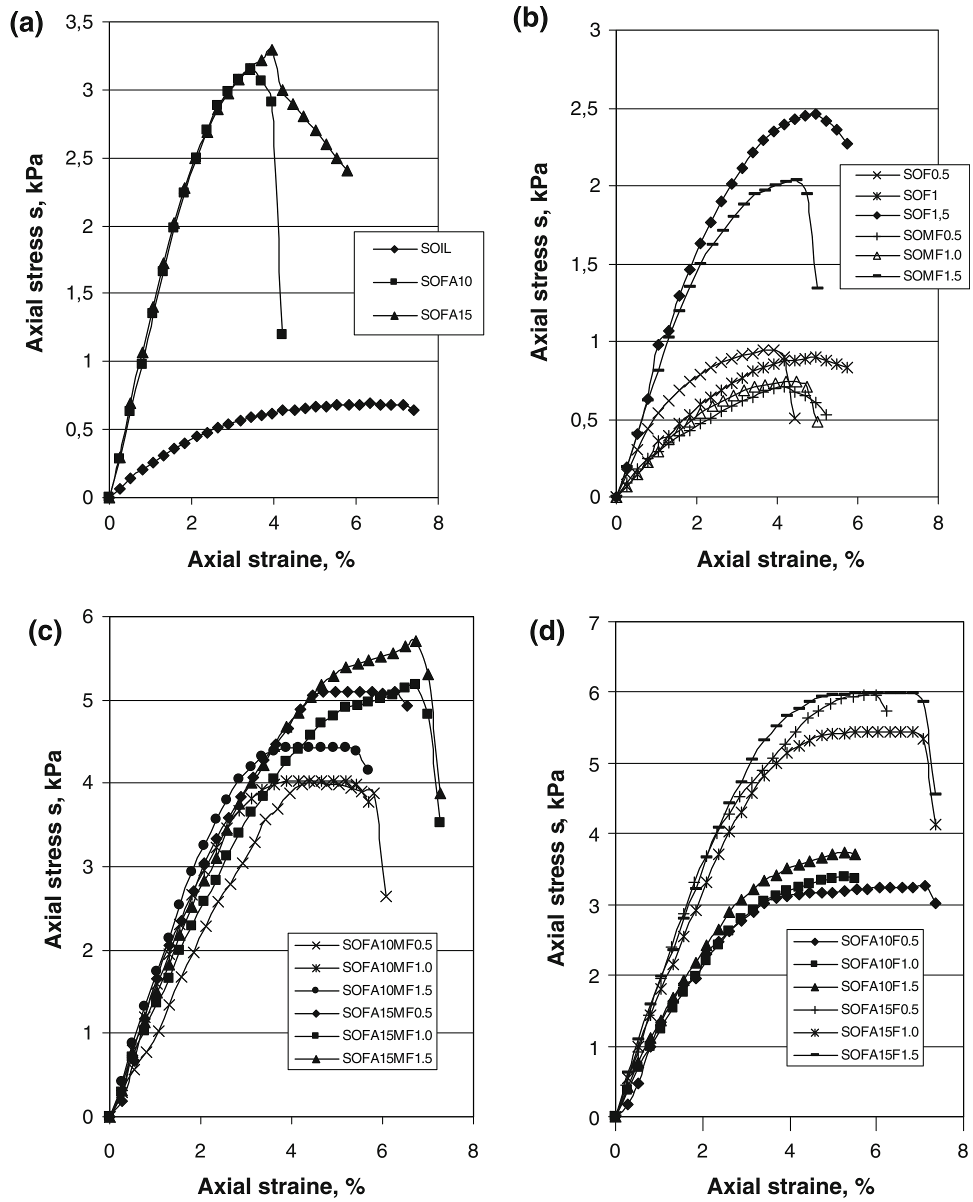

Fig. 7 Stress–strain curves: **a** stabilized soil with varying fly ash content; **b** fiber-reinforced unstabilized soil with varying fiber content; **c** fiber-reinforced stabilized soil with 10%, 15% fly ash and varying fibrillated fibers content; **d** fiber-reinforced stabilized soil with 10%, 15% fly ash and varying multifilament fibers content

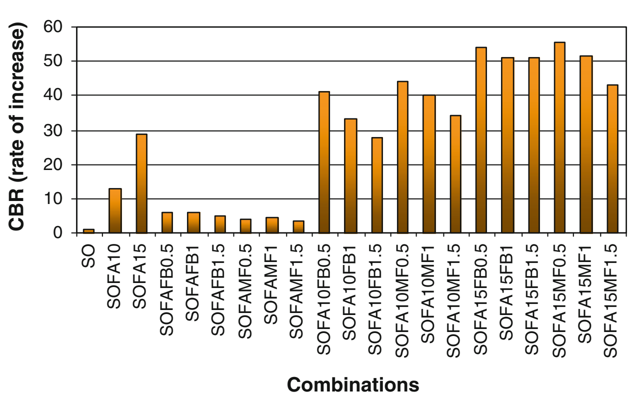

Fig. 8 Different fly ash, fibrillated polypropylene fibers (F19) and multifilament fibers (MF19) content increase in CBR values

the soil particles together, leading to an increase in CBR values of the stabilized soil.

2. The effect on the CBR of a clayey soil is greater for multifilament fibres (MF19) compared with fibrillated fibre (F19). The reason for this result might be the texture of fibrillated polypropylene fibre (F), which is harder and has only one part. In contrast; the softer textured multifilament fibre (MF19) spreads out when mixed with fly ash-soil mixtures, holding the particles together with a lower void ratio.
3. CBR decreased when doses >0.5% F19 and MF19 are used.
4. The inclusion of fibres results in the material having a ductile behaviour.

5. The inclusion of fibre reinforcement with unstabilized-unreinforced specimens and stabilized-reinforced specimens caused an increase in the CBR. Increasing fibre content may increase the peak axial stress and decrease the stiffness and the loss of post-peak strength, weakening the brittle behavior of fly ash stabilized–reinforced specimens. The increase in strength when both fibre and fly ash are included is significantly greater than when only one inclusion is made.
6. The ''bridge'' effect of the fibres can efficiently impede the further development of tension cracks and deformation of the soil.
7. With fibre-reinforced fly ash soil, the interactions which take place between the fibre surface and the stabilized/unstabilised soil have a significant effect on the mechanical behaviour, which depends on the binding material properties in the soil, normal stress around the fibre body, effective contact area and fibre surface roughness.

The study indicates that the combination of fibre and fly ash is an efficient method of ground improvement.

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