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TECHNICAL NOTE

On the Utilization of Fly Ash and Cement Mixtures as a Landfill Liner Material

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Abstract Cement was added to class F type of fly ash in the proportion of 0, 2, 5 and 10 % to study for its suitability as a landfill liner material. Mixtures were compacted to their optimum moisture content (OMC) and maximum dry density (MDD). The results from the consolidation tests showed a relatively lower value of compression index for all the mixtures indicating the settlement due to application of overburden pressure would be small. Hydraulic conductivity of the samples were found to be decreased with the increasing the load. However, none of the mixtures exhibited a hydraulic conductivity value less than 10^{-9} m/s, a limiting criterion set by various environmental agencies for the material to be used as a landfill liner. However, mixtures of 90 % fly ash + 10 % cement compacted at 5 % wet of OMC-MDD exhibited a hydraulic conductivity value less than 10^{-9} m/s. On drying, all the mixtures shrunk marginally. The unconsolidated undrained test results indicated that the shear strength parameters increase with increase in the cement content in the mixtures.

Keywords Landfill liner · Fly ash · Cement · Hydraulic conductivity · Shrinkage

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Introduction

The safe disposal of solid waste materials such as municipal, industrial and hazardous waste has been one of the major environmental problems in recent days. These waste materials are generally placed in a confinement termed as landfill. Landfills are usually provided with layers of nearly impermeable material, called as liner, to prevent contamination of the surrounding soil and underlying groundwater by the leachates generated from these wastes. Hydraulic conductivity is one of the most significant factors affecting the performance of a liner [1]. Due to desiccation, the liner material may shrink and crack resulting in an increase in the hydraulic conductivity of the liner. Similarly, the liner material should have adequate shear strength to prevent the material from failing due to the weight of the overburden waste.

Due to their cost effectiveness and large capacity of contaminant attenuation, compacted clay is widely used as a liner at the waste disposal site. In the absence of impermeable natural soils, mixtures of compacted expansive soil, such as bentonite, and a locally available soil, such as sand, is used as a landfill liner material. If suitable expansive soils are not available locally, the cost of the project can increase manifold as it has to be imported from elsewhere. In addition to this, sand has become an expensive construction material due to its limited availability. Therefore, it is of paramount importance to research new materials for landfill liner construction without compromising on the primary objective of efficient waste containment.

Fly ash is a waste by-product of coal-fired power generating stations which is readily available and need to be disposed of safely. The installed 88 thermal power plants in India had produced around 131.1 million tons of fly ash in the year 2010–2011 [2]. Similarly, the power plants in the US produce more than 70 million tons of fly ash annually [3]. Due to the large area of land required for its disposal, the disposal of fly ash is becoming expensive every year. One of the amicable solutions to this problem is the reuse of fly ash for some meaningful applications. The pozzolanic and self hardening properties of fly ash have naturally made it a very attractive material for use in a variety of construction applications such as fills, concrete, pavements, grouts etc. [4]. However, not all the fly ash, which are generally divided into two types namely class C and F [5], possess pozzolanic properties. The class C type of fly ash, which is produced from sub-bituminous coal sources, shows pozzolanic properties in the presence of water, whereas, class F type of fly ash, which is generally produced from bituminous coal, do not show any pozzolanic properties and require an addition of lime or cement to develop some pozzolanic behaviour [6].

Many studies have been carried out in the past to study the suitability of fly ash or mixture of fly ash with other materials for the use as a liner material at the waste disposal site. Results of a series of tests on compacted fly ash added with rubber and bentonite samples by Cokca and Yilmaz [7] showed that the hydraulic conductivity of the sample decreases with the increase in the bentonite content and decrease in the rubber content in the mixtures. The study by Palmer et al. [8] showed that a hydraulic conductivity value lower than 10^{-9} m/s can be achieved by compacting class F and C type of fly ashes mixed with a coarse aggregate (e.g., bottom ash) above OMC. Investigation by Shackelford and Glade [6] on the mixtures of fly ash-sand-bentonite showed the hydraulic conductivity of the mixture decreases by the increasing the bentonite content up to 18 % in the mixture. Vesperman et al. [9] investigated the hydraulic conductivity of fly ash and sand mixed in various proportions (0–90 %) and observed that the mixtures containing 40 and 100 % of fly ash and compacted at OMC with standard compactive effort possessed a hydraulic conductivity value less than 10^{-9} m/s. Prashanth et al. [10] evaluated the suitability of pozzolanic fly ash as a hydraulic barrier in landfills by studying its strength, volume change and hydraulic conductivity behaviour and concluded that fly ash mixed with lime fulfills the strength and hydraulic criteria required for a liner material. Murat and Yilmaz [11] studied the behaviour of fly ash and bentonite mixture and concluded that fly ash mixed with 20 % bentonite can be used as a liner and cover material at the waste disposal site. Yeheyis et al. [12] investigated the utilization of coal fly ash and fly ash-bentonite mixtures as a barrier material for mine waste containment and concluded that addition of 10 % bentonite reduces the hydraulic conductivity of the coal fly ash to less than 10^{-9} m/s and improves the chemical compatibility for mine waste containment. Sivapullaiah and Moghal [13] investigated the influence of gypsum on the fly ash and observed that with the addition of gypsum the hydraulic conductivity of the lime treated fly ash reduces.

From all these studies it can be concluded that fly ash has a high utility potential as a landfill liner material. However, most of these studies have been carried out with the class C type of fly ash which shows some pozzolanic behaviour. The pozzolanic behaviour of class F type of fly ash can be initiated by addition of cement and can be used as a liner material. However, not many studies have been carried out to find out the suitability of class F type of fly ash and cement mixtures as a landfill liner material. In order to qualify to be used as a liner material, the fly ash–cement mixtures should have a hydraulic conductivity value less than 10^{-9} m/s [14, 15] and volumetric shrinkage less than 4 % [16], the criteria given by various environmental agencies and researchers. Hence, the main purpose of this study was to carry out various tests to evaluate the suitability of various mixtures of fly ash and cement, mixed in different proportions, for the landfill liner application. In addition to the hydraulic conductivity and shrinkage behaviour, compressibility and shear strength parameters were also investigated in this study.

Materials and Methods

Fly ash used in this study was an industrial by-product obtained from the Farakka thermal power plant located in the West Bengal state of India. The ash was obtained from electrostatic precipitator (ESP). The SiO_2, Al_2O_3, Fe_2O_3, and CaO content of this fly ash were 47.5, 26.1, 8.4 and 0.9 %, respectively [17] and classified as class F type as per ASTM C 618 [18]. The particles size distribution curve of the fly ash showed that it was consisting of 25 % of sand and 75 % of silt fraction [17]. Since the fly ash was of class F type and could not initiate pozzolanic reaction as mentioned earlier, cement was added to the fly ash. Number 43 grade ordinary Portland cement (OPC) confirming IS: 8112-1989 [19], which is equivalent to Type I of ASTM C 150 [20], was used in this study. Compaction test was carried out for the fly ash and various fly ash–cement mixtures. Standard proctor compaction test was carried out according to ASTM D 698 [21] to determine the compaction characteristics of the mixtures. The optimum moisture content (OMC) and maximum dry density (MDD) for all these mixtures were found out from Fig. 1 and summarized in Table 1.

Samples compacted at OMC-MDD were used for this study. Consolidation test was carried out as per as ASTM D 2435 [22] to assess the hydraulic conductivity and compressibility of the mixture. Samples were prepared to achieve the desired water content by adding water to the

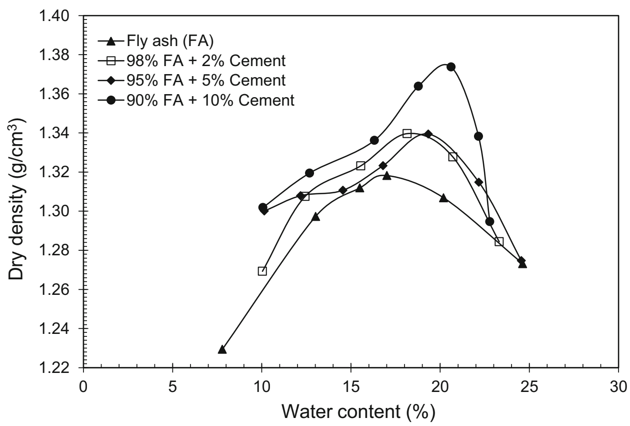

Fig. 1 Compaction curves for various fly ash–cement mixtures

Table 1 Compaction characteristics of fly ash and fly ash + cement mixtures

Sr. no.	Type of mixture	MDD (g/cm^3)	OMC (%)
1	100 % FA	1.319	17.1
2	98 % FA + 2 % C	1.339	18.2
3	95 % FA + 5 % C	1.339	19.3
4	90 % FA + 10 % C	1.377	20.4

mixtures and kept in a humidity controlled desiccator for 24 h in order to attain the moisture equilibrium. Then the mixtures were compacted in the consolidation ring of 60 mm diameter and 20 mm thickness to its MDD. All samples were initially loaded with a stress of 9.8 kPa and then increased gradually by an increment ratio of 1 (i.e. 9.8, 19.6 kPa etc.) to a maximum pressure of 784.5 kPa.

From the consolidation test result, a time-settlement curve was obtained at each pressure increment. The coefficient of consolidation (c_v) was obtained using Taylor's square root of time ($\sqrt{T}$) method.

The co-efficient of volume change (m_v) was calculated by the formula,

$$m_v = \frac{a_v}{1 + e_0}, \quad (1)$$

where e_0 is the initial void ratio and a_v is the coefficient of compressibility

$$\text{Coefficient of compressibility} = -\frac{\Delta e}{\Delta \sigma},$$

where Δe is the change in void ratio and $\Delta\sigma$ is the change in pressure.

The hydraulic conductivity (k) was calculated using the Eq. (2) for various pressure increments using the c_v and m_v as,

$$k = c_v m_v \gamma_w, \quad (2)$$

where γ_w is the unit weight of the water.

The volumetric shrinkage test was carried out on the specimen of 25 mm diameter and 125 mm height using standard mould confirming to IS 12979 [23]. The change in the diameter and length of the specimen was measured after drying it in oven for 24 h. The volumetric shrinkage of the mixtures was calculated using the Eq. (3),

$$\text{Volumetric shrinkage (VS), } (\%) = \left((1 - \frac{V_s}{V}) \times 100 \right), \quad (3)$$

where V is the initial volume of the sample and V_s is the oven dried volume of the sample.

Unconsolidated undrained (UU) test was performed on the specimens of 38 mm diameter and 76 mm height as per as ASTM D 2850 [24] using a strain rate of 1 %/min. Corrections to the cross sectional area was applied prior to calculating the compressive stress on the specimens. Each specimen was loaded until peak stress was obtained, or until an axial strain of approximately 25 % was obtained. Tests were carried out at three different confining pressures, namely 100, 200 and 400 kPa. Similar confining pressure range was also selected by Mitchell and Wong [25] to carry out triaxial tests on cemented tailing sands.

Results and Discussions

Compressibility of the Fly Ash–Cement Mixtures

Similar to the hydraulic conductivity, shrinkage, and shear strength, the compressibility of the mixtures was also taken into consideration in this study as a large amount of deformation of the liner can create cracks and increase its hydraulic conductivity. The compressibility characteristics of the mixtures were determined from the one dimensional consolidation tests. Figure 2 shows the relation between the void ratio and pressure for the four different mixtures compacted at OMC-MDD. The result shows that with an increase in the overburden pressure the void ratio of the mixtures decreases. The increase in the overburden pressure on the mixtures can be correlated to an increase in the pressure on the liner due to the increase in the overburden weight of the waste material. Plot shows that the decrease in the void ratio with increase in the pressure was marginal in the beginning and decreased significantly with a further increase in the pressure. Result shows that the mixture with higher fly ash content possessed a lower void ratio at any given overburden pressure. This can be attributed to the presence of the higher amount of fine particles in the fly ash. With the increase in the fine content in the mixtures the void ratio decreases. Result also shows that mixtures

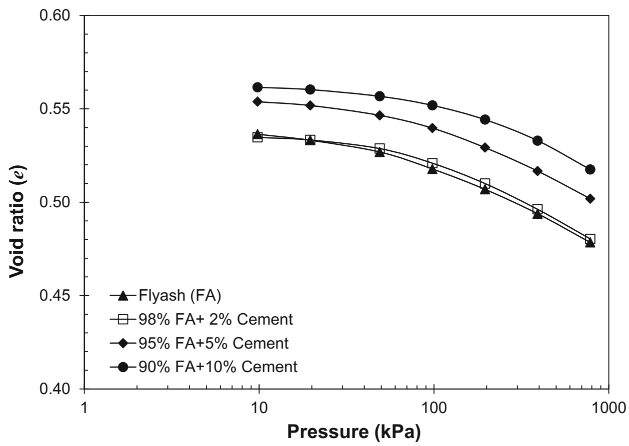

Fig. 2 Pressure-void ratio plot for various fly ash–cement mixtures compacted at OMC-MDD

Table 2 Consolidation characteristics of the mixtures compacted at OMC-MDD

Type of mixture	Compression index (C_c)	Range of co-efficient of consolidation (cm^2/year)
100 % FA	0.044	123.9–154.1
98 % FA + 2 % C	0.048	127.9–147.1
95 % FA + 5 % C	0.045	132.1–161.9
90 % FA + 10 % C	0.041	135.1–159.7

with a higher cement content compressed marginally in comparison to other samples.

Compression index (C_c) of the fly ash and fly ash–cement mixtures was determined from Fig. 2. Compression index is defined as the slope of linear portion of the normal consolidation curve and it indicates the compressibility of samples due to application of vertical load. The data in Table 2 shows that all the samples exhibited a lower value of compression index indicating the mixture would deform marginally due to the weight of the waste material. Similarly, data also showed that the compression index of the mixtures gets affected marginally due to addition of the cement in the mixture. However, all the four samples exhibited higher values of co-efficient of consolidation (c_v) indicating the mixture will get consolidated at a faster rate due to application of load [26].

Hydraulic Conductivity of the Fly Ash–Cement Mixtures

Hydraulic conductivity is one of the most important criteria for soil to be used as a liner material at the waste disposal site. Most of the regulatory authority in the world has recommended that the material to be used as a liner material must have a minimum value of hydraulic conductivity of 10^{-9} m/s [14, 15].

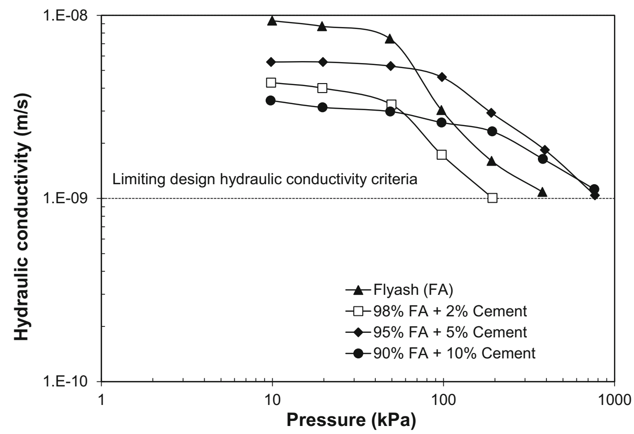

Fig. 3 Hydraulic conductivity-pressure plot for various fly ash–cement mixtures compacted at OMC-MDD

Figure 3 shows the hydraulic conductivity-pressure relationship for the mixtures compacted at OMC-MDD. The plot shows that the hydraulic conductivity of the mixture decreased with increase in pressure. As the weight of the overburden pressure increases, the mixture gets compressed and the void ratio decreases (Fig. 2). As the void ratio of the mixture decreases, the pore space available for the flow of water inside the sample decreases and the hydraulic conductivity decreases. For a pressure up to 98.1 kPa the effect of overburden pressure on hydraulic conductivity was marginal, however, with a further increase in the pressure the hydraulic conductivity decreased significantly. It can also be seen from the plot that irrespective of the type of mixture, almost identical value of hydraulic conductivity was exhibited by all the mixture at a pressure of 784.5 kPa.

The plot between the void ratio and hydraulic conductivity in Fig. 4 shows that the hydraulic conductivity value for the four different mixtures decreased with decrease in the void ratio. With the decrease in the void ratio the hydraulic conductivity decreased quite significantly at the beginning, however, a further decrease in the void ratio the hydraulic conductivity reduced marginally. A comparison among the four different mixtures shows that with the increase in the cement content the hydraulic conductivity decreases. In other words, at the same void ratio the mixture with higher cement content exhibits a lower value of hydraulic conductivity. When the cement content in the mixture increases and as it comes in contact with the water, it holds the fly ash particles on its surface and gets solidified and in turn blocks the flow path thereby reducing the hydraulic conductivity.

The plot shows that none of the mixture satisfies the hydraulic conductivity criteria required for a landfill liner (i.e. $k \leq 10^{-9}$ m/s). All the mixtures exhibited hydraulic

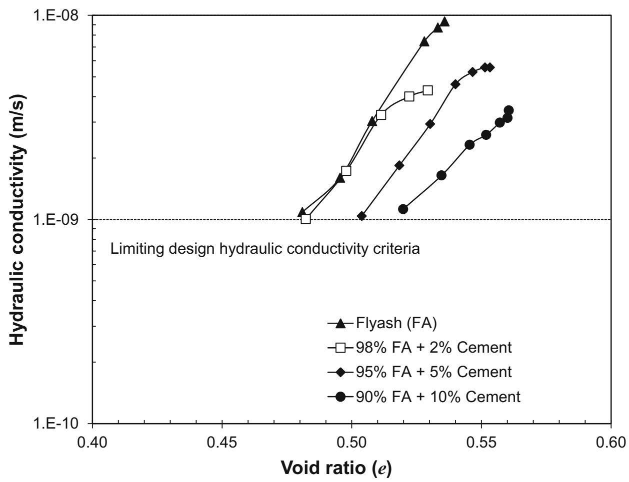

Fig. 4 Hydraulic conductivity-void ratio plot for various fly ash–cement mixtures compacted at OMC-MDD

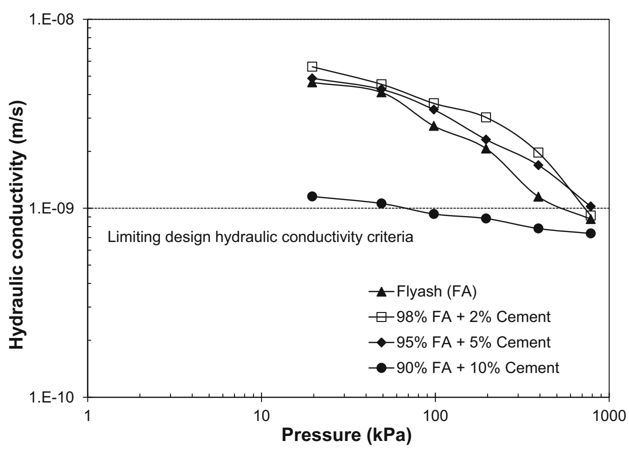

Fig. 5 Hydraulic conductivity-pressure plot for various fly ash–cement mixtures compacted at 5 % wet of OMC-MDD

conductivity in the range of 9.2 × 10^{-9} m/s to 1.2 × 10^{-9} m/s. However, all the mixtures fulfill the hydraulic criteria required for the subsoil material (i.e. $k \leq 10^{-7}$ m/s) for a landfill liner [27].

Since samples compacted on the wet side of OMC-MDD possess a lower value of hydraulic conductivity than the samples compacted at OMC-MDD [15], further tests were carried out on all the four mixtures compacted at 5 % wet of OMC-MDD to check whether the mixtures compacted at wet side of OMC-MDD fulfills the hydraulic criteria for landfill liner or not. To reduce the risk of the desiccation potential [15], a limiting value of 5 % on the wet side of the OMC was chosen for further study. The plots in Figs. 5 and 6 show that when compacted on the 5 % wet of OMC-MDD the hydraulic conductivity of all the mixtures decreases. When the mixtures compacted at higher water content, the hydration reaction increases and cement holds the fly ash particles more strongly and

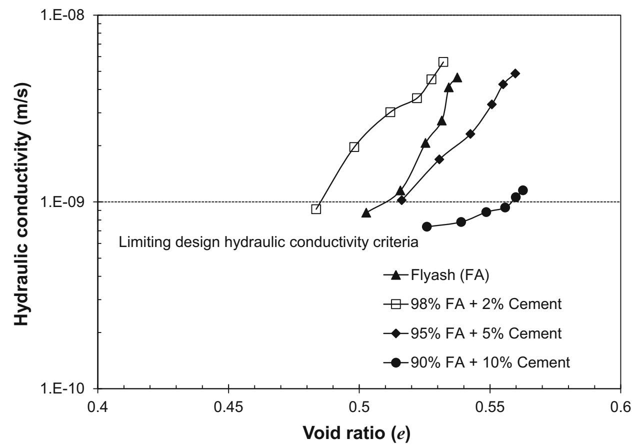

Fig. 6 Hydraulic conductivity-void ratio plot for various fly ash–cement mixtures compacted at 5 % wet of OMC-MDD

reduces hydraulic conductivity. The plots show that the mixture of 90 % fly ash + 10 % cement exhibited hydraulic conductivity value less than 10^{-9} m/s at a minimum overburden pressure of 49 kPa and fulfills the hydraulic conductivity criteria required for a landfill liner. Whereas, an overburden pressure of 600–700 kPa was required for the other mixtures to exhibit a hydraulic conductivity value less than 10^{-9} m/s.

Volumetric Shrinkage of the Fly Ash–Cement Mixtures

Similar to hydraulic conductivity, shrinkage is also another important criterion, which a material must fulfill in-order to be used as a liner material. Evaporation causes the shrinkage of the liner material and as the material shrinks, it forms cracks on the liner and increases the hydraulic conductivity. Kleppe and Olson [16] had concluded from a series of the experiments that a soil can be used as a liner material as long as its volumetric shrinkage is less than 4 %.

Volumetric shrinkage for all the four type of fly ash–cement mixtures compacted at OMC-MDD was determined after drying inside oven at 105 °C for 24 h. The data in Table 3 shows the volumetric shrinkage of all the mixtures were less than the limiting value of 4 %, which

Table 3 Volumetric shrinkage of the mixtures compacted at OMC-MDD

Sr. no.	Type of mixture	Volumetric shrinkage (%)
1	100 % FA	2.81
2	98 % FA + 2 % C	2.48
3	95 % FA + 5 % C	1.84
4	90 % FA + 10 % C	1.52

indicates that the mixtures will be stable from cracking due to reduction in the water content and prevent any potential increase the hydraulic conductivity of liner. Fine particle size and non-swelling nature of fly ash and cement can be attributed to the lower volumetric shrinkage of the mixtures.

Shear Stress–Strain Behaviour of the Fly Ash–Cement Mixtures

Unconsolidated undrained (UU) test was carried out on the mixtures compacted at OMC-MDD and cured for 24 h. The stress–strain curves obtained from the triaxial compression tests are shown in Figs. 7, 8, and 9 for the four mixtures with a confining pressure (σ_3) of 100 kPa, 200 kPa and 400 kPa, respectively. The effect of cement content on the stress–strain behavior of the various

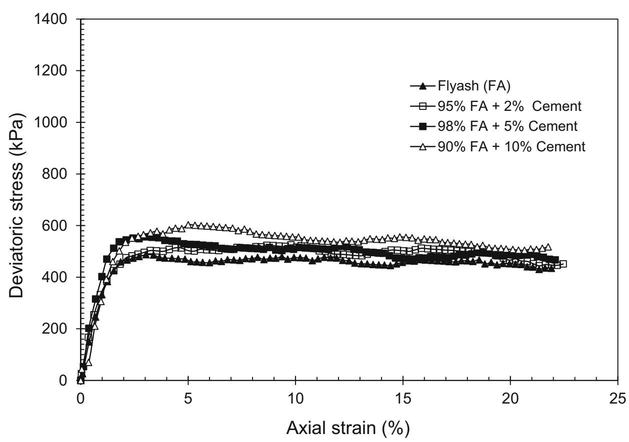

Fig. 7 Stress–strain plot for various fly ash–cement mixtures at a confining pressure of 100 kPa

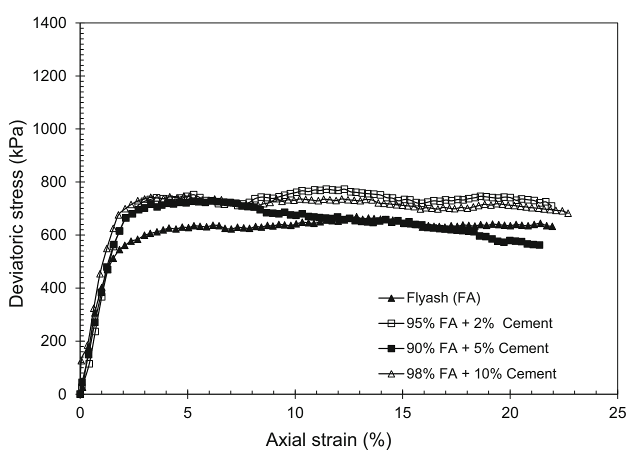

Fig. 8 Stress–strain plot for various fly ash–cement mixtures at a confining pressure of 200 kPa

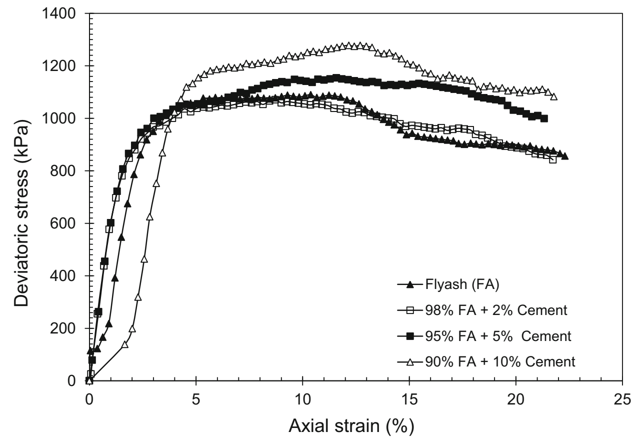

Fig. 9 Stress–strain plot for various fly ash–cement mixtures at a confining pressure of 400 kPa

mixtures is shown in Figs. 7, 8, and 9. The plot showed that due an increase in the strain up to 3–5 % the stress increased. The stress almost remained constant with a further increase in strain up to 20 % and decreased afterwards. The result shows that with increase in the cement content in the mixture, the peak deviatoric stress increases. The increase in the peak deviatoric stress was quite significant for the fly ash + 10 % cement mixtures. Result shows that the effect of confining pressure was more prominent for mixtures with less cement content. The data in Table 4 also shows that the cohesion (c) and angle of friction (ϕ) of the mixtures increased with an increase in the cement content. With increase in the cement content the cementatious bond between the particles increases which leads to a higher value of deviatoric stress, cohesion and internal friction.

Conclusions

Tests were carried out to study the suitability of mixtures of class F type of fly ash and cement as landfill liner material. The hydraulic conductivity of all the mixtures compacted at OMC-MDD was found to be higher than the limiting value of 10^{-9} m/s. Therefore, fly ash added with cement up to 10 % and compacted at OMC-MDD is not found suitable for the use as a landfill liner material; instead, they can be used as a subsoil material at the waste disposal site. However, when compacted on the 5 % wet of OMC-MDD the hydraulic conductivity of 90 % fly ash + 10 % cement mixture was found to be lower than 10^{-9} m/s and satisfied the hydraulic conductivity criteria for a landfill liner material. The volumetric shrinkage for all the samples was found to be lower than the limiting value of 4 %. This study concluded that, 90 % fly ash + 10 % cement mixture compacted at 5 % wet of OMC-MDD can be used as a landfill liner material. However, further test in regard to

Table 4 Peak deviatoric stress and shear strength parameters of the mixtures compacted at OMC-MDD

Type of mixture	Peak deviatoric stress (kPa)			c (kPa)	ϕ (°)
	$\sigma_3 = 100$ kPa	$\sigma_3 = 200$ kPa	$\sigma_3 = 400$ kPa		
100 % FA	472	622	1051	78.2	27.6
98 % FA + 2 % C	496	711	1088	88.0	28.1
95 % FA + 5 % C	551	716	1149	95.4	30.1
90 % FA + 10 % C	578	742	1278	115.8	32.7

σ_3 confining pressure, c total cohesion, ϕ total angle of internal friction

leachability characteristics of the fly ash is recommended before being used as a landfill liner material.

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