Geotechnical Behaviour of Fly Ash-Bentonite Mixture as a Liner Material

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Abstract. The landfill liners are used to barrier the flow of leachate and hence prevent the migration of contaminants. Clay liners are increasingly used due to their low permeability and high attenuative capacity. The shrinkage of these liners during unsaturated state may cause cracking, and that lead to the leakage of leachate. Hence, it is needed to develop an alternative material having low shrinkage potential and low permeability. Treated fly ash is a good alternative and can be used as landfill liners. Fly ash is a by-product generated due to coal combustion and contains silt-sized hollow spherical particles. In the current study, an attempt has been made to reduce the permeability of fly ash by addition of Bentonite and evaluate the suitability of this mixture as a liner material. Different percentages of Bentonite (0, 2, 4, 6, 8, 10 and 12%) were mixed in the fly ash, and the geotechnical properties of this mixture were examined through various experiments such as liquid limit, unconfined compression and consolidation tests. The results of liquid limit tests indicated that water holding capacity of fly ash is increasing with the increase in Bentonite content. The unconfined compressive strength and stiffness of the specimens were observed to be increased with the addition of Bentonite till 8%, after that it started reducing. Swell pressure and permeability of these mixtures were determined through consolidation tests along with compressibility characteristics. Permeability was observed to reduce below $1*10^{-9}$ m/s with the increase in Bentonite content in the fly ash indicating its suitability as a liner material.

Keywords: Landfill liner; Fly ash; Bentonite; Permeability; Shear strength

1 Introduction

The landfill liners are used to prevent the migration and leakage of leachate. They act as barrier and reduces the ground water pollution through ingress of leachate. Mitigation of pollutant migration, low shrinkage and swelling, sufficient shear strength and resistance to erosion are the main requirements of any liner system (Brandl, 1992). Natural materials such as compacted clay, compacted shale, soil sealant and Bitumen materials are used as a liner material. Geomembranes are also used recently in a conjunction with natural materials in a liner system due to its less thickness and extremely low permeability. Out of above all mentioned materials, compacted clay liners (CCL) containing Bentonite are widely used due to their low permeability, higher cost effectiveness, higher resistance to damage and puncture, and higher sorption capacity. However, during unsaturated state, Bentonite shrinks excessively and cracks are developed within soil mass, which increases the risk of leakage of leachate. Hence, it is required to develop an alternative material that has low shrinkage potential and low permeability. Bentonite mixed fly ash can be a good alternative material. Fly ash is a waste product of coal combustion generated from thermal power plant. The effective utilization and storage of fly ash itself is an issue. Both the above problem can be solved, if treated fly ash will be used as a liner material. Few previous researchers suggested to use fly ash in the construction of geotechnical and geoenvironmental applications (Edil et al. 1987; Sharma 1996; Cokca 1997). Edil et al. (1992) examined the feasibility of fly ash-sand mixture as a liner material and found permeability values of mixture less than 10^{-9} m/s. Prashanth et al. (2001) performed experiments on three different types of raw fly ash to access their suitability as a hydraulic barrier. They concluded that the pozzolanic fly ash developed low permeability with time and can be used as a hydraulic barrier. Cokca (2001) and Phani Kumar & Sharma (2004) investigated the effect of fly ash content on the basic geotechnical behaviour of expansive soil. They reported that the swelling pressure decreased and hydraulic conductivity increased with increase in fly ash content. Pal and Ghosh (2012) performed falling head permeability tests on nine different fly ash with varying content of Bentonite. They found reduction in permeability with decrease in degree of saturation and also proposed to use Bentonite mixed fly ash as a liner material. Ravi Shankar and Niranjan (2015) investigated the effect of compaction conditions on hydraulic and compressibility properties of fly ash-Bentonite mixture. They found reduced hydraulic conductivity with decrease in compaction water content.

Very limited research has been done to investigate the applicability of fly ash in the construction of landfill as a liner material. Hence, the aim of the current study is to find the suitability of fly ash-Bentonite mixture as an alternative material to conventional Bentonite. Different percentages of Bentonite (0, 2, 4, 6, 8, 10 and 12%) were added in the fly ash and a series of experiments such as liquid limit tests, unconfined compression tests, and consolidation tests were performed on these mixtures. The optimum Bentonite content was evaluated based on the permeability, swell pressure and shear strength characteristics.

2 Material Properties

Fly ash used in the current research was obtained from Gandhinagar thermal power plant (Gujarat, India). Fly ash contains 80% silt-sized particles and 20% sand-sized particles having very low specific gravity (G_s) of 2.11. The other important geotechnical properties such as compaction parameters and Atterberg limits are presented in Table 1. Commercially available Bentonite was used in the present study as an admixture and obtained from Pinal corporation Ahmedabad (Gujarat, India). Bentonite is a high plasticity clay contains large amount of Montmorillonite mineral. The specific gravity of Bentonite was obtained to be 2.78 with all the particles had dimension less than 2 µm. The differential free swell index (DFSI) of Bentonite was obtained as 662%, and classified as highly expansive soil according to IS: 2911 Part III-1980. The Atterberg limits of Bentonite is listed in Table 1. The scanning electron microscope (SEM) image of Gandhinagar fly ash and Bentonite is shown in Fig. 1a and 1b, respectively. Fly ash particles are spherical in shape whereas, the Bentonite had layered structure of montmorillonite mineral, which contained sheets of silica tetrahedral and alumina octahedral.

Table 1. Geotechnical Properties of fly ash and Bentonite

Soil	**Fly ash**	**Bentonite**
Sand	20%	0%
Silt	80%	0%
Clay	0%	100%
Specific Gravity, G_s	2.11	2.78
Liquid Limit, w_L	50%	609%
Shrinkage Limit, w_S	-	6%
Plasticity Index, I_p	Non-Plastic	558%
Maximum Dry Density	1.21 g/cc	-
Optimum Moisture Content	29%	-
DFSI	-	662%

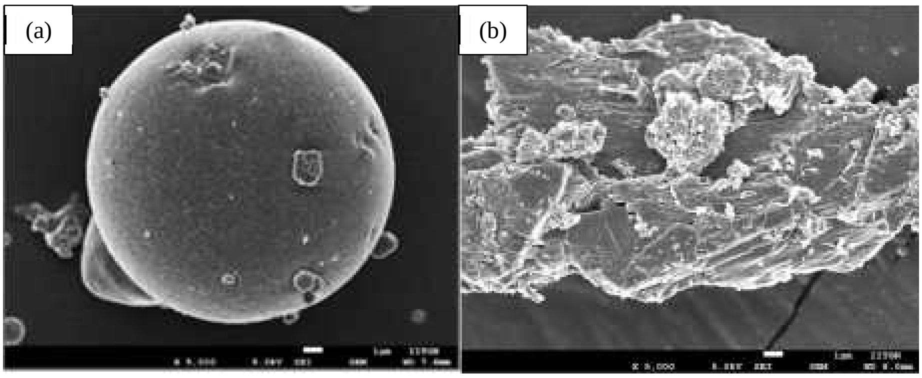

Fig. 1. Scanning electron microscope (SEM) image of (a) fly ash (Gupta and Sachan, 2017) (b) Bentonite

3 Specimen Preparation and Experimental Program

Bentonite was mixed in the fly ash in a proportion of 0, 2, 4, 6, 8, 10 and 12% by weight to investigate the effect of Bentonite content on geotechnical properties of fly ash. A small percentage of bentonite was selected, such that the adverse effect of excessive shrinkage and swelling do not overcome the benefits of its usage. The experimental program includes a series of liquid limit tests, unconfined compression (UC) tests and consolidation tests on all the specimens of raw fly ash and Bentonite mixed fly ash. The oven-dried fly ash was mixed with specified percentage of oven-dried Bentonite by weight to prepare the B-0 to B-12 specimens. The specimen name indicates the percentage of Bentonite added. For example, B-12 indicates the 12% Bentonite mixed fly ash specimen. The liquid limit tests was conducted using cone penetrometer method as per IS: 2720 (Part 5)-1985. All the specimens for UC test and consolidation test were prepared by moist tamping method at MDD (1.21 g/cc) and OMC (29%) of raw fly ash. The comparable compaction state was considered while preparing the specimens. The specimens of size 50 mm diameter and 100 mm height were prepared in four equal layers in three piece metal mould for UC tests. The experiments were performed according to IS: 2720 (Part 10)-1991 at a constant shearing strain rate of 1.25 %/min. Three specimens of each Bentonite content were tested to ensure repeatability of the results. The consolidation test was performed on the specimens of 20 mm height and 60 mm diameter prepared in three equal layers within the consolidation ring itself. The initial swelling of the specimens was allowed under the seating load of 5 kPa till the increase in the specimen height became constant. The specimen than loaded sequentially as 10, 20, 50, 100, 200, 400 and 800 kPa with an loading interval of 24 hours. The unloading was done in the same sequence till 50 kPa normal stress. The procedure was followed according to guidelines of IS: 2720 (Part 15)-1986. The swell pressure and permeability was also determined through the results of consolidation test.

4 Result and Discussion

4.1 Variation in Liquid Limit Characteristics

Figure 2 shows the variation of liquid limit with Bentonite content in fly ash. The liquid limit was found to increase from 50% to 74% with increase in Bentonite content from 0 to 12%. The reason could be due to high water retention capacity of Bentonite particles. Whenever, Bentonite particles comes in a contact with water, they formed diffused double-layer around them and that raised the their water holding capacity. Hence, addition of Bentonite in the fly ash, induced plasticity in the non-plastic fly ash particles. The values of liquid limit for B-0 to B-12 specimens are presented in Table 2.

4.2 Variation in Shear Strength Characteristics

Figure 3 shows the results of UC tests in terms of axial stress-axial strain curves of B-0 to B-12 specimens. It is observed that unconfined compressive strength (q_u) increases with increase in Bentonite content till 8%. After that, it reduced with further addition of Bentonite up to 12%. The UCS increased from 325 kPa to 550 kPa with addition of Bentonite till 8%. In terms of percentage increase, the 84% strength increased with ingress of Bentonite particles to fly ash. The initial stiffness of the specimens also improved till 8% Bentonite and then it reduced. The reason for that could be the pore filling phenomena, which happened with addition of very small sized Bentonite articles to larger fly ash particles. The small Bentonite particles can go inside the void spaces created by the spherical fly ash particles and that will stiffens the whole soil matrix (Fig. 4a). Which in turn enhances the strength and stiffness of mixture. After a particular percentage of Bentonite, with further addition can make the structure weakens as the Bentonite can now come in between the contact points of fly ash particles in addition to pore filling (Fig. 4b). This phenomena increased the lubrication between fly ash particles and resulted in low value of shear strength. All the specimens showed sudden failure after achieving peak axial stress. The failure strain (ε_f) for most of the specimens were obtained around 2% axial strain. The variation in cohesion (c_u) value with Bentonite content is shown in Fig. 5 and their values are presented in Table 2.

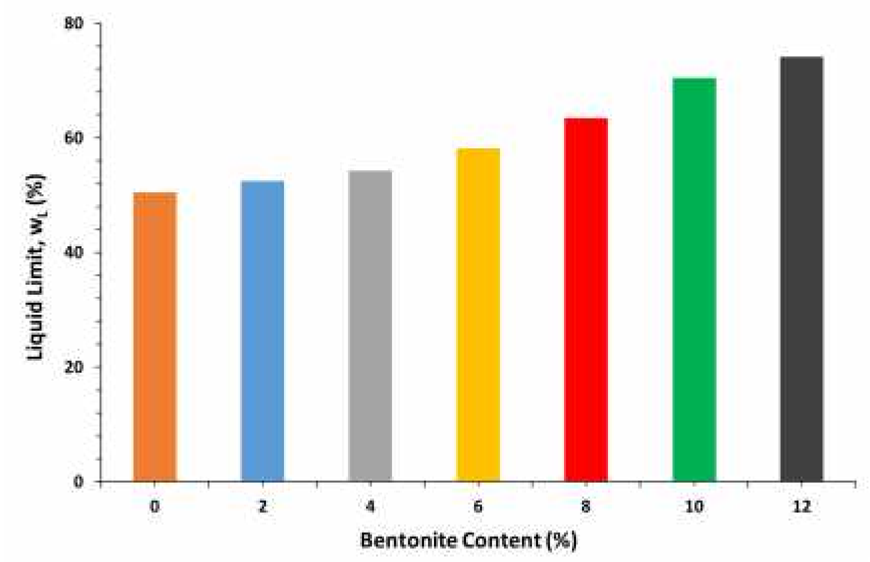

Fig. 2. Effect of Bentonite content on liquid limit of fly ash-Bentonite mixture

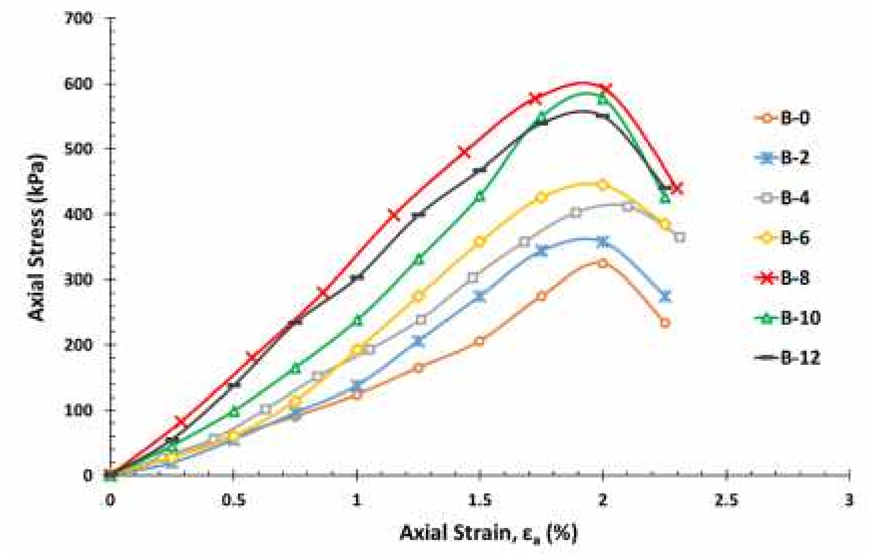

Fig. 3. Effect of Bentonite content on unconfined compressive strength (q_u) of fly ash-Bentonite mixture

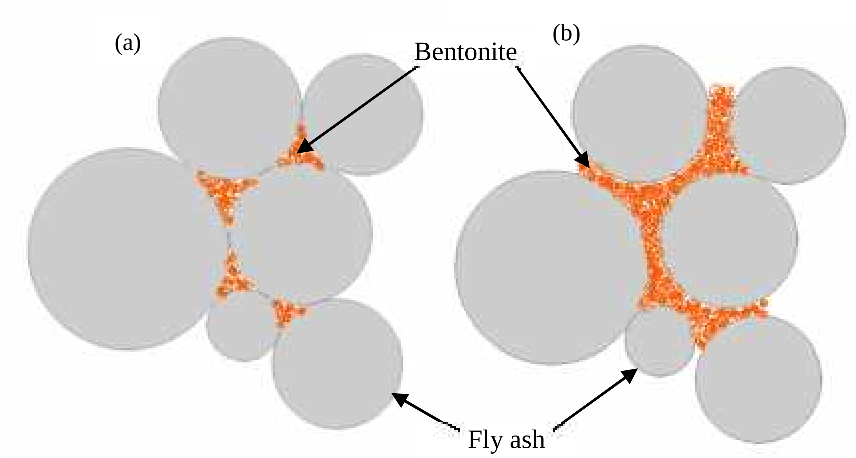

Fig. 4. Schematic diagram of possible mechanism: (a) Pore filling phenomena (Bentonite content-2% to 8%) (b) Lubrication phenomena (Bentonite content > 8%)

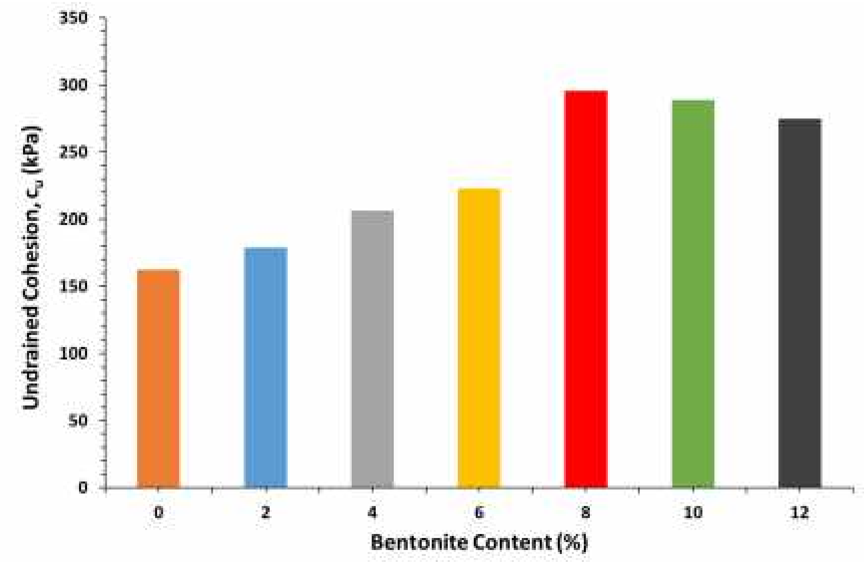

Fig. 5. Effect of Bentonite content on cohesion (c_u) of fly ash-Bentonite mixture

Table 2. Effect of Bentonite content on liquid limit, unconfined compressive strength, consolidation behaviour, swell pressure and permeability

Property	**Bentonite Content (%)**						
	0	**2**	**4**	**6**	**8**	**10**	**12**
Liquid Limit, w_L (%)	50	52	54	58	63	70	74
Unconfined Compressive Strength, q_u (kPa)	325	358	413	446	591	578	550
Undrained Cohesion, c_u (kPa)	162	179	206	223	296	289	275
Compression Index, C_c	0.048	0.059	0.060	0.064	0.070	0.081	0.115
Swelling Index, C_s	0.011	0.009	0.010	0.011	0.012	0.014	0.018
Swell Pressure (kPa)	0	0	1	7	10	15	23
Permeability, k (m/s)	$8.5* 10^{-7}$	$8.9* 10^{-9}$	$5.8* 10^{-10}$	$3.5* 10^{-10}$	$2.8* 10^{-10}$	$2.7* 10^{-10}$	$2.2* 10^{-10}$

4.3 Variation of Consolidation, Swell, and Permeability Characteristics

Figure 6 shows the consolidation curves of B-0 to B-12 specimens plotted between void ratio (e) and effective stress (p’) in semi-log scale. The results in terms of consolidation indices (C_c & C_s), swell pressure and permeability (k) are presented in Table 2. The compression index (C_c) and Swelling index (C_s) of the specimens increased from 0.048 to 0.115 and 0.011 to 0.018 with increase in Bentonite content from raw fly ash to 12% Bentonite mixed fly ash, respectively. It indicates that addition of Bentonite makes fly ash matrix more compressible due to possible lubrication effect of Bentonite on rearrangement of fly ash particles with increased loading. The higher values of compression index made the clay liner more susceptible to differential settlement and damage. Hence, very high Compression index (C_c) values are not recommended in the design of clay liners. Based on the determined values of C_c, the 4% to 8% Bentonite content addition is recommended. The swell pressure was also determined through 1-D consolidation test for each Bentonite mixed specimens and presented in Fig. 7. The maximum swell pressure of 23 kPa was obtained for highest Bentonite content specimen (B-12). The 23 kPa swell pressure value was observed to be not very high and can be neglected as compared to huge swell pressure commonly observed for raw Bentonite liners. The permeability of the B-0 to B-12 specimens were determined indirectly by taking average of permeability calculated for each loading increment from 200 to 800 kPa. The permeability (k) was found to decrease drastically from 8.5*10^{-7} m/s to 5.8*10^{-10} m/s from little variation in Bentonite content from 0 to 4%. After that, very small reduction in the permeability (k) value was found till 12% Bentonite content. Least permeability of 2.2*10^{-10} m/s was obtained for B-12 specimen. The permeability variation with Bentonite content on semi log scale is given in Fig. 8. Fly ash should have low permeability to act as a hydraulic barrier. Raw fly ash specimens had very high permeability in the order of 10^{-7} m/s and can not be used directly as a hydraulic barrier in its raw form. But, with addition of only 4% Bentonite, fly ash permeability reduced less than 10^{-9} m/s, which is acceptable range for the permeability of hydraulic barrier or clay liner according to the minimum specifications given by Central Pollution Control Board (CPCB), Government of India (HAZWAMS/17/2000-01) and US Environmental Protection Agency (EPA/600/R-02/099) [2, 14].

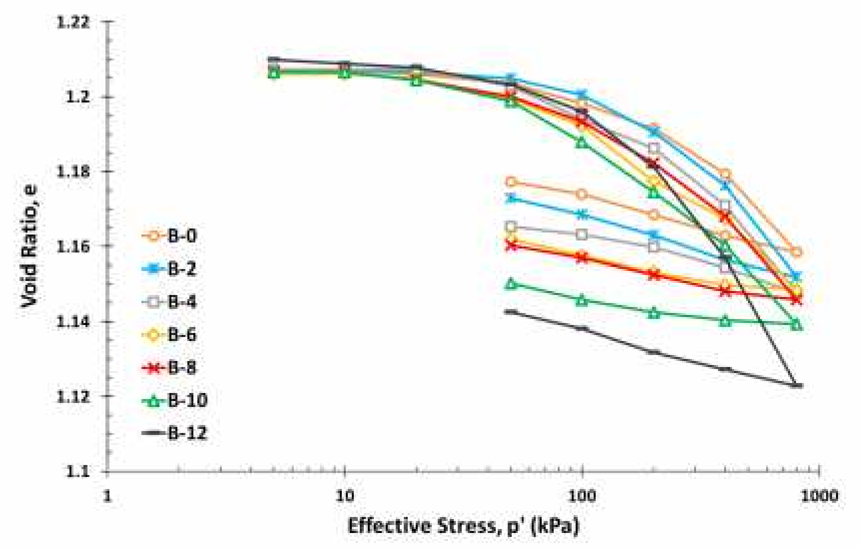

Fig. 6. Effect of Bentonite content on consolidation behaviour of fly ash-Bentonite mixture

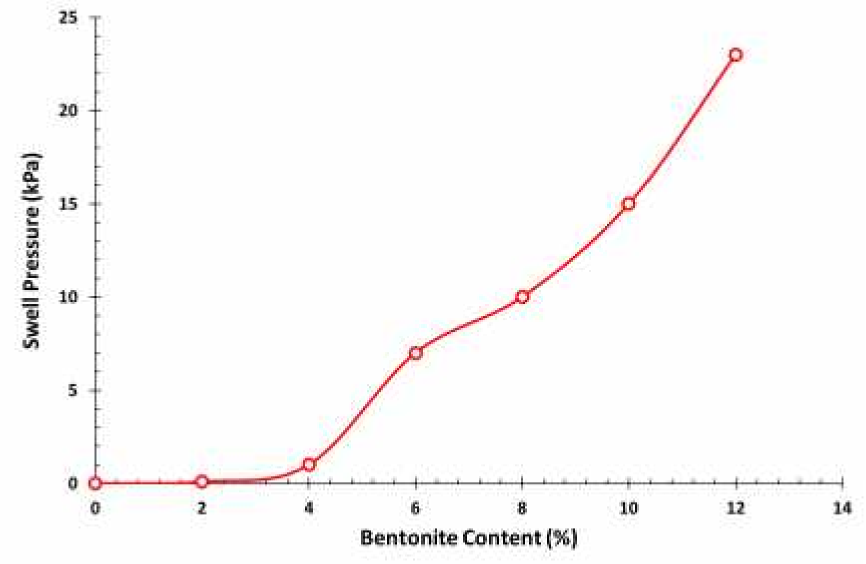

Fig. 7. Effect of Bentonite content on swell pressure behaviour of fly ash-Bentonite mixture

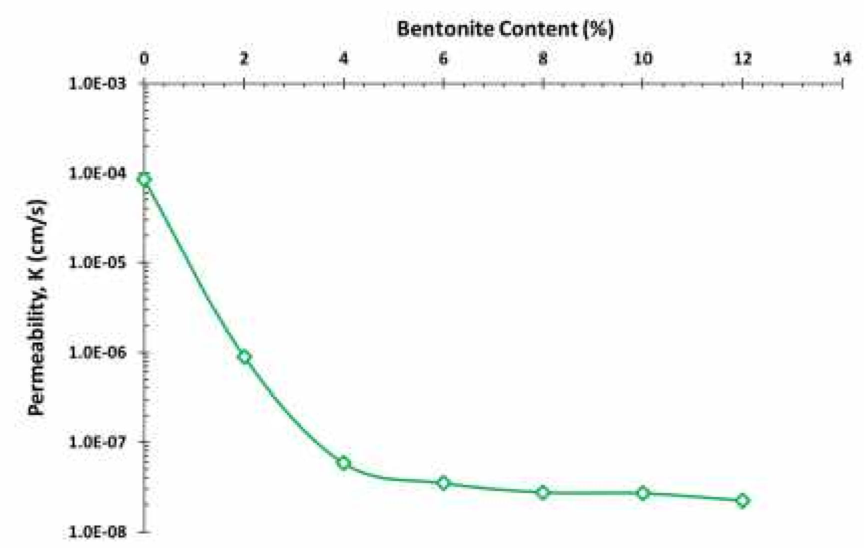

Fig. 8. Effect of Bentonite content on permeability (k) of fly ash-Bentonite mixture

5 Conclusions

The major conclusions derived from the current study can be summarised as follows:

- The water holding capacity and compressibility of fly ash increased with addition of Bentonite content from 0 to 12%.
- The unconfined compressive strength (q_u) and stiffness of fly ash increased till addition of 8% Bentonite content and thereafter it decreased with further Bentonite addition. The formation of strong matrix due to pore filling phenomena is responsible for the strength enhancement.
- The order of permeability of the fly ash reduced from 10^{-7} m/s to 10^{-10} m/s with addition of even small amount of Bentonite (4%). The negligible swell pressure of 23 kPa was generated at highest Bentonite content of 12%.
- The optimum content of 8% Bentonite was suggested as a admixture in the fly ash to make the mixture suitable for landfill liner with all the consideration of shear strength, compressibility, swell pressure and permeability.

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