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Permeability of Sand-bentonite and Sand-fly Ash Mixtures

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Abstract: Laboratory hydraulic conductivity (HC) tests have been conducted on mixtures of fine sand with bentonite and fly ash with four fluids with different pH and metal concentrations with a view to assess their suitability for liner constructions for waste containment facilities. HC of sand-bentonite mixtures which was low, due to effective reduction void ratio because of swelling of negatively charged bentonite particles, further reduces with increase in the density and with increase in the pH of the fluid by increase in the cation exchange capacity and fabric of the clay assuming relatively more dispersed structure. The hydraulic conductivity of mixtures of fly ash sand were higher and were in the range of 1×10^{-5} cm/s which however decreases slightly with increase in the density. HC of sand fly ash mixtures with increase in pH of the solution due to increase in the reactivity of fly ash in alkaline medium produces more pozzolanic compounds leading to reduction in the void ratio. It is also found, however, that hydraulic conductivity of fly ash mixtures is not suitable for liner application. The precipitation of metal ions at higher pH in sand fly ash mixtures may reduce the HC depending on the concentration of metal ions. However, bentonite needs to be incorporated to lower the HC range required for liner application. Thus both sand bentonite and sand fly ash-bentonite mixtures can be used for liner application for waste containment facilities.

Key words: Sand-bentonite, sand-fly ash, permeability, laboratory study, hydraulic conductivity.

Introduction

Compacted clay liners are low cost and effective barrier materials for bottom liners and cover systems for waste containment facilities. Clay liners must be compacted to a reasonable density to control their hydraulic conductivity. In order to contain the uncontrolled release and movement of toxic contaminants in to the drinking water aquifers, the liners for scientifically designed landfills should possess low permeable materials (less than 10^{-7} cm/s) (Benson and Daniel, 1990; Chapuis et al., 1992). The most commonly used liner material because of its rheological properties is bentonite, at least in part. Bentonite alone will have very low hydraulic conductivity but is not suitable because of its high swelling capacity and low strength when saturated. Thus bentonite is amended only on small but in optimized proportion to sand to maintain its long-term stability, deformability without substantially as well as to maintain hydraulic conductivity as low as possible. Generally bentonite when used along with other mixtures acts as a sealant reducing the hydraulic conductivity to the permissible levels and can be used as a liner at the base of landfills to prevent migration of leachate (Hoeks et al., 1987). Fly ash which is a by-product of combustion of coal for production of electricity, contains unburnt carbon and hence has got adsorption capacity and also can

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be used for liner construction after mixing with soils. It also is a pozzolanic material when combined in optimum ratios. However, they can form an excellent barrier to leachate because of the potential to achieve a low value of hydraulic conductivity. A compacted mixture of bentonite and sand is often used to form a seepage barrier (Haug and Wong, 1992). An attempt has been made, in this paper, to study the possibility of using a mixture of fine sand with bentonite or fly ash for barrier materials for bottom liners. This study investigates the hydraulic conductivity values of seven mixtures of fine sand with bentonite or fly ash and bentonite.

Materials Used

Sand Used

A fine sand which consists primarily of clean, uniformly graded, high-quality silica sand or lake sand is bonded to form molds for ferrous (iron and steel) and non-ferrous (copper, aluminum, brass) metal castings. The automotive industry and its parts suppliers are the major generators of foundry sand. Silica fine sand was collected from foundry lab of Amrita School of Engineering, Bangalore, supplied by Arun Alloy Cast Company.

Fly Ash Used

A fly ash of class "F" category procured from Raichur Thermal Power Station (RTPS), in Karnataka, India, called Raichur Fly ash (RFA), is used in the present study. The fly ash used was grey in colour. The physical properties and the chemical composition of the fly ash are given in Tables 1 and 2**.**

Table 1: Physical properties of fly ash

Specific gravity	2.03
Liquid limit (%)	35
Plastic limit (%)	-
Plasticity Index (%)	-
Shrinkage limit (%)	18.5
Compaction characteristics	
Maximum dry density (kN/m^3)	11.7
Optimum moisture content (%)	25.0
Grain size distribution	
Gravel (%)	00
Sand (%)	58
Silt and clay (%)	42

Table 2: Chemical composition of fly ash

Constituents	*Percentage*
SiO_2	61.10
Al_2O_3	28.00
TiO_2	1.30
Fe_2O_3	4.20
MgO	0.80
CaO	1.7
K_2O	0.18
Na_2O	0.18
L.O.I	1.40

Bentonite Used

Bentonite is a natural clay mineral and is found in many places of the world; it belongs to 2:1 clay family. The basic structure is composed of two tetrahedrally coordinated sheets of silicon ions surrounded by a sandwiched octahedrally coordinated sheet of aluminum ions. The isomorphs substitution of Al^{3+} for Si^{4+} in the tetrahedral layer and Mg^{2+} or Zn^{2+} for Al^{3+} in the octahedral layer results in a net negative surface charge on the clay. Compared with other clay types, it has excellent sorption properties and possesses sorption sites available within its interlayer space as well as on the outer edges. Bentonite procured from Kolar region of Karnataka was used in the present study and typical analysis is presented in Table 3.

Table 3: Physical properties of bentonite

Specific gravity	2.76
Liquid limit (%)	374
Plastic limit (%)	63
Plasticity index (PI)%	311
Sediment volume in water (ml/g)	16
Max dry unit weight (kN/m^3)	11.7
Optimum moisture content (%)	45
Soil classification (ASTM D24487-unified Soil classification system	CH-Fat clay
Percentage clay fraction (%)	2

Chemicals Used

Synthetic heavy metals solutions were prepared by dissolving a known quantity of ammonium ferrous sulphate in distilled water to represent iron; similarly cupric sulphate crystals were dissolved in distilled water to represent copper. pH adjustments were carried out using 0.1N hydrochloric acid (HCl) and 0.1N sodium hydroxide (NaOH). The chemicals used were supplied by Qualigens company of Analytical Grade (AR).

Experimental Methods

The sand was mixed with several percentages of bentonite in applied ratios (5%, 10% and 20%) based on the mass of dry bentonite to the mass of sand. Similarly several percentages of fly ash in applied ratios (10%, 20% and 50%) based on the mass of dry fly ash to the mass of sand. There is a strong relationship between the ratios of bentonite, fly ash, permeating fluid, pH, and hydraulic conductivity. The above soil mixtures were tested for HC with different fluids, pH and densities.

Compaction Test for Soil Mixtures

Compaction parameters are required for the design to meet the requirement of material for liner application (Benson and Daniel, 1990). The compaction tests were conducted using a specially made apparatus (Sridharan and Sivapullaiah, 2005), which requires about 1/10th of soil needed for the standard Proctor test. Also the time and effort involved to carry out the compaction test were less. The sample mold is of 3.81 cm internal diameter and 4.61 cm external diameter and 10 cm in height. The sample mold assembly has detachable base plate and a removable collar of 3.50 cm in height. A hammer of 1kg in weight falls freely through a height of 16 cm. The number of blows required to achieve standard proctor energy per layer is 36 and in three layers. The remaining procedure is same as that of Light Compaction test as per IS 2720 (part 7) – 1980. The results of the compaction test are presented in Figures 1 and 2. From the plots, maximum dry density and optimum water content were determined.

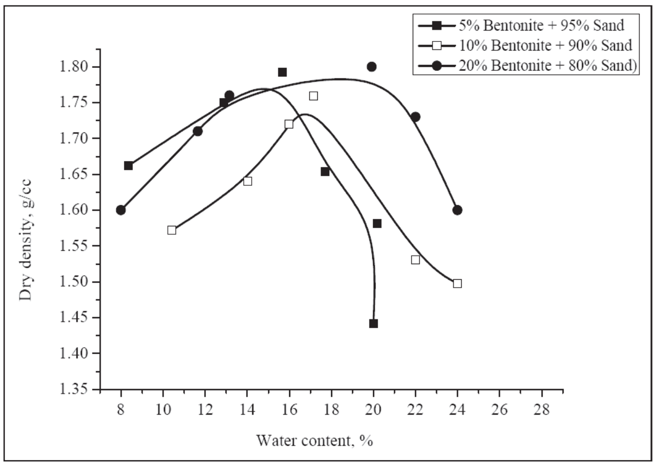

Figure 1: Compaction curves for sand-bentonite mixtures.

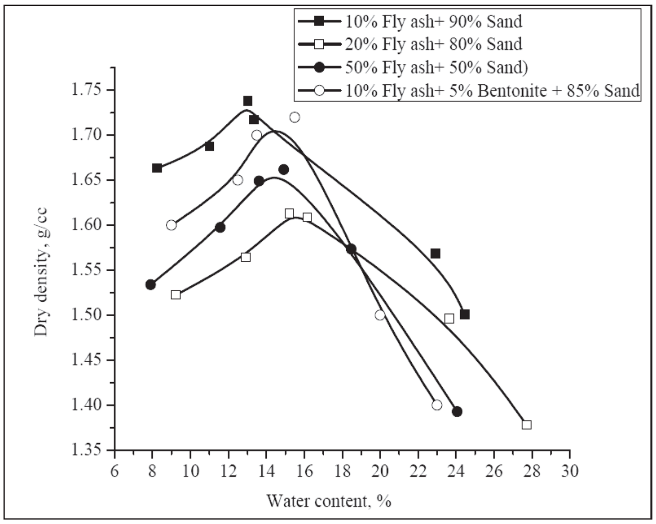

Figure 2: Compaction curves for sand-fly ash mixtures.

Column Assembly for Measuring Hydraulic Conductivity

The column assembly consists of plexiglas cylinder of 10 cm long, 4 cm inner diameter and 0.3 cm thick. The plexiglas cylinder is attached to the base plate which houses a filter paper and a porous stone as shown in Figure 3. The soil specimen of 4 cm diameter and 10 cm height is pressed into the plexiglas cylinder using a screw jack to ensure uniform compaction for the entire specimen. Once the soil sample is in place one more set of porous stone and filter paper are placed at the top and capped with top plate as shown in the figure. The influent line is connected at the top of the column assembly and effluent line at the bottom to collect the effluent.

The schematic diagram of hydraulic conductivity test set up is given in Figure 3. The bentonite/fly ash after dry mixing sand were added with the amounts of water corresponding to their respective Proctor maximum dry densities. The wet mixed material was then compacted using static compaction technique in the column cell as per ASTM D5856-07. Before compacting the sample in to the cell, the inside curved wall of the cell was coated with a thin layer of silicon grease. This will check that there is good contact between the compacted material and the inner surface of the cell wall. Porous discs were placed at the top and bottom of the mould and the caps were tightened. The column cell with the compacted mix was fitted into the setup and connected to the flexible tube as shown in Figure 3. Water was allowed to flow through the specimen and the entrapped air if any was removed using the air vent provided at the top of the hydraulic conductivity mould and the hydraulic conductivity of the specimen was determined as per ASTM D5856-95 (2007).

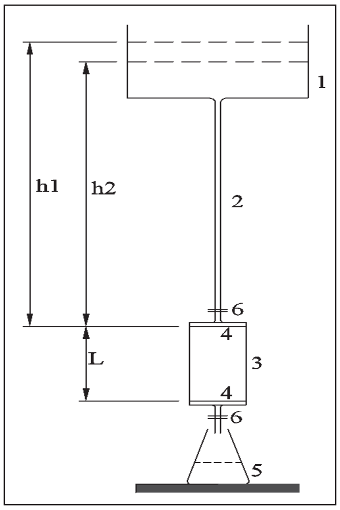

Figure 3: Schematic diagram of hydraulic conductivity test set up.

(1) Graduated water reservior, (2) Flexible tube, (3) Column cell, (4) Porous stone, (5) Sampling flask and (6) Regulating valve.

The time required for a particular fall in head in the graduated water reservoir was noted and the hydraulic conductivity k (cm/s) was calculated using the equation:

$$k = 2.303\left(\frac{aL}{At}\right)\log_{10}\left(\frac{h_1}{h_2}\right) \text{ cm/s}$$

where a is the cross-sectional area of the graduated water reservoir, cm^2; L—length of the specimen, cm; A—cross-sectional area of the specimen, cm^2; and t is time taken for the hydraulic head to fall from h_1 to h_2, s.

Results and Discussion

Hydraulic conductivity tests were carried out on compacted sand fly ash and sand bentonite with four different pore fluids, viz., distilled water, acidic solution of pH 4, alkaline solution of pH 9 and aqueous solution containing 100 ppm iron/copper. The changes in HC of mixture as effected by fly ash/bentonite content, density of the mixture along with the nature of pore fluid are brought and the mechanisms explained.

Effect of Pore Fluid for Fly Ash Sand Mixtures

The hydraulic conductivity of sand-fly ash mixtures, compacted to their respective maximum dry density at optimum water content, were established with different pore fluids.

Effect of Fly Ash Content with Different Permeating Fluids

From Figure 4, it can be seen that as the fly ash content increases, the hydraulic conductivity decreases. As the percentage of fly ash increases up to 20%, the hydraulic conductivity decreases steeply, and thereafter the hydraulic conductivity decreased steadily. This indicates that fly ash particles up to about 20% are mostly accommodated within the voids created by sand particles. Beyond 20% only small amount of fly ash can be accommodated and thus the decrease is less. The same trend continues not only with water also with acid solution of pH 4. Even a solution of Fe containing 100 ppm of Fe has not shown any significant change. However a solution of pH 9 has decreased the hydraulic conductivity at any fly ash content. Also the HC decreases with increased fly ash content. Thus it is clear that the decrease in HC with higher pH solution is due to better production of pozzolanic reaction compounds with increase in pH (Mitchell, 1976). When the acidic solution is passed, the lime in fly ash will be dissolved and whatever compounds are formed due to hydration will dissolve thereby increasing the hydraulic conductivity (Howell and Shackelford, 1997; Nhan et al., 1996).

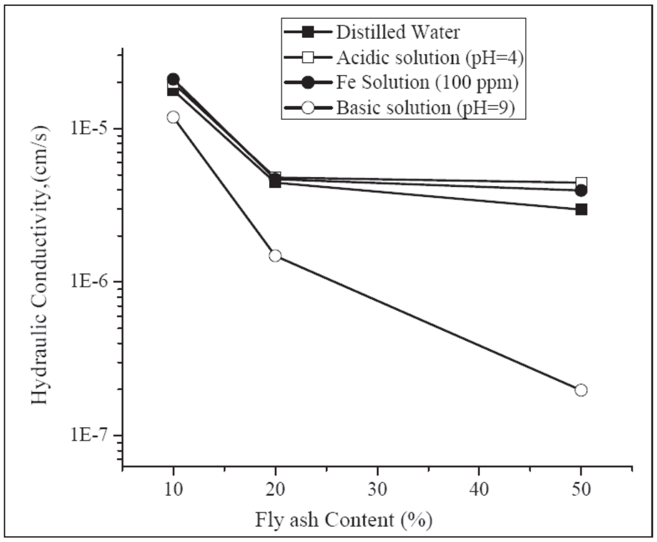

Figure 4: Variation of hydraulic conductivity with fly ash content and different permeating fluids.

Effect of Pore Fluid for Bentonite Sand Mixtures

The hydraulic conductivity of sand-bentonite mixtures, compacted to their respective maximum dry density at optimum water content, were established with different pore fluids.

Effect of Bentonite Content with Different Permeating Fluids

From Figure 5, it can be seen that with the bentonite content increasing the hydraulic conductivity decreases. As the percentage of bentonite increases up to 10%, the hydraulic conductivity decreases very steeply and thereafter the hydraulic conductivity decreased steadily. Bentonite has got very fine particles; it has got high swelling potential i.e. bentonite will swell and block the pores; thus reducing the hydraulic conductivity very drastically further. The voids available for conduction are not real air voids but voids with water, and how this is efficient at different pH has been shown in the figure. In this case when the acidic solutions are passed the effect is marginal as there is no change in Cation Exchange Capacity (CEC) of the bentonite. When basic solution is passed the swelling ability is more as CEC of bentonite can increase with pH of the solution (Howell and Shackelford, 1997; Prashanth, 2000). Here hydraulic conductivity for basic solution is not shown as it is lower than the range indicated in Figure 5.

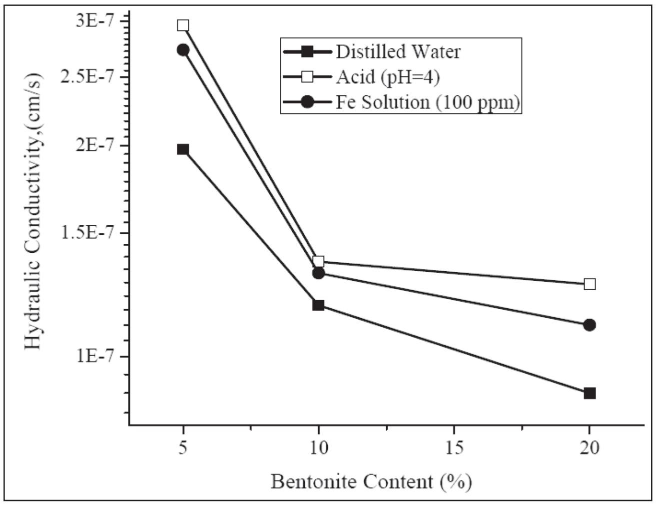

Figure 5: Variation of hydraulic conductivity with bentonite content and different permeating fluids.

Effect of Density for Sand-Bentonite Mixtures

With 5% of Bentonite

From Figure 6, it can be seen that as the dry density increases the hydraulic conductivity decreases due to reduction of voids. It is observed that hydraulic conductivity decreases irrespective of the four fluids. And how the hydraulic conductivity varies or is efficient at different pH has been shown in the figure. At any dry density the hydraulic conductivity is maximum with acidic solution and lowest in alkaline solution. In acidic solution the swelling capacity of bentonite to block the pores is less compared to alkaline solution. Thus the capacity of bentonite to block the pores is maximum in alkaline solution due to increase in CEC in alkaline environment.

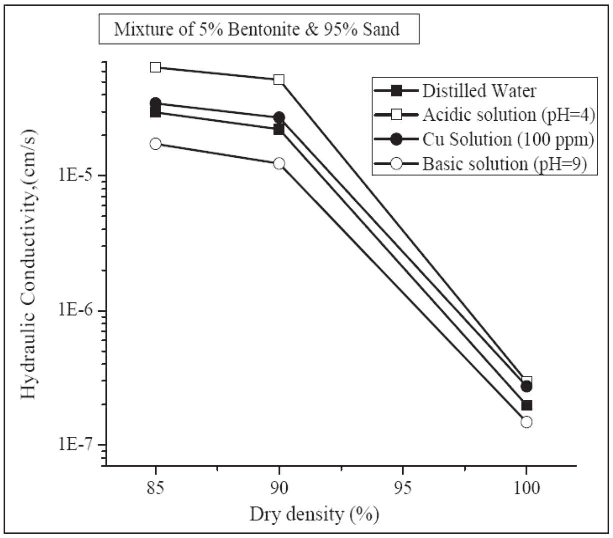

Figure 6: Variation of hydraulic conductivity with dry density and different permeating fluids.

With 10% of Bentonite

From Figure 7, it can be seen that as the dry density increases the hydraulic conductivity decreases. As the percentage of dry density is increased from 85 to 90%, hydraulic conductivity decreases marginally and thereafter the hydraulic conductivity decreases drastically and becomes lower than 1×10^{-7} cm/s, because the void available for conduction will reduce as the density increases.

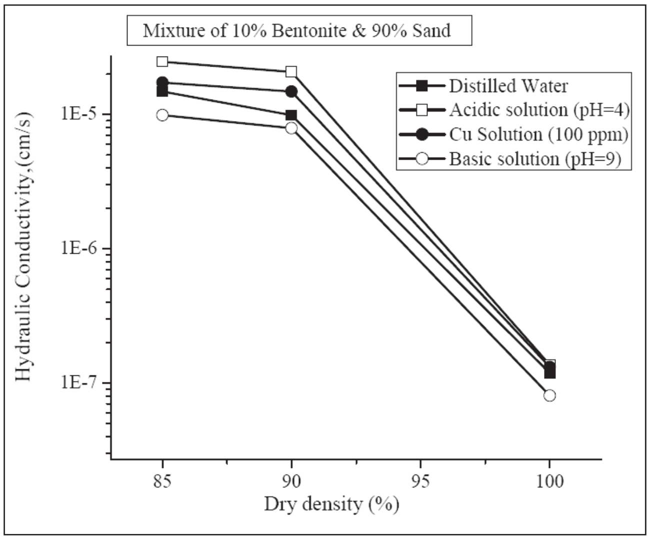

Figure 7: Variation of hydraulic conductivity with dry density and different permeating fluids.

It is known that bentonite particles assume dispersed structure as the water content is increased. This in turn will decrease the HC more effectively. With 10% of bentonite, its effect is not sensitive to the type of pore fluid.

With 20% Bentonite

From Figure 8, it can be seen that as the dry density increases the hydraulic conductivity decreases. As the percentage of dry density is increased from 85 to 90%, hydraulic conductivity decreases marginally except basic solution and then the hydraulic conductivity decreases drastically further, because the void available for conduction will reduce as the density increases. Also bentonite has got very fine particles; it has got high swelling potential i.e. bentonite will swell and block the pores and reduce the hydraulic conductivity. As the swelling ability of the bentonite is high at high pH, the reduction is with 20% in this mixture, the decrease is more significant. It is clear from the graph that basic solution decreases the HC drastically when high content bentonite is incorporated in the liner material.

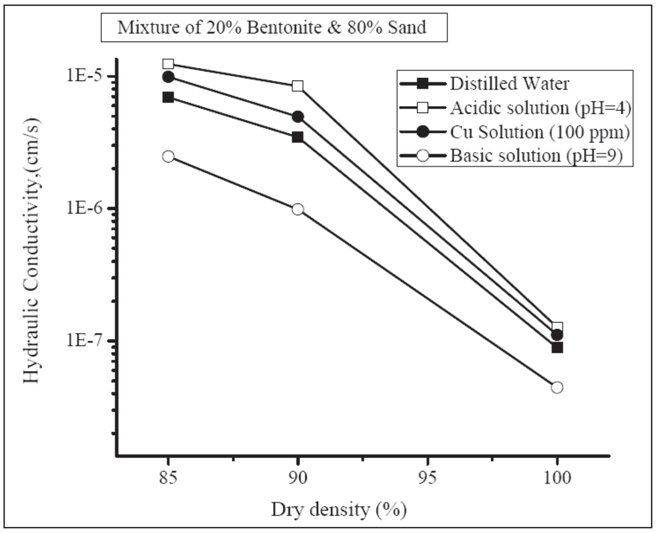

Figure 8: Variation of hydraulic conductivity with dry density and different permeating fluids.

Effect of Density for Sand-Fly Ash Mixtures

With 10% of Fly Ash

From Figure 9, it can be seen that as the dry density increases the hydraulic conductivity decreases due to reduction of voids. Hydraulic conductivity decreases irrespective of the four fluids. And how the hydraulic conductivity varies/efficient at different pH has been shown in the figure. At any dry density the hydraulic conductivity is maximum with acidic solution and lowest in alkaline solution. At the acidic pH, increase in hydraulic conductivity is due to dissolution of pozzolanic compounds. However the presence of metal ions decreases the hydraulic conductivity due to precipitation. Also this effect is marginal where dry density is very high. The hydraulic conductivity variation, with respect to type of permeating fluid, is in the order, acidic solution>copper solution>distilled water>basic solution.

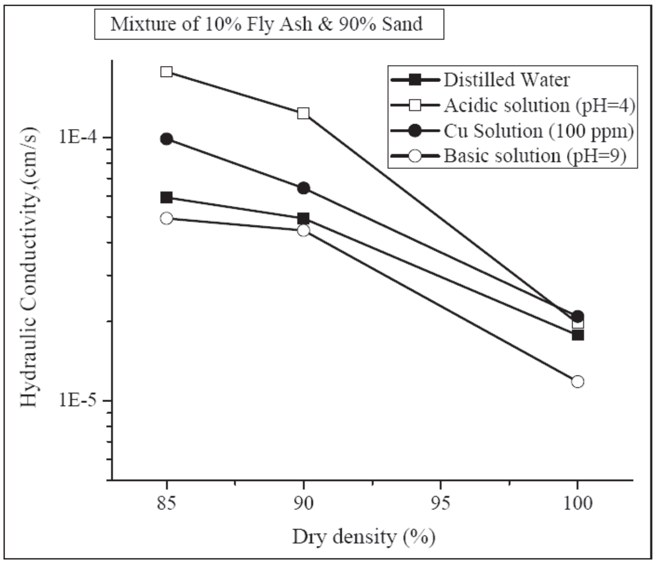

Figure 9: Variation of hydraulic conductivity with dry density and different permeating fluids.

With 20% of Fly Ash

Here again the variation of HC with dry density for different permeating fluid is shown. From Figure 10, it can be seen that as the dry density increases the hydraulic conductivity decreases. As the percentage of dry density is increased from 85 to 90%, hydraulic conductivity decreases marginally and then the hydraulic conductivity decreases drastically further, because the void available for conduction will reduce as the density increases. When leachate containing heavy metal percolates through fly ash, it precipitates metals as hydroxides and block the pores and reduce the hydraulic conductivity further. And how this is efficient at different pH has been shown in the figure. Here also the hydraulic conductivity variation, with respect to type of permeating fluid, remains same as, acidic solution>copper solution>distilled water>basic solution.

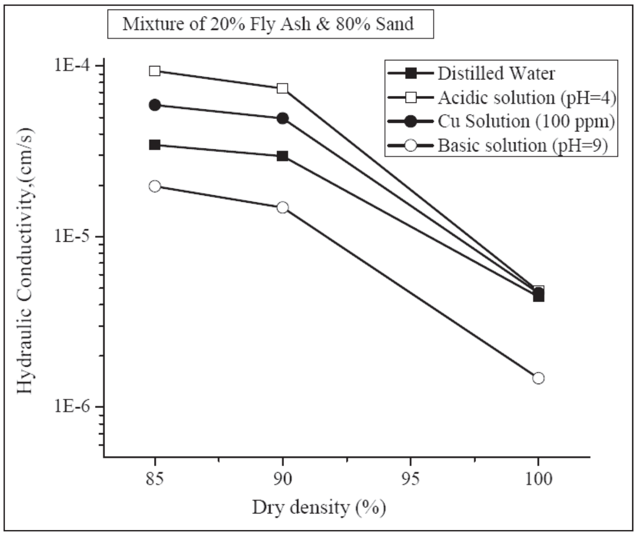

Figure 10: Variation of hydraulic conductivity with dry density and different permeating fluids.

With 50% Fly Ash

It is observed in Figure 11 that as the dry density increases the hydraulic conductivity decreases. As the percentage of dry density is increased from 85 to 90%, hydraulic conductivity decreases marginally and then the hydraulic conductivity decreases drastically further, because the void available for conduction will reduce as the density increases. Fly ash has high pH; it will not reduce the hydraulic conductivity very much, but leachate containing heavy metal percolates through fly ash will precipitate metals as hydroxides and block the pores and reduce the hydraulic conductivity further. And how this is efficient at different pH has been shown in the figure.

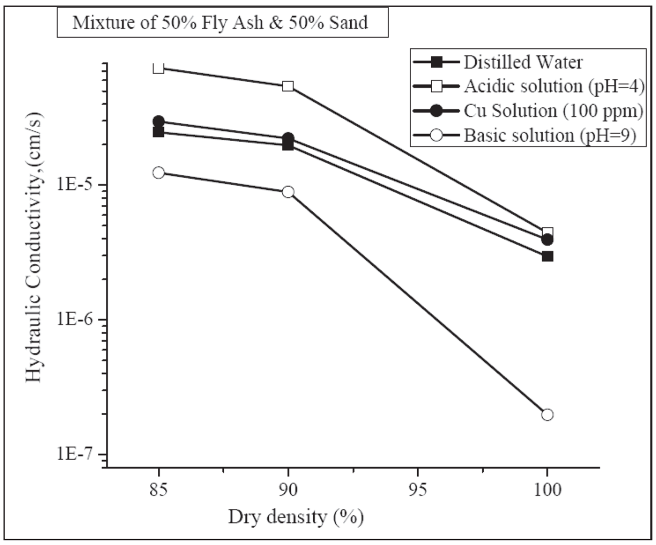

Figure 11: Variation of hydraulic conductivity with dry density and different permeating fluids.

Effect of Bentonite on the HC of Sand-Fly Ash Mixtures

It is clear from the above discussion that the HC of most sand-fly ash mixtures is high for its use in the construction of liners, whereas sand-bentonite mixtures are suitable for HC criteria. Hence, addition of 5% of bentonite is considered to sand-fly mixture to control its HC.

Figure 12 shows the variation of hydraulic conductivity with dry density and different permeating fluids for mix B5+F10+85S. It was observed that HC of sand-fly ash mixtures which were in the range of 1×10^{-5} to 1×10^{-6} cm/s only be brought to the desired level with addition of 5% bentonite. As the percentage of dry density is increased from 85 to 90% hydraulic conductivity decreases marginally and then the hydraulic conductivity decreases drastically further, because the void available for conduction will reduce as the density increases. Also bentonite has got very fine particles; it has got high swelling potential i.e. bentonite will swell and block the pores and reduce the hydraulic conductivity, as the swelling ability of the bentonite is very high at high pHs. When basic solution is passed considerable reduction in HC may be due to increase in CEC and swelling of the bentonite (Howell and Shackelford, 1997; Sivapullaiah and Stalin, 2000). Fly ash has high pH; it will not reduce the hydraulic conductivity very much, but leachate containing heavy metal percolates through fly ash will precipitate metals as hydroxides and block the pores and reduce the hydraulic conductivity further. And how this is efficient at different pH has been shown in the figure.

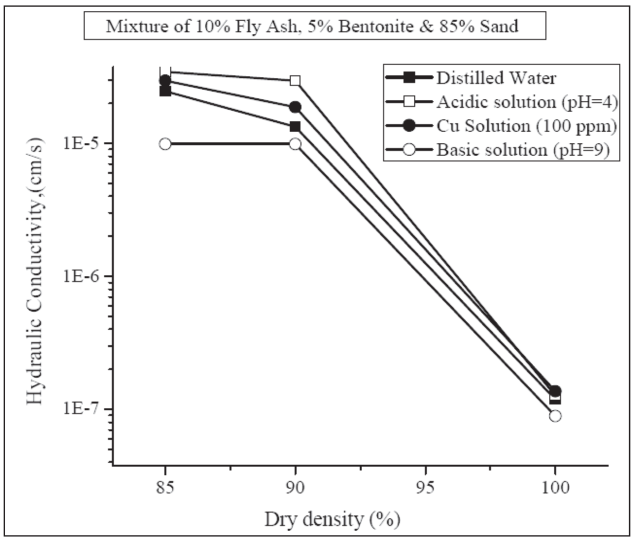

Figure 12: Variation of hydraulic conductivity with dry density and different permeating fluids for mix B5+F10+85S.

Conclusion

Based on the hydraulic conductivity evaluation of the sand-bentonite and sand-fly ash mixtures as liners for waste disposal facilities with experimentally determined hydraulic conductivity of compacted sand bentonite mixtures with different fluids, the following conclusions are drawn:

1. The HC of compacted mixtures varied considerably both with the amount of bentonite and fly ash. For the same amount of sand the mixture with bentonite gives lower values. This is because of swelling of bentonite particles in the presence of water as well as its ability to adsorb water reducing the effective void ratio, even with total void ratio being the same.
2. The reduction in HC with increased density is marginal up to about 10% of Proctor's maximum dry density but is steep as the density is increased from 90 to 100% of maximum dry density. This is relatively more for bentonite and for alkaline solution.
3. For all the mixtures tested, the HC with basic solution has yielded lowest values. The effect of pH is more for fly ash. The significant reduction in hydraulic conductivity values is due to formation of cementitious compounds and the precipitation of unreacted lime.
4. The effect of decreasing the HC with permeating fluid with metal ions is due to their precipitation.
5. To bring the HC to acceptable levels of sand-fly ash mixtures it is necessary to incorporate bentonite.

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