Compatibility studies on index properties of fly ash-stabilised expansive clay liners

4.1 INTRODUCTION

Earthen barriers or clay liners are a major concern in geo-environmental engineering. They are designed to preclude or reduce leachate migration. Hence, a low hydraulic conductivity \((k)\) is an important parameter in the design of clay liners. Materials such as bentonite and lateritic soils, which have a low hydraulic conductivity at high dry densities, are used in the construction of clay liners. Compacted expansive clays which are high in montmorillonite content also have a very low hydraulic conductivity. When expansive clays are blended with fly ash, an industrial waste, the hydraulic conductivity further reduces as the ash-clay blends result in increased dry densities at increased fly ash contents. Hence, fly ash-stabilised expansive clay can also be proposed as an innovative clay liner material. It is, therefore, required to study various physical and engineering properties of this new clay liner material. Liquid limit \((LL)\) and free swell index \((FSI)\) are important index properties to be studied in the case of this clay liner material. Laboratory experimental studies were performed on expansive clay-fly ash blends, which would be suggested as a new clay liner material. This chapter discusses \(LL\) and \(FSI\) determined using deionised water and \(CaCl_2, NaCl,\) and \(KCl\) solutions of varying concentration at 0%, 10%, 20% and 30% fly ash content in the blend.

4.2 EFFECT OF FLY ASH CONTENT AND CONCENTRATION OF \(CaCl_2, NaCl\) AND \(KCl\) ON LIQUID LIMIT \((LL)\)

The effect of fly ash content in the clay-fly ash blend and concentration of permeating fluids used such as \(CaCl_2, NaCl\) and \(KCl\) on liquid limit \((LL)\) is presented in graphical manner. Figures 4.1 to 4.3 show the variation of \(LL\) with fly ash content when the tests were performed with deionised water and other permeating fluids such as \(CaCl_2, NaCl\) and \(KCl\) respectively with varying concentration (5mM, 10mM, 20mM, 50mM, 100mM and 500mM). Liquid limit decreased significantly with increase in fly ash content when the fluid used was deionised water. The variation of \(LL\) with fly ash content when deionised water was used is the same in Figures 4.1 to 4.3.
Fig 4.1. Variation of $LL$ with fly ash content (calcium chloride)

Fig 4.2. Variation of $LL$ with fly ash content (sodium chloride)
Liquid limit depends upon the particle size of the clay used. The finer the particles of the clay, the higher the value of $LL$. In the clay-fly ash blend, non-plastic and silt-sized fly ash particles replace clay particles having higher plasticity. This means that the average particle size of the blend would be higher than the average size of the clay liner material when clay alone is used. The average particle size would increase when fly ash content in the blend increases. Moreover, fly ash is also a pozzolanic material apart from being a silt-sized non plastic material. Hence, pozzolanic reactions also take place in the clay-fly ash blend, resulting in effects like flocculation and increase in particle size, which also lead to reduction in $LL$ and plasticity. Therefore, $LL$ of the blend also decreased when the fly ash content in the blend increased. $LL$ determined with deionised water decreased from 98.6% to 82.90% when fly ash content in the blend increased from 0% to 30%. This is in accordance with the previous research by Phanikumar and Sharma (2004).

Similarly, $LL$ decreased notably with increasing fly ash content in the blend when the test fluids were CaCl$_2$, NaCl and KCl (see Figures 4.1 to 4.3). This reduction in $LL$ determined with salt solutions such as CaCl$_2$, NaCl and KCl could also be attributed to
increase in the average particle size of the blend, pozzolanic reactions resulting in flocculation and increased particles size of the blend and a consequent reduction in the plasticity of the clay-fly ash blend. This trend in the reduction of LL was observed in the case of all concentrations of CaCl$_2$, NaCl and KCl used in the test programme, namely, 5mM, 10mM, 20mM, 50mM, 100mM and 500mM. For example, LL determined with CaCl$_2$ decreased from 95% to 82% and from 80.5% to 71% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. Similarly, LL determined with NaCl decreased from 91.5% to 82% and 84.2% to 74.5% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. In the case of KCl, LL decreased from 93.5% to 81.6% and 86.6% to 60.5% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. For all other concentrations of the salt solutions also, LL decreased notably (see Figures 4.1 to 4.3). The numerical values are presented in appendix A. The data shown in Figures 4.1 to 4.3 indicate that reduction in LL increased from CaCl$_2$ to NaCl to KCl for a given fly ash content in the blend.

When net negatively charged expansive clay particles are treated with electrolytes like CaCl$_2$, cation exchange takes place. The most common adsorbed cations are calcium, magnesium, sodium and potassium. Cation exchange capacity (CEC) varies for different types of clays. Further, CEC is also related to specific surface or ion size, relative abundance of different ion types and surface charge density or valence. Generally trivalent cations are held more tightly than divalent cations, and divalent cations are held more tightly than monovalent cations (Mitchell and Soga, 2005). In this test programme, experiments were performed with one divalent cation (Ca$^{2+}$) and two monovalent cations (Na$^+$ and K$^+$). Of the two monovalent cations, potassium is easier to exchange than sodium. Hence, potassium chloride (KCl) gave the best results and resulted in the maximum reduction in LL.

Figures 4.4 to 4.6 depict the reduction in LL with increasing salt solution concentration respectively for CaCl$_2$, NaCl and KCl. LL decreased with increasing concentration for all fly ash contents (see Figures 4.1 to 4.3 also). This was found to be true for all the salt solutions used (see Figures 4.4 to 4.6). When the concentration of salt
solution increases, cation exchange increases, or the amount of cation deposition increases on the clay surface, resulting in flocculation of particles which, in turn, results in increase in particle size of the blend. Hence, $LL$ decreases with increasing concentration as shown Figures 4.4 to 4.6. For a given salt solution concentration, $LL$ decreased as the fly ash content in the blend increased. This was found true for all the solutions used (Sivapullaiah and Lakshmikantha, 2004). Increase in fly ash content also increases flocculation, resulting in reduced $LL$ for a given concentration of the salt solution.

Fig 4.4 Variation of $LL$ with CaCl$_2$ concentration
Fig 4.5. Variation of $LL$ with NaCl concentration

Fig 4.6. Variation of $LL$ with KCl concentration
For example, the value of $LL$ was 95% and 80.5% for CaCl$_2$ concentrations of 5 mM and 500 mM when fly ash content was 0%, and the value of $LL$ was 82% and 71% for CaCl$_2$ concentrations of 5mM and 500mM when the fly ash content in the blend was increased to 30%. Similarly, $LL$ for NaCl concentrations of 5mM and 500mM was 91.5% and 84.2%, and 82% and 74.5% respectively for the fly ash contents of 0% and 30%. For KCl concentrations of 5mM and 500mM, $LL$ was 93.5% and 86.6% and 81.6% and 60.5% respectively when the fly ash content in the blend was 0% and 30%. As can be seen, the potassium ion was the most effective of all the cations in resulting in maximum reduction in $LL$.

4.3 EFFECT OF FLY ASH CONTENT AND CONCENTRATION OF CaCl$_2$, NaCl AND KCl ON FREE SWELL INDEX ($FSI$)

The effect of fly ash content in the clay-fly ash blend and concentration of permeating fluids used such as CaCl$_2$, NaCl and KCl on free swell index ($FSI$) is also presented in graphical pattern. Figures 4.7 to 4.9 show the variation of $FSI$ with fly ash content when the $FSI$ was determined with deionised water and other salt solutions such as CaCl$_2$, NaCl and KCl respectively having varying concentration (5mM, 10mM, 20mM, 50mM, 100mM and 500mM). $FSI$ decreased significantly with increase in fly ash content when the fluid used was deionised water (see Figures 4.7 to 4.9).

![Graph showing variation of $FSI$ with fly ash content](image-url)

*Fig 4.7. Variation of $FSI$ with fly ash content (calcium chloride)*
Fig. 4.8 Variation of FSI with fly ash content (sodium chloride)

Fig. 4.9. Variation of FSI with fly ash content (potassium chloride)
The value of \( FSI \) of a montmorillonite clay depends upon the particle size of the clay. The finer the particles of the clay, the higher would the value of \( FSI \). In the case of montmorillonite clays blended with fly ash, non-plastic and silt-sized fly ash particles replace clay particles. Hence, the average particle size of the clay-fly ash blend would be higher than the average size of the mere montmorillonite clay. Further, the average particle size of the blend would increase when fly ash content in the blend increases. Apart from being a non plastic material of silt size, fly ash is also pozzolanic in nature. Hence, pozzolanic reactions resulting in flocculation also take place in the clay-fly ash blend, resulting in increase in particle size, which also lead to reduction in \( FSI \). Therefore, \( FSI \) of the blend also decreased when the fly ash content in the blend increased. \( FSI \) determined with deionised water decreased from 222% to 109% when fly ash content in the blend increased from 0% to 30%. Phanikumar and Sharma (2004) also reported a similar reduction in \( FSI \) when a highly swelling expansive clay was blended with fly ash.

Similarly, \( FSI \) determined with salt solutions such as CaCl\(_2\), NaCl and KCl also decreased significantly with increasing fly ash content in the blend (see Figures 4.7 to 4.9). The reduction in \( FSI \) determined with salt solutions such as CaCl\(_2\), NaCl and KCl could also be attributed to increase in the average particle size of the blend and flocculation. A similar trend in the reduction of \( FSI \) was observed for all the concentrations of CaCl\(_2\), NaCl and KCl, namely, 5mM, 10mM, 20mM, 50mM, 100mM and 500mM (see Figures 4.7 to 4.9). \( FSI \) determined with CaCl\(_2\) decreased from 178% to 70.5% and from 144.5% to 41% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. Similarly, \( FSI \) determined with NaCl decreased from 208% to 60.5% and 187.5% to 50% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. In the case of KCl, \( FSI \) decreased from 152.8% to 56.8% and 66.7% to -13.65% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. For all other concentrations of the salt solutions also, \( FSI \) showed a significant reduction (see Figures 4.7 to 4.9). The numerical values are not presented here. They are shown in Appendix A. The data shown in Figures 4.7 to 4.9 indicate that reduction in \( FSI \) increased from CaCl\(_2\) to NaCl to KCl.
for a given fly ash content in the blend. For example, $FSI$ was negative at -13.65% when determined with KCl of 500 mM concentration at a fly ash content of 30%. This indicated that the blend showed collapse instead of swelling when KCl of 500 mM concentration was used at a fly ash content of 30%. Similar collapse behaviour in the blend was not observed in the case of other salt solutions at any concentration. As the potassium ion was the most effective of all the cations in reducing $FSI$, negative $FSI$ values were obtained when tests were performed with 500 mM KCl at 30% fly ash content.

Figures 4.10 to 4.12 show the reduction in $FSI$ with increasing salt solution concentration respectively for CaCl2, NaCl and KCl. $FSI$ decreased with increasing concentration for all fly ash contents (see Figures 4.7 to 4.9 also). This was found to be true for all the salt solutions used (see Figures 4.10 to 4.12). When the concentration of salt solution increases, cation exchange increases, or the amount of cation deposition increases on the clay surface, resulting in flocculation of particles which, in turn, results in increase in particle size of the blend. Hence, $FSI$ decreases with increasing concentration as shown in Figures 4.10 to 4.12. For a given salt solution concentration, $FSI$ decreased as the fly ash content in the blend increased. This was found true for all the solutions used. Increase in fly ash content also increases flocculation, resulting in reduced $FSI$ for a given concentration of the salt solution.
For example, the value of $FSI$ was 178% and 144.4% for $CaCl_2$ concentrations of 5mM and 500mM when fly ash content was 0%, and the value of $FSI$ was 70.45% and
41% for CaCl$_2$ concentrations of 5mM and 500mM when the fly ash content in the blend was increased to 30%. Similarly, $FSI$ for NaCl concentrations of 5mM and 500mM was 208.2% and 187.5%, and 60.55% and 50% respectively for the fly ash contents of 0% and 30%. For KCl concentrations of 5mM and 500mM, $FSI$ was 152.78% and 66.67% and 56.8% and -13.64% respectively when the fly ash content in the blend was 0% and 30%.

4.4 CORRELATION BETWEEN $LL$ AND $FSI$

Figures 4.13 to 4.15 show the variation of free swell index ($FSI$) with liquid limit ($LL$) obtained at different concentrations of CaCl$_2$, NaCl and KCl respectively. The data shown in the figures pertain to different fly ash contents used in the test programme. The figures indicate that there was an excellent correlation between $LL$ and $FSI$ obtained at different fly ash contents in the case of all three electrolytes used in the test programme. As discussed in previous sections, both liquid limit and free swell index, the two most important index properties of fly ash-stabilised expansive clay liner material, decreased with increasing concentrations of all the electrolytes and also with increasing fly ash content in the blends. This resulted in a useful correlation between $LL$ and $FSI$ as shown in Figures 4.13 to 4.15.

![Graph](image)

Fig 4.13. Variation of $FSI$ with $LL$ (calcium chloride)
Fig 4.14. Variation of FSI with LL (sodium chloride)

Fig 4.15. Variation of FSI with LL (potassium chloride)
4.5 CONCLUSIONS

Liquid limit (LL) and free swell index (FSI) of fly ash-stabilised expansive clay using deionised water and salt solutions such as CaCl₂, NaCl and KCl were determined. The following are the chief conclusions drawn from the experimental study:

1. Liquid limit (LL) and free swell index (FSI) determined with deionised water decreased significantly with increase in fly ash content. As the average particle size of the fly ash-expansive clay blend would be higher than the average size of the clay alone, LL and FSI decrease. Further, the average particle size would increase when fly ash content in the blend increases. Moreover, pozzolanic reactions taking place upon addition of fly ash to clay result in flocculation, leading to reduction in LL and FSI. Similarly, LL and FSI determined with CaCl₂, NaCl and KCl also decreased notably with increasing fly ash content in the blend.

2. For all fly ash contents, LL and FSI decreased with increasing concentration of salt solution in the case of all the test fluids, namely, for CaCl₂, NaCl and KCl. Of all the test fluids used, namely, CaCl₂, KCl and NaCl, KCl resulted in the maximum reduction in LL and FSI.

3. LL determined with CaCl₂ decreased from 95% to 82% and from 80.5% to 71% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. Similarly, LL determined with NaCl decreased from 91.5% to 82% and 84.2% to 74.5% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. In the case of KCl, LL decreased from 93.5% to 81.6% and 86.6% to 60.5% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%.

4. FSI determined with CaCl₂ decreased from 178% to 144.4% and from 70.45% and 41% respectively for the concentrations of 5mM and 500mM when the fly ash content in the blend was increased from 0% to 30%. Similarly, FSI for NaCl concentrations of 5mM and 500mM was 208.2% and 187.5%, and 60.55% and 50% respectively for the fly ash contents of 0% and 30%. For KCl concentrations of 5mM and 500mM, FSI was 152.78% and 66.67% and 56.8% and -13.64% respectively when the fly ash content in the blend was 0% and 30%.
5. As both LL and FSI decreased with increasing fly ash content in the blend and the concentration of the salt solution, a cogent correlation was obtained between LL and FSI values corresponding to different fly ash contents and concentrations of salt solutions. The correlation would be useful for further studies.