CHAPTER 8

CONCLUSION AND SUGGESTIONS FOR FUTURE RESEARCH

8.1 General

India's unique geological features and the prevalence of soft soils in numerous locations require careful planning and engineering considerations before building embankments over soft soil. The deep soil mixing (DSM) method of soft ground reinforcement has been used worldwide for several reasons, such as reducing settlements and increasing stability of the highway and railway embankments built over soft soils, enhancing the earthquake resilience of civil infrastructures, short realization time, and significant cost savings over alternative methods. However, the use of cement as a binder in the DSM technique results in a carbon footprint. Therefore, using sustainable binding materials instead of cement has become imperative, particularly to minimize CO_2 emissions.

Geopolymer, also called "green cement," provides the strength and durability required for engineering applications and can potentially replace OPC completely with a lower carbon footprint. This study explores the use of GGBS and dolomite-based geopolymer with sodium hydroxide and liquid sodium silicate as an alkali activator as an alternative material for cement in deep soil mix columns to stabilize soft soil so that it can facilitate decisions on using geopolymer as binders for future ground improvement projects on soft soil deposits.

A series of model tests were performed on single geopolymer stabilized soil columns (GPSC) installed in soft ground and subjected to static and cyclic loading. Furthermore, the performance of an embankment supported on groups of end-bearing and floating geopolymer stabilized soil columns (GPSCs) in very soft clay under traffic loading conditions was studied. A comprehensive description of the methodology, material characterization, scaling and physical modeling details, and model testing process is included. The embankment model test results are also validated using finite element analyses with PLAXIS 3D. The major conclusions from all the chapters are listed below.

8.2 Engineering properties of soft soil stabilized using GGBS-dolomite-based geopolymer

- Results indicate that the UCS increases with an increase in GGBS content, and the UCS of the specimens treated with 20% GGBS is 36.4% higher than those treated with 10% cement for all the curing periods.
- The addition of dolomite speeds up the geopolymerization process and provides extra nucleation sites to form C-S-H and C-A-S-H precipitate. An improvement in strength was observed with the inclusion of dolomite, showing the potential of dolomite replacement in GGBS up to 4% for all the NH:NS mass ratios.
- NaOH helps in leaching alumina and silica in the amorphous phase of kaolin clay and GGBS, and Na_2SiO_3 acts as a binding material. The optimum NH:NS ratio for the S:D ratio of 20:0 was 50:50, and for the S:D ratio of 18:2, 16:4, and 14:6 was found to be 25:75.
- The strength of kaolin clay stabilized with S:D ratio of 16:4 and NH:NS ratio of 25:75 was found to be 26.3%, 32.59%, and 38.35% higher than the kaolin clay stabilized with 20% cement for 7, 14, and 28 days curing period respectively. The UCS values were notably enhanced by 70.82%, 67.29%, and 55.94% with the increase in D content in S:D ratio for water content of 0.8LL, 1LL, and 2LL, respectively, and the optimum ratio of S:D ratio was found to be 16:4.

- For a particular NaOH concentration of 8M and NaOH: Na_2SiO_3 ratio of 25:75, the optimum L/P ratio of 1 provided the highest UCS value, and the further increase in L/P ratio resulted in the decrease of UCS value.
- Overall, a NaOH concentration of 8M, NaOH: Na_2SiO_3 ratio of 25:75, S:D ratio of 16:4 (precursor/ kaolin clay = 20%), and L/P ratio of 1 were found to be the optimum mix with UCS value of 2.75 MPa, 1.47 MPa, and 1.21 MPa for water content of 0.8LL, 1LL, and 2LL, respectively indicating that geopolymer process can significantly modify the properties of soft soil.
- At optimum NH:NS mass ratio, the static triaxial stress-strain response of the geopolymer-treated kaolin clay changes from strain-softening to strain-hardening with an increase in dolomite content. Also, the peak stress ratio decreased with an increase in confining pressure.
- The addition of D showed an upgradation in G and degradation in λ up to an optimum S:D ratio of 16:4. G/G_{max} with respect to the shear strain of the S:D ratio of 16:4 was the lowest, and the maximum strain accumulation was 0.73% under long-term cyclic loading. The strain of geopolymer-stabilized kaolin clay increases gradually with the number of loading cycles. Minor degradation in strain was found for CSR up to 1. A further increase in CSR resulted in larger strain accumulation, inducing softening behavior and more degradation in the cementation bond with increased loading cycles. G decreases, and λ increases with an increase in CSR.
- With the elapse of curing time, the pores of the geopolymer-stabilized kaolin clay would be filled with C-(A)-S-H gels by the hydration process. Thus, there is a significant improvement in the cyclic behavior with the increase in the curing time. The proposed Martin-Davidenkov model to predict G of

geopolymer stabilized kaolin clay for long-term cyclic loading fitted well with the experimental results.

- The FTIR spectrum and SEM micrographs revealed amorphous geopolymer gel network formation. NH:NS mass ratio of 25:75 developed a very dense microstructure by binding the soil particles and filling pores, thereby contributing to higher strength development.
- The TCLP test results revealed that the leached heavy metal concentration of GGBS and dolomite was under the USEPA limit. Also, in the GGBS-dolomite-based geopolymer stabilized soil, the toxic heavy metals and hazardous elements were immobilized and were under the USEPA limits.

8.3 Model tests on single GPSC improved soft soil under static and cyclic loading.

- The inclusion of a geopolymer-stabilized soil column (GPSC) in soft soil ground increased the bearing capacity and the stiffness of the improved composite ground. The bearing improvement ratio for end-bearing GPSC improved ground increased with the area replacement ratio and was 2.28, 3.74, 7.67, and 9.24 for A_r of 9%, 16%, 25%, and 36%, respectively.
- The maximum increase of 104.98% in the bearing capacity ratio was observed, with an increase in A_r from 16% to 25%.
- The bearing improvement ratio was 1.49, 1.82, 2.82, and 7.67 for l/h ratios of 0.35, 0.5, 0.75, and 1, respectively. A significant change in the bearing improvement ratio was observed in end-bearing GPSC-improved soft soil compared to floating GPSC-improved soft soil.

- A decrease in accumulated settlement under cyclic loading was observed as the area replacement ratio increased and CSR decreased. The impact of cyclic loading was higher at a lower area replacement ratio.
- The increase in A_r from 16% to 25% reduced the settlement by 59.11% under a static load of 100.65 kPa, whereas the settlement was reduced by 73.11% under a cyclic load of 100.65 kPa.
- A CSR of 0.5 was found to be the threshold CSR value, and the settlement was more profound with a further increase in CSR.
- The SCR increases gradually with an increase in A_r and l/h ratio under static loading. Under cyclic loading, the SCR increased with increased A_r and cyclic loading amplitude.
- The excess pore water pressure development in the surrounding soil was reduced due to the inclusion of GPSC. Also, the development of excess pore water pressure reduced with an increase in A_r and l/h under static loading, and reduced with an increase in A_r and CSR under cyclic loading.

8.4 Static and cyclic model tests on GPSC$_s$ supported embankment rested on the soft soil.

- Both end-bearing and floating GPSCs enhanced the q_{ult} and stiffness of the composite soft ground. In the end-bearing GPSCs case, the q_{ult} improved by 246.92% to 418.8%, whereas the installation of floating GPSCs increased the q_{ult} by 126.9% to 181.64%. Hence, end-bearing GPSCs are more effective in reducing the settlement of the soft ground under static loading.
- The end-bearing GPSCs failed due to shearing and outward bending, while for the floating GPSCs, punching failure with outward movement of GPSCs was observed under static and cyclic loading.

- For the same level of vertical stress under static and cyclic loading, both end-bearing and floating GPSCs improved ground showed 1.11 to 1.68 times higher settlement under cyclic loading of 10,000 cycles compared to static loading.
- All the end-bearing and floating GPSCs stabilized embankment models showed less settlement under cyclic loading of 10,000 cycles compared to a total failure settlement of 50 mm under static loading.
- The end-bearing GPSCs are comparatively more effective than floating GPSCs in reducing the settlement during static and cyclic loading. In the case of floating GPSCs, a higher area replacement ratio is required for better load bearing under static and cyclic loading.
- With an increase in area replacement ratio and *l/h* ratio, higher vertical stresses are transferred to the column, resulting in lower stress on the surrounding soil. The stress concentration ratio greatly influences the settlement behavior of the composite ground. The increase in the A_r and *l/h* ratio results in increases in the SCR value under both static and cyclic loading.
- The inclusion of GPSCs in the soft soil embankment model effectively reduces the excess pore water pressure. Also, excess pore water pressure development reduces with an increase in the A_r and *l/h* ratio under static and cyclic loading.

8.5 Carbon footprint analysis and cost estimation

- The carbon footprint study revealed that the geopolymer binder has the potential to reduce CO_2 emissions by 33.73% when compared to the conventional OPC binder.
- The cost of the geopolymer mainly depends on the NaOH and Na_2SiO_3 due to its higher cost. In comparison to OPC, geopolymer was also a little less expensive.

- Although the alkali activators still have some effect on the environment, it is significantly less than that of the energy-intensive cement manufacture when it comes to the total carbon footprint.

8.6 Plaxis 3D validation

- The predictions made by the finite element analyses compare well with the laboratory modeled soft ground improved with groups of end-bearing and floating GPSCs subjected to static loading.
- Both finite element predictions and laboratory model test results show that end-bearing columns give higher failure stress at lower settlement values compared to floating columns.

8.7 Limitations and future scope

- In this study, strength analysis was performed for up to 28 days of curing period. Long-term mechanical and microstructural analysis should be done to identify the geopolymer reaction mechanism.
- Along with laboratory tests, it is recommended to perform field tests to determine the efficacy of geopolymer stabilization of soft soil in the DSM technique. The effect of parameters such as binder injection speed, rate of rotation of mixing blades during column installation, and area replacement ratio (area of columns to the area of the ground) needs to be studied.
- A consolidation study is recommended to be performed to study the consolidation behavior and the impact of the geopolymerization process on related test parameters.
- Both drained and undrained 3D finite element analysis static and dynamic conditions may be investigated.