CHAPTER- IX

CONCLUSIONS AND FUTURE SCOPE

9.1 SUMMARY AND CONCLUSIONS

In this study, a detailed investigation has been conducted on the potential use of fly ash and Nano-SiO_2 as a feasible stabilizing agent to enhance the strength characteristics of high plasticity clayey soil. The primary objective of the study was to use the stabilized clayey soil as a subgrade material for the flexible pavement. In order to accomplish this main objective, the clay soil treated with fly ash and nano silica was subjected to various laboratory tests, including physical, chemical, geotechnical, static strength and dynamic strength characterization tests. The shear strength characteristics and failure behaviour of the treated and untreated soil under consideration were determined by a series of static triaxial experiments carried out in the laboratory. A series of cyclic triaxial and bender element tests were conducted in the laboratory to ascertain the dynamic properties and small-strain shear modulus characteristics of the parent soil, soil treated nano silica, and soil treated with a combination of fly ash and nano silica. The normalised shear modulus of the stabilized materials has been evaluated by incorporation of the shear modulus from the cyclic triaxial test with the small-strain shear modulus from the bender element test. The suitability of the treated soil in the application of pavement engineering has also been analyzed. In addition, the carbon footprint and cost analysis of the Nano-SiO_2 and fly ash-treated clay soil were compared with the traditional stabilizing additives. The details of the materials, apparatus used, methodology, and detailed testing program have been discussed in the previous chapters. By taking into consideration of the results discussed in the previous chapters, the primary conclusions of the study can be summarized as follows.

9.1.1 Chemical Analysis Test Results

- The fly ash exhibits a composition of glassy, spherical-sized particles along with a few coarse particles with irregular shapes. The light weight of fly ash is attributed to the spherical particles, which are commonly referred to as cenospheres and plerospheres.
- Nano Silica exhibits a micro-sized cauliflower like porous structure. The soil consists flaky, angular, thin chipped particles and large number of pore spaces within the particles. Whereas the treated soil has a dense soil matrix.
- The fly ash has a variety of elemental compositions, including Si, Al, Fe, K, Mg, Na, and Ca. The primary chemical elements of fly ash are Si, Al, and Fe.
- Nano-SiO_2 has a variety of elemental compositions such as Si, Ca, Na, Ti, and Fe, with Si as the major constituents of the element.
- The soil consists of various elemental compositions including O, Na, Mg, Al, Si, S, K, Ca, and Fe, with O, Si, Al, and Fe being the primary constituents.
- The sum of SiO_2 (60.46%), Fe_2O_3 (5.54%), and Al_2O_3 (29.36%) of fly ash contributes for more than 70% of the chemical elements. As a result, the fly ash used in the present study was classified as class F type.
- The main constituents of soil+1% NS and soil+1% NS+20% FA treated specimens are silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3).
- Several reactions occur when binders such as fly ash and Nano-SiO_2 are blended with soil in the presence of water. The cementitious and pozzolanic

gels known as CSH and CASH are produced when these reactions lead to the dissociation of the chemical element CaO in the binders. These cementitious gels can create a stronger soil matrix by binding soil particles together.

9.1.2 Geotechnical Characterization Test Results

- The fly contains a larger amount of sand (76.02%), followed by silt (23.52%) and clay (0.44%). The fly ash classified as silty sand (SM). The soil has 1.3% sand, 66.67% silt, and 32% clay. The clay soil categorised as clay with high plasticity (CH).
- The LL and PL of the parent clay soil decreased from 53.4% to 43.4% and 27.84% to 22.4%, respectively, upon the inclusion of 1% of Nano-SiO_2 and 10-30% of fly ash. SL was found to marginally increase upon the combination of the fly ash and the optimised Nano-SiO_2 treated soil.
- As the amount of Nano-SiO_2 in the treated soil increased from 0.5% to 7%, the OMC increased from 21.5% to 34% and MDD reduced from 15.4 kN/m^3 to 12.6 kN/m^3 with the rise in Nano-SiO_2 content. The compaction characteristics of the optimized Nano-SiO_2 and different variation of fly ash to the clayey soil indicated that MDD decreased and that the OMC had only marginally increased to 20% fly ash before decreasing.
- The permeability characteristics of soil, soil+1% NS, and soil+1% NS+20% FA are found to be 4.92×10^{-6} cm/sec, 4.12×10^{-6} cm/sec, and 3.5×10^{-5} cm/sec respectively.
- The compression index values of soil, soil+1% NS, and soil+1% NS+20% FA are found to be 0.26, 0.22 and 0.15, respectively. The addition of fly ash and nano silica to the clayey soil caused a decrease in its plasticity characteristics

and the development of pozzolanic activity, which resulted in a decline in the compressibility value.

- The highest compressive strength was attained with the higher loads of Nano-SiO_2, the strength growth rate was marginally lower than the lower loads of Nano-SiO_2. A significant development in strength was achieved with 1% of Nano-SiO_2.
- The unsoaked CBR value of soil, soil+1% NS, and soil+1% NS+20% FA are 8.37, 14.13 and 15.47, while soaked CBR value of soil, soil+1% NS, and soil+1% NS+20% FA are 2.19, 3.67 and 6.12 respectively.

9.1.3 Shear Strength Characteristics

- The shear strength parameters of the treated soil raised with the rise in Nano-SiO_2 and fly ash dosages.
- The shear strength was enhanced to approximately 232%, 295%, and 214% at 28 days of curing with the addition of 1% Nano-SiO_2 and different fly ash contents (10%, 20%, and 30%), respectively. The highest shear strength was obtained with 1% Nano-SiO_2 and 20% fly ash.
- The cementitious and pozzolanic reactions with the presence of siliceous or aluminous materials in the soil matrix or binding agent result in the development of calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gel, which results in the strength growth rate of the specimens induced by the addition of fly ash.

9.1.4 Dynamic Shear Modulus and Damping Characteristics

- The shear modulus of the untreated soil dropped from 4.72 to 0.88 MPa, with the rise in number of cycles under varying γ from 0.6% to 3.0%. Further, G decreased from 5.01 to 0.98 MPa with varying γ from 0.6% to 3.0% at 28 days of curing.

- The shear modulus of soil treated with the optimal dosage of Nano-SiO_2 reduced from 5.59 to 0.98 MPa with the increment in the number of cycles at cyclic shear strain amplitudes ranging from 0.6% to 3.0%. Furthermore, after 28 days of curing, the shear modulus dropped from 8.8 to 1.27 MPa for γ varying from 0.6% to 3.0%.
- As the number of cycles at γ increased from 0.6% to 3.0%, the shear modulus of the optimal content of Nano-SiO_2 and fly ash treated soil reduced from 5.39 to 0.90 MPa. Additionally, after 28 days of curing, the shear modulus decreased from 11.38 to 1.33 MPa for γ ranging from 0.6% to 3.0%.
- The damping ratio of the untreated soil increased from 18.16% to 28.32%, with the rise in the number of cycles at γ ranging from 0.6% to 3.0%. The damping ratio increased from 17.45% to 26% at γ, varying from 0.6% to 3.0% at 28 days of curing age.
- The damping ratio of the soil treated with the optimal dosage of Nano-SiO_2 increased from 17.65% to 27.23% as the cyclic shear strain increased from low strain to high strain. At 28 days of curing age, the damping ratio improved from 16.54% to 25.56% under γ ranging from 0.6% to 3.0%.
- The optimal dosage of Nano-SiO_2 and fly ash treated soil's damping ratio increased from 16.34% to 26.67%, with the increment in the number of cycles for γ ranging from low strain to high strain. At cyclic shear strain from 0.6% to 3.0% and 28 days of curing, the damping ratio increased from 15.67% to 24.89%.

- The stiffness degradation index falls rapidly for the first 20-40 cycles, then becomes almost constant or insignificant. Greater stiffness degradation magnitude was indicated by lower cycle degradation index values.

9.1.5 Small Strain Shear Modulus and Correlation Studies

- The specimen's small-strain shear stiffness (G_{max}) increased with the inclusion of fly ash and 1% Nano-SiO_2 at various confinement pressures and curing times.
- The maximum values of shear wave velocity (V_s) and thereby small-strain shear modulus (G_{max}) of soil matrix was achieved with 1% of Nano-SiO_2 and 20% of fly ash.
- A strong relationship was developed between small-strain shear modulus (G_{max}) and shear strength (τ) with the inclusion of fly ash and 1% Nano-SiO_2 to CH type soils.
- The correlations between normalized shear modulus ratio (G/G_{max}) with cyclic shear strain (γ) for the clay soil, optimized Nano-SiO_2 treated soil, and optimized Nano-SiO_2 and fly ash treated soil were best fitted to a hyperbolic model.
- The correlations between damping ratio (D) and cyclic shear strain (γ) for the present clay soil, optimal content of Nano-SiO_2 treated soil, and optimal content Nano-SiO_2 and fly ash treated soil were best fitted to a hyperbolic model. The developed G/G_{max} and damping ratio curves fit the database well.

9.1.6 Performance of Untreated and Treated Soil as a Pavement Material

- The total thickness of the pavement with clay soil was found to be 1.025 m for a soaked CBR value of 2.19 %.

- The total thickness of the pavement with Soil+1%NS+20%FA was found to be 775 mm and 700 mm, for a soaked CBR value of 6.12 % and 15.02 % with a curing period of 0 day and 28 days respectively. The inclusion of fly ash and Nano-SiO_2 resulted in a total pavement thickness reduction of 24.39% and 31.70%, respectively, with 0 day and 28 days curing time.

9.1.7 Carbon footprint and Cost analysis

- The utilization of 1% NS and 20% FA-treated clay soil can lower CO_2 emissions by approximately 88.02% and 82.21%, respectively, as compared to cement and lime-treated clay soil.
- The cost of a 1kg of fly ash applied at 20% by weight of soil mass was ₹1. It costs about ₹200 to stabilize 1 tonne of soil mass. The amount of Nano-SiO_2 used was 1% by weight of the soil mass, which was ₹675. It costs around ₹6,750 to stabilize 1 tonne of soil mass
- Although Nano-SiO_2 is more costly than lime and cement, this treatment method may be a good substitute since it may be used as an enhancing medium with cement to lower the amount of cement needed.
- Using fly ash as an additive to improve soil properties results in decreased or eliminated waste storage costs and less negative environmental effects, in addition to increasing soil strength properties.
- The main advantages of nanoparticles over cementitious additives are that they are inert, safe for the environment, and do not contaminate the soil.

9.2 LIMITATIONS AND SCOPE FOR FUTURE WORK

9.2.1 Limitations

The present study is limited to the static and dynamic strength characteristics of the treated and untreated clay soil for a shorter period of time, which need to be explored for long term strength and durability performance. Moreover, this study involves small size reconstituted cylindrical specimen that should be investigated under large scale model testing in the laboratory as well as in the field to make the study more realistic. This study is limited to ash collected from a single thermal power plant, hence similar type of studies on the ash produced at other thermal power plants may assist in the standard codal provisions, which will ease the application of fly ash in the stabilization of clayey soil. FA is considered a waste that needs to be handled carefully since it contains heavy metals that could harm the environment. From the experimental test results, it can be noticed that Nano-SiO_2 and other additives like fly ash can significantly enhance the strength and dynamic properties of the CH-type soils. Therefore, the composite mix can be recommended for small-scale geotechnical engineering purposes. The cost of Nano-SiO_2 is comparatively higher than the traditional additives. As a result, to establish itself as a competent stabilizer, a cost-effective variety must be synthesized.

9.2.2 Scope for Future Work

The limitations addressed in the above section open a wide scope for future work. The future scope of the present study has been discussed below:

- The present study focuses only on the influence of Nano-SiO_2 and fly ash on the strength performance of clayey soil. The application of other nano materials and industrial wastes can be further extended for the strength improvement of clayey soil under static and dynamic loading condition.

- The whole experimental investigations were carried out with a maximum size of a cylindrical sample having 50 mm diameter and 100 mm height. Therefore, large scale model testing is required in order to make the study more realistic.
- The complete testing of triaxial specimen was done either under small-strain or large strain condition. Hence, for better prediction of the modulus reduction curve for the treated and untreated soil, the performance of these samples must be investigated under medium strain range using Resonant column apparatus also.
- The treated and untreated soil behaviour has been examined only for the dry and saturated condition that need to be explored under the unsaturated condition because any of this situation can be encountered in the field depending upon the weather conditions.
- The long-term strength and durability performance of the treated and untreated soil can be studied.