ABSTRACT

In fast-growing economies like India, there is a significant demand for large-scale infrastructure projects. The Government of India (GOI) has initiated extensive plans to establish bullet trains, or high-speed rail (HSR) routes, that connect important cities and regions. These initiatives are essential for accelerating the nation's economic growth and development. Furthermore, GOI has started Bharatmala Pariyojana as one of the most extensive road infrastructure development programs, aiming to construct and upgrade about 34,800 km of National Highway. The project includes the development of economic corridors, inter-corridors, feeder routes, coastal and port connectivity roads, and border roads to improve connectivity and facilitate freight movement. Therefore, there is a requirement to construct more embankments, even over soft soil, to satisfy the demand for rapid construction of railways, highways, and expressways in India.

The construction of an embankment over soft soil requires implementing suitable ground improvement techniques to enhance the bearing capacity and stability of the ground beneath the embankment. Among numerous ground improvement techniques, deep soil mixing (DSM) has proven to improve the bearing capacity and reduce the settlement of soft or very soft soils. The deep soil mixing 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.

Traditionally, Ordinary Portland Cement (OPC), lime, or a mix of OPC and lime in either dry powder or slurry form, has been used as a binder in the DSM method.

However, a considerable portion of natural resources and energy are exploited/utilized during cement production, releasing about 8-10% of the anthropogenic CO_2 into the atmosphere. 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.

Moreover, moving vehicles cause cyclic loading on embankments that support roads, highways, trains, and other transportation infrastructure. The repetitive vehicle movement produces cyclic stress and strain variation in the subgrade, which can lead to fatigue and deformation over time. However, proper guidelines and specifications regarding the performance of deep soil mix columns under cyclic loads are not available in the literature.

Considering these two objectives, this study presents a novel approach to addressing two important challenges in environmental sustainability and geotechnical engineering. An attempt has been made to study the efficacy of ground granulated blast furnace slag (S) and dolomite (D)-based geopolymer with sodium hydroxide (NH) and sodium silicate (NS) as an alkali activator to stabilize soft soil for DSM technique. The optimum mix proportion of geopolymer was obtained by analyzing the various parameters that affect the strength improvement of geopolymer stabilized soil, such as the effect of precursor content, GGBS-dolomite ratio, NH:NS ratio, water content of kaolin clay, alkali activator/precursor (L/P) ratio and curing time using unconfined compressive strength (UCS) tests and consolidated undrained static and cyclic triaxial tests, and the microstructural analysis was done using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) test. The optimum mix was determined to consist of an 8M NaOH concentration, a 25:75 NH:NS ratio, a 16:4 S:D ratio (precursor/kaolin clay = 20%), and a 1 L/P ratio. Furthermore, the findings of the toxicity characteristic leaching procedure (TCLP) test showed that the concentration of leached heavy metals in dolomite, GGBS, and GGBS-dolomite-based geopolymer was below the USEPA (U.S. Environmental Protection Agency) limit.

A set of 1-g physical model tests have been conducted to examine the behavior of a single geopolymer-stabilized soil column (GPSC) as a DSM column in soft soil ground treatment under static and cyclic loading. Moreover, a series of tests have been carried out on the reduced-scale designed embankment model resting on soft soil (c_{us} = 5-5.5 kPa) reinforced with end-bearing and floating GPSCs with different area replacement ratios (A_r) to analyze the vertical stress-settlement behavior and failure pattern of the improved ground under static and cyclic loading. During the test, measurements were taken for surface settlement, excess pore water pressure, and the stresses on both the GPSC and the surrounding soil.

The main findings indicate that both end-bearing and floating GPSCs enhanced the ultimate bearing capacity and stiffness of the composite soft ground. End-bearing GPSCs were more effective than floating GPSCs at the same A_r under static and cyclic loading. For installing floating GPSCs, a higher area replacement ratio is required for better load bearing under static and cyclic loading. In the end-bearing case, GPSC failed due to shearing and bending, whereas in the floating columns, punching with slight outward displacement and horizontal cracks in GPSCs was observed. A general expression of N_c was developed for GPSCs improved soil under the embankment with variation in A_r and length of column (*l/h)* ratio, which was valid for A_r ranging between 12.7% to 21.2%, the *l/h* ratio between 0.75 to 1 for soil with undrained shear strength of 5-5.5 kPa. Under the same vertical stress conditions, the ground improved with both end-bearing and floating GPSCs exhibited 1.11 to 1.68 times greater settlement under 10,000 cycles of cyclic loading compared to static loading.

In addition, a life cycle assessment of geopolymer in comparison to OPC was performed, showing that geopolymer is a sustainable and eco-friendly construction material. A three-dimensional finite element analysis of embankment model tests on soft ground improved with soil-geopolymer deep mix columns under static loading has been conducted to validate the measured embankment model test results using PLAXIS 3D software.