CHAPTER- VIII

PERFORMANCE OF TREATED AND UNTREATED SOIL AS A PAVEMENT MATERIAL

8.1 INTRODUTION

Sustainable development has emerged as one of the most important global concerns since the Brundtland Report was released in 1987 and the Earth summits that followed in Rio de Janeiro (1992) and Johannesburg (2002). In recent times, civil engineering has been regarded as one of the least sustainable practices because construction activities that consumes the most energy and natural resources. In this case, recycling and reusing waste products have gradually gained importance. Furthermore, the concept of "green material" was also introduced in order to meet the performance requirements and advance the idea of sustainable development without negative environmental effects. The new non-traditional materials ought to be affordable, practical, safe, and environmentally friendly (Cuddihy et al. 2005). The idea of sustainable development has been popular in the twenty-first century, leading to the development of a range of unconventional materials for soil improvement in recent decades instead of more conventional materials (Chong et al. 2009; Liu et al. 2020). The contribution of nanotechnology in the field of civil engineering and construction has been increasingly helpful in enhancing material properties. This technology has the ability to lessen the energy and environmental impact of structures, increase safety, and lower the cost of civil infrastructure (Hanus and Harris 2013). The construction material cost is one of the most important considerations for field applications, along with its impact on the environment. The utilization of Nano-SiO_2 and fly ash-treated clay soil for various civil engineering applications has been addressed in this chapter. Furthermore, the carbon footprint and cost analysis of Nano-SiO_2 and fly ash-treated clay soil were compared with the traditional stabilizing additives (lime and cement).

8.2 APPLICATION AS PAVEMENT MATERIAL

According to earlier research, there are several benefits to using nanomaterials directly in soil stabilization that can offer a number of benefits over conventional treatment techniques. Water seepage and thermally induced crack failures are two examples of road failures that could be controlled by nanomaterials. The hydrophobic behaviour of the treated building materials reduces the damage from water seepage by covering the entire road from top to bottom in a waterproof layer. There are several options to use readily available local materials that would not usually meet performance criteria in their natural state when using nanoparticles as a preventive engineering solution. This advances the delivery of road transport infrastructure projects that are secure, long-lasting, cost-effective, and environmentally friendly. It also supports sustainable civil engineering practices (Ugwu et al. 2013). Fig. 8.1 depicts the typical cross-section of a road embankment with the present clay soil with a soaked CBR value of 2.19 %. The total thickness of the pavement was designed as per IRC SP 72 (2015). The total thickness of the pavement with clay soil was 1.025 m. Fig. 8.2 depicts the typical cross-section of a road embankment with Soil+1%NS+20%FA with a soaked CBR value of 6.12 %. Fig. 8.3 depicts the typical cross-section of a road embankment with Soil+1%NS+20%FA with 28 days soaked CBR value of 15.02 %. The total thickness of the pavement with Soil+1%NS+20%FA was 775 mm and 700 mm, with a curing period of 0 day and 28 days. Table 8.1 presents the flexible pavement thickness of untreated and treated soil. 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. The addition of slag, Nano-SiO_2, and lime to the silt subgrade resulted in enhanced cation exchange, pozzolanic reaction, and hydration of the soil particles. As a result, the soil's porosity was reduced, and its intermolecular force increased. After that, it was applied to maintain the silt subgrade to meet the need for highway construction (Wang et al. 2021). When Nano-SiO_2 was employed for pre-grouting, particularly in the sandy soil grouting approach, because of its adjustable setting time, low permeability, and non-toxicity to the environment, it has remarkable potential and practical field applications as a grouting strengthening material in coastal locations (Cheng et al. 2022). The combination of Nano-SiO_2 and fly ash acts as grouting materials that can minimize the development of pore water pressure caused by rainwater infiltration on slopes and prevent landslides (Gao et al. 2020). The alternate design approaches and performance evaluation methods for nano silica and fly ash-based soil stabilization can be used in ranking distance analysis and ranking measure techniques for assessing stabilization performance. This method has been adapted to analyze how different stabilization compositions (nano-silica, fly ash, and their combinations) affect unconfined compressive strength relative to field SPT-N values (Güllü et al. 2019; Güllü et al. 2018). Güllü and Fedakar 2018 reported a study to identify the effectively usable dosages of sewage sludge ash (SSA) for highway construction applications by using factorial experimental approach and effect size estimation. This supports the identification of the most effective mix from laboratory and field performance perspectives. These methods provide a structured and quantifiable framework to assess the applicability and reliability of stabilization techniques across varying soil conditions, aiding in better engineering decisions and enhancing real-world implementation.

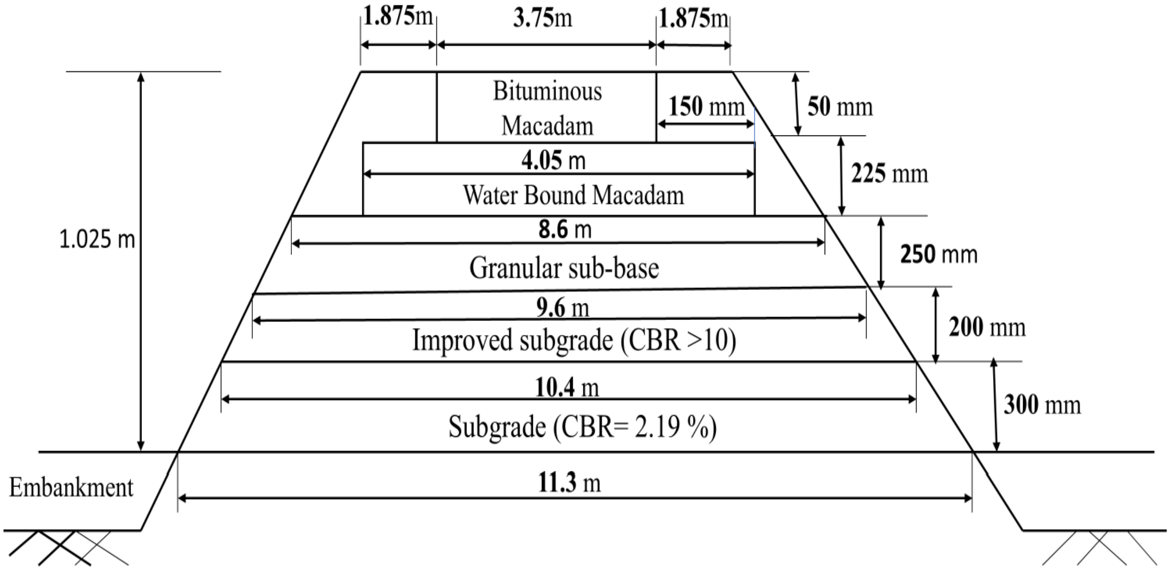

Fig. 8.1. A typical cross section of pavement of clay soil with soaked CBR.

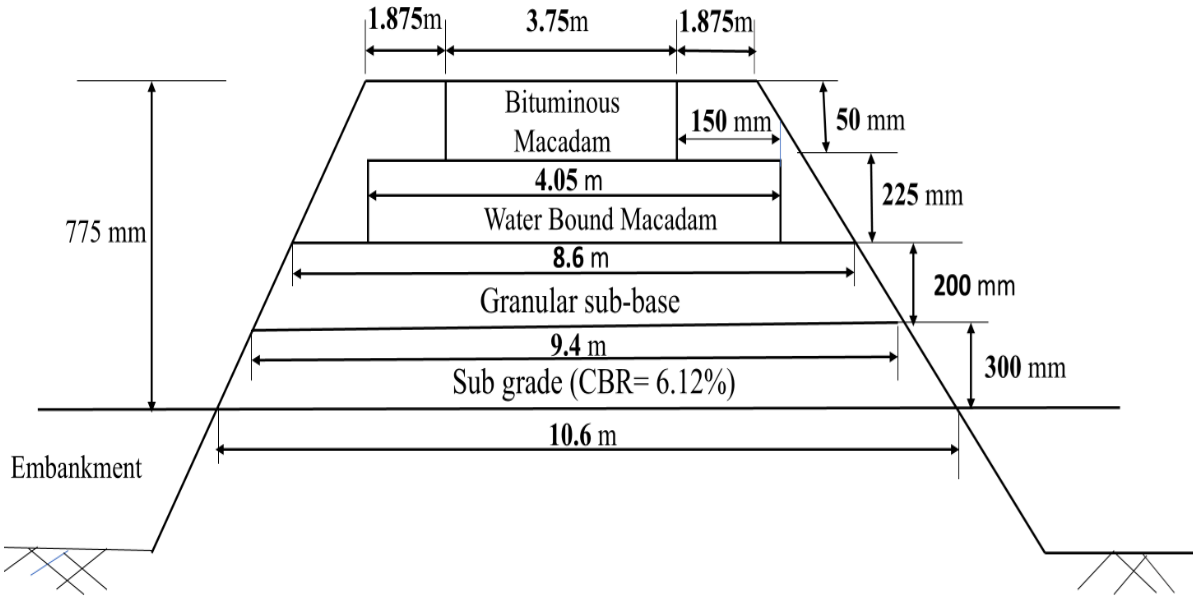

Fig. 8.2. A typical cross section of pavement of Soil+1% NS+20% FA with soaked CBR.

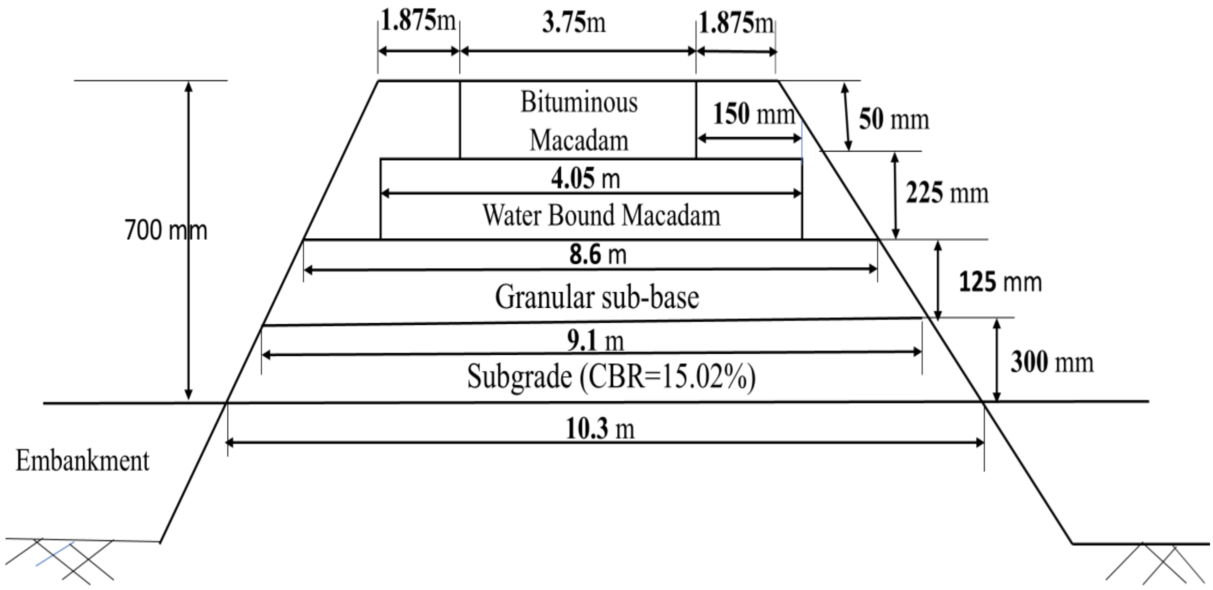

Fig. 8.3. A typical cross section of pavement of Soil+1%NS+20%FA with 28 days of soaked CBR.

Typical example of calculation of pavement thickness:

The total thickness of the pavement was designed as per IRC SP 72 (2015) (Page No. 22, Fig. No. 4: Pavement Design Catalogues for Gravel/Granular Bases and Sub-bases) used for flexible pavement thickness for rural road.

For CBR = 6.16 %. The Traffic category for T9 (1,500,000 to 2,000,000) Equivalent single axle load (ESAL).

1. The thickness for subgrade for low volume road is 300 mm as per IRC SP 72 (2015) section 4.1 and sub section 4.1.1.
2. Roadway width: 7.5 m (IRC: SP: 20-2002, Page No: 30, Section:2.6.3)
3. Carriageway width: 3.75 m (IRC: SP: 20-2002, Page No: 30, Section:2.6.4)
4. Slope of Embankment (H: V): 2:1 (IRC: SP: 20-2002, Page No: 34, Section:2.6.6, Table 2.7)

5. A minimum 150 mm thick base course should be provided in the flexible pavement designs for ESAL applications from 1,00,000 to 10,00,000 (IRC SP 72 (2015), Page No:32, Sl No. (v)).

   Width of Water Bound Macadam: 7.5+(2×0.550) =8.6 m

   Width of Granular sub-base: 7.5+ (2×0.950) =9.4 m

   Width of sub grade: 7.5+(2×1.550) =10.6 m

Table 8.1. Flexible pavement thickness of untreated and treated soil.

Flexible Pavement layers	Clay soil with soaked CBR (2.19%)		Clay soil+1%NS+20%FA with soaked CBR (6.12%)		Clay soil+1%NS+20%FA with soaked CBR (15.02%)	
	Thickness(mm)	Width(m)	Thickness(mm)	Width(m)	Thickness(mm)	Width(m)
Subgrade	300	11.3	300	10.6	300	10.3
Improve Subgrade (CBR>10)	200	10.4	×	×	×	×
Granular sub-base	250	9.6	200	9.4	125	9.1
Water Bound Macadam	225	8.6	225	8.6	225	8.6
Bituminous Macadam	50	4.05	50	4.05	50	4.05

8.3 CARBON FOOTPRINT AND COST ANALYSIS

One of the most alarming issues confronting the world today is the increasing agglomeration of greenhouse gases (GHGs) and global warming. Each year, the average temperature is rising, and the effects of global warming are getting worse (Labaran et al. 2022). More than 80% of global warming is caused by CO_2, the primary component of greenhouse gases (Fang et al. 2023). The rise in CO_2 has been recognized as the tipping point at which the effects of climate change become hazardous. The effects of these acts will be widespread, resulting in public health issues, unpredictable agricultural production, and weather disruptions (Labaran et al. 2022). The carbon footprint is the estimation of the total quantity of CO_2 emissions, either directly or indirectly, caused by an activity or accumulated over the course of a product's life cycles, which is measured in tonnes of CO_2 emissions annually and represented in equivalent CO_2e (Wiedmann and Barrett 2011; Gao et al. 2014). Using the relevant carbon emission coefficient (EC), the CO_2 emissions are computed. The EC represents the total amount of carbon emissions associated with fuel and processes from cradle to gate (Hammond et al. 2011). Table 8.2 depicts the carbon emission coefficient (EC) of materials from past researchers. The usage of cement and lime poses a significant environmental risk in terms of CO_2 emissions due to their higher EC. Fig. 8.4 depicts the comparison of CO_2 emission of Nano-SiO_2 and fly ash with the traditional stabilizing additives such as lime and cement for high plastic clay. The CO_2 emission of optimum dosages required for 4% of lime to the CH soil was 30.4 kg CO_2 -e/tonne. The CO_2 emission of optimum dosages required for 5% of cement to the CH soil was 45.15 kg CO_2 -e/tonne. The CO_2 emission of optimum dosages required for 20% of fly ash to the CH soil was 5.4 kg CO_2 -e/tonne. The total CO_2 emission of optimum dosages of 1% Nano SiO_2 and 20% of fly ash to the CH soil was 5.41 kg

CO_2 -e/tonne. The production of cement has a substantial negative impact on the environment due to its high CO_2 emissions compared to other materials (Shao et al. 2023). The utilization of only 20% FA-treated clay soil also lower CO_2 emissions by approximately 88.04% and 82.23%, respectively, as compared to cement and lime-treated clay soil. 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 energy required for fly ash's milling, grinding, drying, and transportation accounts for minimal CO_2 emissions (Adamu et al. 2018). Furthermore, the inclusion of Nano-SiO_2 in clay soil has minimal effect on greenhouse CO_2 emissions. This is due to the fact that the Nano-SiO_2 itself emits minimal CO_2 because it is mostly made by dissolving olivine, which emits zero CO_2 (Adamu et al. 2018).

The cost is a key consideration when choosing the construction materials for any project. It has been found that, despite the relatively expensive unit cost of nanoparticles, just a very little quantity of nanomaterials is sufficient to significantly improve the soil's strength (Krishnan and Shukla 2019). Cement is one of the most often used traditional binders for ground improvement. The conventional cement manufacturing industry is an energy-intensive and severely polluting enterprise that consumes much energy, water, and raw materials while emitting hazardous pollutants, including CO_2, SO_2, and NO_x, into the atmosphere (Van Oss and Padovani 2003; Thomas and Rangaswamy 2020; Shafigh et al. 2014). Another difficulty is that cement grout has a greater viscosity and larger particle size in suspension, requiring more pressure during grout injection into soil particles. This resulted in increased costs and more disruption to the environment. The colloidal silica is nano-scale particle sizes, allowing them to permeate the pore spaces of soil particles, eliminating the need for higher pressure infusion, avoiding damage to the already established surroundings, and becoming economically viable (Gallagher and Lin 2009). Indian fly ash is provided free of charge at the power plant; therefore, the only expenses associated with fly ash are those related to transportation, laying, and rolling. The cost of waste bagasse fly ash is \$2 per ton^{-1}, and the final product would come to about \$15 per ton^{-1} once transportation, chemicals, electricity, and other expenses are taken into account (Gupta and Sharma 2003). The costs of construction of roads using fly ash with flexible and rigid pavement for varying transportation distances were computed using cost data of various resources. It is clear that using fly ash to construct embankment roads results in cost savings of about 31%, which is comparable to the 30–40% savings range was reported by Indian construction companies (Naskar and Sharma 2024). Additionally, it has been observed that the granular sub-base (GSB) layer can achieve the highest percentage savings in construction costs when fly ash is used in place of all other materials. It was discovered that when transportation distance increases, the percentage of total cost savings from road construction falls because fly ash transportation costs rise. The impact of transportation distance on savings on construction costs indicates that fly ash-based road construction investments would only be financially viable for transportation distance lengths of less than 60 and 90 km, respectively, for flexible and rigid pavements (Kumar and Patil 2006).

Despite the fact that Nano-SiO_2 is more expensive than cement, this Nano-SiO_2 treatment approach could be a successful alternative, reducing the quantity of cement required by using it as an enhancing medium with cement. In comparison to cementitious additives, nanoparticles are primarily inert, environmentally beneficial, and harmless in the soil structure and will not produce soil contamination (Huang and

Wang 2016). Nanomaterials and nanotechnology equipment are now relatively expensive. This is primarily due to the unique technology and complex equipment for material synthesis and characterization. At the same time, it is projected that material costs will reduce over time as production technologies and equipment improve (Kannan and Sujatha 2022).

The cost comparison of different types of materials is depicted in Table 8.3. The material cost of lime, cement, fly ash, and Nano-SiO_2 was taken from the current market rates. The cost of a 1kg bag of cement applied at 5% by weight of soil mass was ₹8.9. It costs about ₹445 to stabilize 1 tonne of soil mass. The cost of a 1kg of lime applied at 4% by weight of soil mass was ₹6.5. It costs about ₹260 to stabilize 1 tonne of soil mass. 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 (Kannan and Sujatha 2022). Based on the availability of raw materials, the cost of materials might vary with different countries. 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. The main advantages of nanoparticles over cementitious additives are that they are inert, safe for the environment, and do not contaminate the soil (Huang and Wang 2016).

Table 8.2. CO_2 emission of different types of materials.

Material	CO_2 emission ($kg\ CO_2/kg$)	References for CO_2 Emission
Lime	0.76	(Hammond et al. 2011)
Cement	0.903	(Shao et al. 2023)
Fly Ash	0.027	(Adamu et al. 2018)
Nano-SiO_2	0.00084	(Adamu et al. 2018)

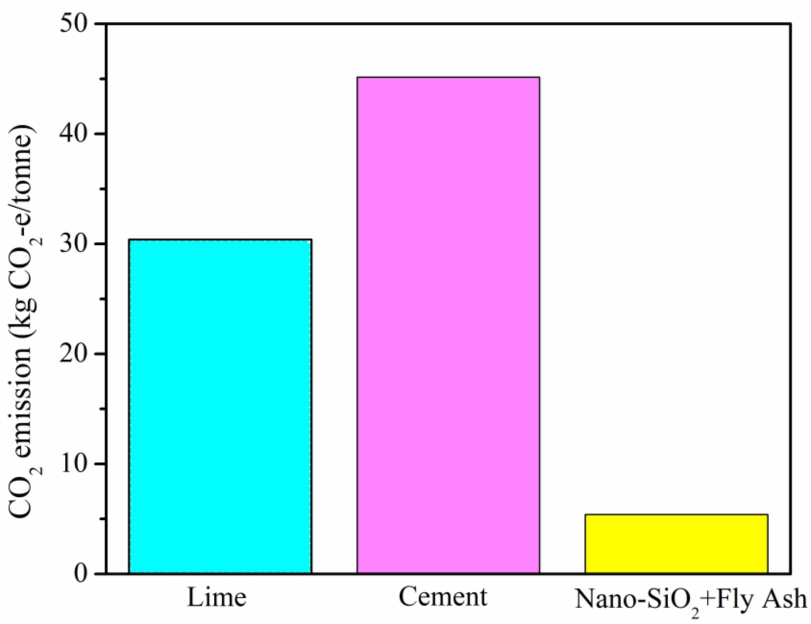

Fig. 8.4. Total CO_2 emission in lime, cement and 1% NS+20% FA treated clay soil per 1 t of stabilized material.

Table 8.3. Cost comparison of different types of materials.

Material	Cost per Kg (₹)	Dosage required for stabilization of high plastic clay	Mass required for stabilizing 1 tonne of soil	Cost required for stabilizing 1 tonne of soil
Lime	6.5	4	40	260
Cement	8.9	5	50	445
Fly ash	1	20	200	200
Nano-SiO_2	675	1	10	6750

8.4 ENVIRONMENTAL IMPACT ON HEALTH

Research on nanotechnology and the environment is focused on the impact of different nanomaterials on the environment. Several investigations have been prompted by uncertainty about the possible consequences of materials that exist on the nanoscale yet have attributes distinct from those when using the material on a micro- or macroscale (Karn et al. 2003). The possibility of exposure and the hazards that nanoparticles pose to human health determine the health risks associated with them. It is advisable for users of nanoparticles to reduce any possible dangers as early in the design process as possible rather than waiting until after manufacturing or customer use. According to past studies on the biological impacts of nanoparticles, engineered nanomaterials are unexpectedly hazardous to living organisms and have negative consequences on human health (Kreyling et al. 2006; Simkó and Mattsson 2010). It is important to note that not all nanoparticles have these harmful effects on health; rather, the toxicity of a given nanoparticle relies on a number of parameters, such as its size, composition, aggregation, crystallinity, surface functionalization, etc. Nanoparticles that penetrate the bloodstream are associated with heart problems, arteriosclerosis, blood clots, arrhythmias, and ultimately cardiac death. The translocation of diseases affecting these organs to other organs, like the liver, spleen, etc., can also occur. Exposure to specific nanoparticles has been associated with autoimmune illnesses, including rheumatoid arthritis, scleroderma, and systemic lupus erythematosus (Buzea et al. 2007). The Escin mixture protected the liver architecture in both male standard pellet diet (SPD) and high-fat diet (HFD)-fed mice and prevented the negative effects of oxidative stress (Küçükkurt et al. 2010; Ince et al. 2010; Avci 2013). It was discovered that crystalline silica was more hazardous than amorphous or colloidal silica particles when the pulmonary responses of rats to the two types of silica were examined (Warheit et al. 1995). 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 (Sengul et al. 2023).

8.5 SUMMARY

This chapter covered the utilization of Nano-SiO_2 and fly ash-treated clay soil for pavement applications. 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 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 energy required for fly ash's milling, grinding, drying, and transportation accounts for minimal CO_2 emissions. Furthermore, the inclusion of Nano-SiO_2 in clay soil has minimal effect on greenhouse CO_2 emissions. This is due to the fact that the Nano-SiO_2 itself emits minimal CO_2 because it is mostly made by dissolving olivine, which emits zero CO_2. The inclusion of fly ash and Nano-SiO_2 resulted in a total flexible pavement thickness reduction of 24.39% and 31.70%, respectively, with 0 day and 28 days curing time. The amorphous silica particles were less hazardous than crystalline silica polymorphs. The exposure to amorphous silica dust may cause milder small airway illness than exposure to crystalline silica dust. 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. In addition, the utilization of Nano-SiO_2 and fly ash-treated clayey soils in various civil engineering applications contributes towards sustainable development and a reduced carbon footprint.