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NANOSILICA AS AN AUXILIARY ADDITIVE IN BEHAVIOUR ENHANCEMENT OF WEAK SOIL SUBGRADE

NANOSILIKA KOT POMOŽNI DODATEK ZA IZBOLJŠANJE SLABE NOSILNOSTI TAL

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Nanosilica has enormous potential for applications in pavement engineering. The present study evaluated the contribution of nanosilica as a secondary additive towards enhancement of the compressive strength of soil for its application in the construction of roads and embankments with lime as the primary additive. Considering both short-term and long-term curing, unconfined compressive strength tests were performed on soil modified with lime and the soil-lime mixture with the optimal proportion of nanosilica for curing periods of (0, 7, 14, 28, 90 and 120) days. Though lime-modified soil had good strength characteristics, the present study revealed an elevated compressive strength with the addition of the optimum dosage of nanosilica (0.75 % by mass of soil) in a short-time span. Strength improvement of 11.05 times and 17.57 times that of the virgin soil were achieved in the case of lime-modified soil without and with nanosilica, respectively. Durability tests were conducted to evaluate the effective contribution of nanosilica to the strength retention of soil subgrade subjected to wetting-drying and freeze-thaw cycles. The increase in the California bearing ratio (CBR) of the lime-modified soil without and with nanosilica by 4.23 times and 5.36 times that of the virgin soil demonstrated the efficacy of nanosilica in the reduction of pavement thickness. The study thus provided an improved assessment of the use of nanosilica for strengthening weak soil subgrade.

Keywords: clayey soil, nanosilica, California bearing ratio, wetting-drying cycles

Material izdelan iz nanodelcev SiO_2, imenovan tudi nanosilika ima velik potencial za uporabo v gradbeništvu pri izdelavi cest in pločnikov. V tem članku avtorji predstavljajo študijo s katero so ocenili prispevek sekundarnega dodatka nanosilike k izboljšanju tlačne trdnosti glinene zemljine pri razvoju izdelave cest in nasipov, kjer se kot primarni dodatek uporablja apnenec. Upoštevajoč tako kratkotrajno kot tudi dolgotrajno obdelavo so avtorji izvedli preizkuse tlačne trdnosti stisnjenih preizkušancev iz dveh različnih zamljin in sicer: zemljine modificirane z apnencem ter mešanice zemljine z apnom in optimalno vsebnostjo silike. Sledilo je utrjevanje in njihovo staranje različno dolgo časa (0, 7, 14, 28, 90 in 120) dni. Čeprav je imela z apnom modificirana zemljina dokaj dobro tlačno trdnost je pričujoča študija pokazala, da je dodatek optimalne količine silike (0,75 *w*/%) še povečal njeno tlačno trdnost v krajšem časovnem obdobju. Izboljšanje tlačne trdnosti je bilo 17,75-kratno v primerjavi z osnovno nemodificirano zemljino in 11,5-kratno v primerjavi z zemljino, ki je bila modificirana samo z apnom. Avtorji so trajnostne teste, ki so se nanašali na efektivni prispevek nanosilike k ohranjanju trdnosti podlage izvajali v ciklusih vlaženje-sušenje in zamrzovanje-odtajevanje. Povečanje kalifornijskega merila nosilnosti podlage (CBR; angl.: California bearing ratio) je za 4,23-krat zmanjšalo debelino pločnika pri uporabi podlage iz zemljine modificirane z apnencem. Pri uporabi podlage iz zemljine, ki je bila še dodatno modificirana s siliko pa se je debelina pločnika zmanjšala kar za 5,36-krat v primerjavi z osnovno nemodificirano glineno zemljino. S to študijo so avtorji dokazali, da je uporaba dodatka nanosilike smiselna, če se zahteva izboljšanje nosilnosti glinenih zemljin, ki imajo slabo nosilnost.

Ključne besede: glinena zemljina, nanosilika, kalifornijsko merilo nosilnosti podlage ali temeljev, omakanje-sušenje

1 INTRODUCTION

Stabilising soft sub-grade soil is important for infrastructure development, especially in civil engineering projects involving road construction. Weak soil subgrade usually has a low California bearing ratio (CBR), which can cause instability, rutting, and pavement distress under traffic loading. In recent years, nanomaterials are finding numerous applications owing to their ability to alter the properties of materials from the atomic level to a larger scales.[1] The significant attributes of nanoparticles, which distinguish them from their macro-sized counterparts, arise from their size range of 1–100 nm and include unique qualities such as a large surface-area-to-volume ratio and increased chemical reactivity. Nanosilica is the most researched nanoparticle for cementing applications as it has been found to create better cementitious materials with exceptional performance.[2,3] It is sourced by processing various agricultural wastes such as rice, wheat and coffee husk, sugarcane bagasse, corn-cob ash, as well as naturally available quartz and silica sand. Nanosilica has drawn a lot of interest in the field of soil engineering due to its good strength enhancement capabilities applicable to all soil types, easy availability and early strength gain when compared to other nanomaterials.

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Nanosilica can be used both as a standalone additive and as a secondary additive. It was reported that nanosilica supplementation increased the compressive strength and compactability characteristics of soil while accelerating the pozzolanic reaction resulting in the formation of calcium-silicate-hydrate (CSH) gel.[4,5] Also, density of the soil increased due to addition of nanosilica as it fills its pores. Consequently, the permeability of the soil reduced considerably.[6] It was reported that an addition of lime to clayey soil resulted in a strength improvement of 8.9 times that of the virgin soil after 28 days of curing. On the other hand, for the same curing period, the strength improvement was observed to be 16.9 times that of the virgin soil with the addition of nanosilica to lime-modified soil.[7]

Sharo et al.[8] reported a reduction in the swell potential of the soil due to inclusion of a nanomaterial which is one of the most important requirements of soil subgrade. Changizi et al.[9] reported a CBR increment of 76 % due to an addition of 0.7 % of nanosilica. The addition of nanosilica enhanced the CBR value of silty sand and laterite soil by preventing water from entering the soil layers due to its hydrophobic nature. During hydrolysis, the chemical interactions between nanosilica and soil particles results in the formation of cementitious compounds that replace the adsorbed water layer on soil particles, thereby reducing the thickness of the double layer. The entire process induces hydrophobicity of the medium, and lowers the repulsive forces creating an environment for increased forces of attraction between soil particles.[10]

Studies relating to freeze-thaw (F–T) cycles in the soil suggest the movement of water associated with cryosuction forms ice lenses in the frozen zone. This was identified as one of the primary reasons for the deterioration of the subgrade as the thawing of these ice lenses dramatically reduces its mechanical performance.[11] Lime treatment proved to be effective for the strength retention of soil subjected to F-T. Similar observations were made when modified soil was subjected to wetting-drying (W-D).[12] Nanomaterials were also found to be effective in resisting W-D cycles.[13] Tebaldi et al.[14] reported that mechanical performance of lime-modified soil was appreciable as compared to untreated soil when subjected to F-T. Also, F-T resistance improved with a higher lime content and curing period.[15] Aksu et al.[16] reported that an addition of nanosilica was effective in preventing the strength loss of a specimen subjected to F-T in the case of clay, sand and clayey sand.

Previous researchers focused mostly on the strength and durability aspects of lime-modified soil. Though some of the existing studies addressed the strength improvement of lime-modified soil with nanosilica, its behaviour upon exposure to varying climatic conditions needs to be investigated. As most of the studies address the role of nanosilica as a standalone additive in improving the CBR of soil, its contribution to the CBR improvement as a secondary additive is to be explored further. Hence, the present study focused on both the strength and durability of lime-modified soil with an addition of nanosilica.

2 MATERIALS AND METHODS

2.1. Materials

Soil – Soil (**Figure 1a**) was excavated at a depth of 2 m from the ground level at a site in Tiruvallur district, Tamil Nadu, India. The soil had a specific gravity of 2.61.[17] With a liquid limit of 54 %,[18] shrinkage limit of 12.6 %,[19] plasticity index of 32.3 % and free swell index of 80 %,[20] the soil was classified as clay of high compressibility (CH) as per the IS 1498–1970 code.[21] The maximum dry unit weight (MDUW) and optimum moisture content (OMC) of the soil were 19.8 kN/m^3 and 18 %, respectively.[22]

Lime – Lime (**Figure 1b**), used as the primary activator in the study, was procured from M/s Shiyal Chemicals, Chennai, India. It was a white powder with a den-

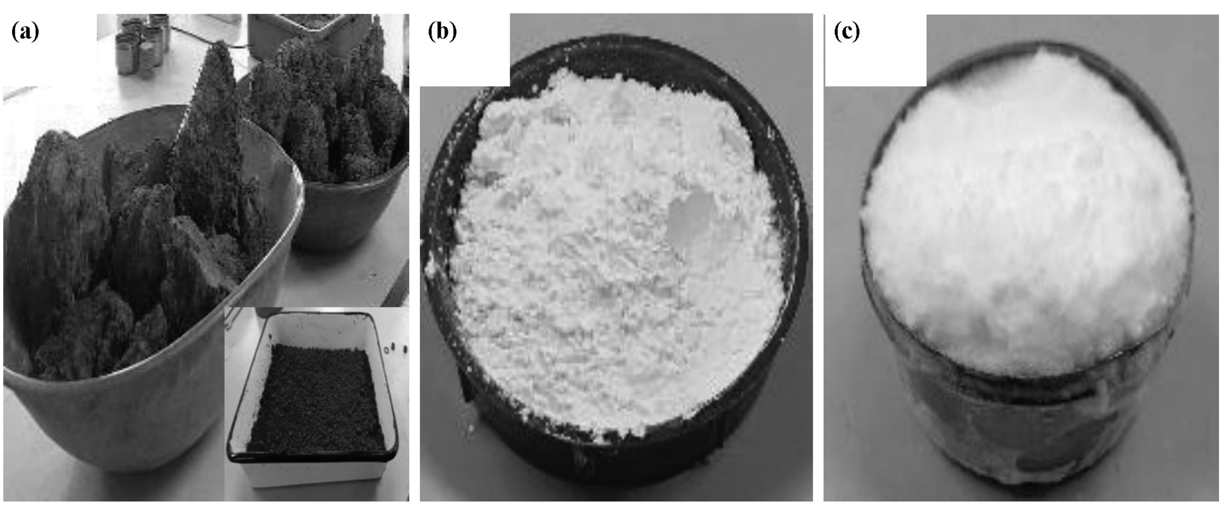

Figure 1: Materials used: a) soil sample, b) lime powder, c) nanosilica powder

sity of 2.24 g/cc. The initial lime content was set as 3 %, based on the Eades and Grim pH test following the procedure standardized in the ASTM D6276-19 code.[23]

Nanosilica – Nanosilica (**Figure 1c**), used as the secondary additive, was procured from Astrra Chemicals, Chennai, India. It was a fine, white powder having a specific surface area of 200 m^2/g, tapped density of 50 g/L, and average particle size of 12 nm.

2.2 Methodology

Unconfined compressive strength (UCS) tests were conducted on specimens having a diameter of 38 mm and height of 76 mm at a controlled strain rate of 1.25 mm/min.[24] The soil was modified with 3 % lime and nanosilica dosage varied as (0, 0.25, 0.5, 0.75 and 1) % by mass of the soil. The optimum nanosilica dosage was determined from the results of the tests performed on samples cured for 2 h (initial curing condition corresponding to 0 day curing) for each of the above-mentioned combination of additives. A similar curing period was adopted by previous researchers.[13] The UCS specimens were prepared at specimens with the MDUW corresponding to the OMC and stored them in airtight containers to ensure a minimal moisture loss during curing. A mini Proctor test was performed to find the optimum OMC and MDUW for all proportions of the additive.[25] The UCS of the soil with 3 % lime, and lime-modified specimen with the optimal dosage of nanosilica, was further found for curing periods of (7, 14, 28, 90 and 120) days.

Durability tests with respect to W-D and F-T (**Figure 2**) were performed over twelve cycles to determine the strength reduction of the specimens as per the procedure followed by James et al.[13] For W-D tests, the samples were wetted by wrapping them with soaked cotton for 24 h, followed by drying them at an atmospheric temperature of 28 ± 2 °C for 24 h, which marked the completion of one cycle. Similarly, for F-T tests, samples were placed in a deep-freezer unit having a temperature of –23 °C for 24 h, followed by thawing them at room temperature of 28 ± 2 °C for 24 h. Specimens were tested for their compressive strength at the end of cycles 1, 3, 5, 7, 9, 11 and 12, including both cases.

A CBR test was performed for lime-modified soil with and without the optimum dosage of nanosilica under the initial curing condition as per IS 2720: Part 16 (1987)[26] specifications, for both unsoaked and soaked condition. The soaked condition test was performed to consider the effect of water intrusion into the subgrade soil due to ground water fluctuations and seasonal changes.

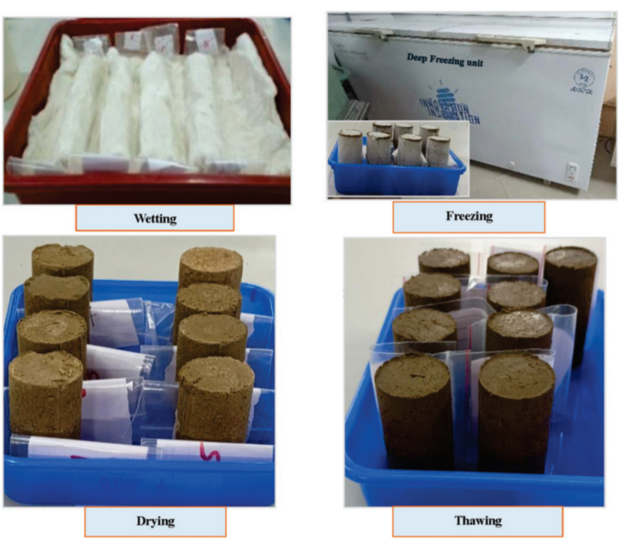

Figure 2: Durability test samples

3 RESULTS AND DISCUSSIONS

3.1. Stress-strain characteristics of the modified soil

The UCS of untreated soil was 85 kPa and it increased to 184.2 kPa upon the addition of 3 % lime during the initial curing. Dosage of nanosilica was varied from 0.25 % to 1 % in lime-modified soil.[27] The UCS increased with the increase in nanosilica dosage of up to

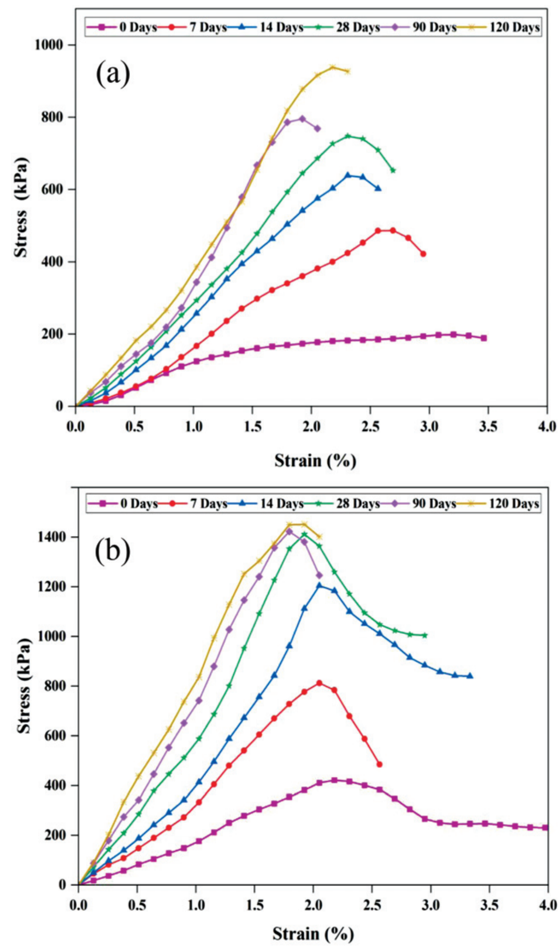

Figure 3: Stress-strain curve for: a) soil + 3 % lime; b) soil + 3 % lime + 0.75 % nanosilica

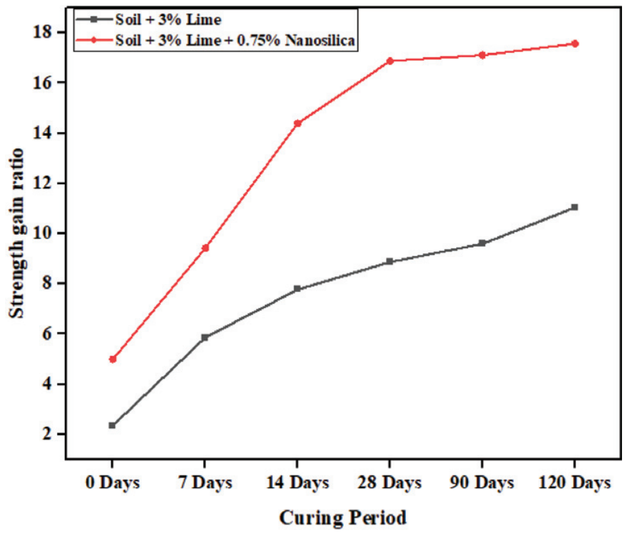

Figure 4: Variation in the strength gain ratio with the curing period

0.75 % and reduced thereafter. Thus, 0.75 % nanosilica was considered the optimal dosage with the soil-lime mixture. It was further observed that with curing, the optimum dosage of nanosilica remained the same. Addition of nanosilica beyond 0.75 % resulted in the reduction of the UCS due to its dispersive effect. In this case, the CSH gel formation is retarded due to reduced spacing between nanosilica particles leading to an insufficient supply of lime for the gel formation.[7,28,29]

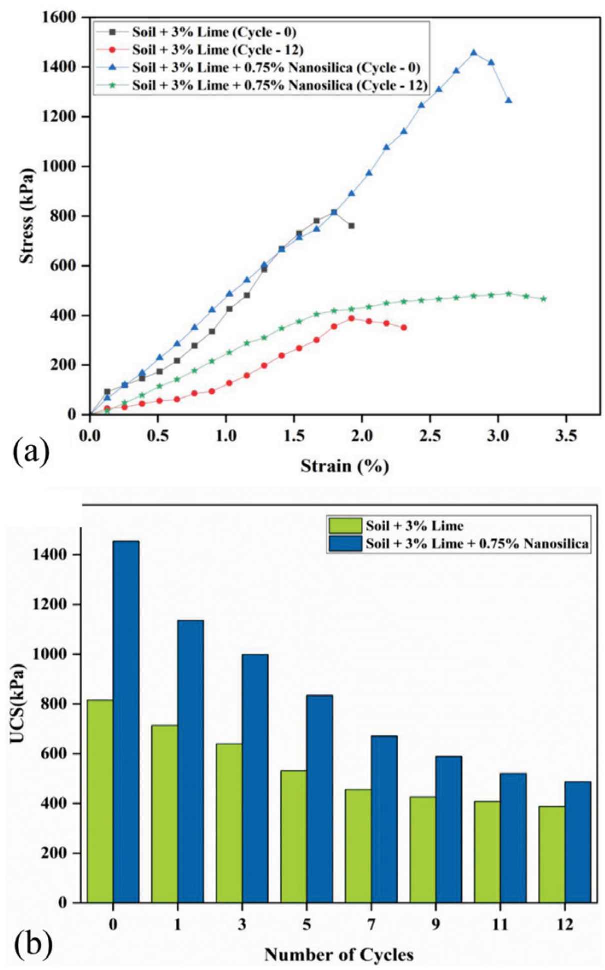

Figure 5: a) Stress-strain curve for modified soil – 0^{th} and 12^{th} cycle of W-D; b) variation in the UCS with W-D cycles

To evaluate the effect of compressive strength gain with curing, UCS tests were performed on soil + 3 % lime and soil + 3 % lime + 0.75 % nanosilica at the end of (7, 14, 28, 90 and 120) days of curing (**Figure 3**). The strength gain ratio defined as the UCS ratio of the treated soil to the untreated soil was found at the end of each curing period (**Figure 4**). The strength gain ratio improved from 2.35 at the initial curing to 11.05 at the end of 120 days of curing for the soil modified with lime. Addition of nanosilica to the soil-lime mixture resulted in an increase in the strength gain ratio from 4.99 at initial curing to 17.57 at the end of 120 days of curing. The increase in strength in the case of lime-modified soil was gradual, whereas the addition of nanosilica resulted in accelerated strength improvement at the initial curing period. For instance, the strength gain ratio at the end of 14 days of curing for lime-modified soil without and with nanosilica was 7.77 and 14.4, respectively. Also, it was noticed that the addition of nanosilica to the lime-modified soil resulted in achieving around 80 % of its maximum strength gain within 14 days of curing. The strength gain almost flattened after 28 days of curing.

Early strength gain supports the application of nanosilica in strengthening the soil subgrade for a rapid completion of road development projects, where traffic diversion for a longer period is challenging.

3.2 Durability of modified soil

The fact that soil subgrade may get influenced by seasonal changes is to be considered before suggesting any ground improvement technique. The current study evaluated the effect of both W-D and F-T on modified soil. Choobbasti et al.[28] reported that nanosilica-treated soil exhibited a dense and compact structure after 90 days of curing. Therefore, durability tests were performed on the samples cured for 90 days. As per recommendations of standard IS 4332 Part 4 (1968),[30] it was decided to subject the samples to twelve W-D and F-T cycles. UCS tests were performed on the samples after alternate cycles up to the twelve cycles. Weight loss of the samples at the end of the cycles was noted to understand its effect on the UCS.

Wetting and drying – the UCS of lime-modified soil was 815.3 kPa at the 0^{th} cycle and it reduced to 387.98 kPa at the 12^{th} cycle. Addition of nanosilica to lime-modified soil altered the UCS from 1455.36 kPa at the 0^{th} cycle to 487.24 kPa at the 12^{th} cycle (**Figure 5a**). **Figure 5b** shows the variation in the UCS of lime-modified soil without and with nanosilica subjected to W-D cycles. The strength reduction and weight loss recorded after W-D cycles are shown in **Figures 6a** and **6b**, respectively. The strength reduction (%) is calculated as the difference in the UCS of the 0^{th} cycle and n^{th} cycle with respect to the UCS of the 0^{th} cycle of the corresponding specimen. The weights of the samples were recorded before and after subjecting them to W-D cycles. The difference in the weight with respect to the initial weight in % was recorded as the weight loss.

At the end of the first cycle, strength reduction was only 12.47 % for lime-modified soil whereas addition of nanosilica resulted in a 21.93 % reduction and the weight loss was 1.43 % and 2.54 %, respectively. At the end of the 12^{th} cycle, the weight loss recorded was 11.31 % and 9.86 %, respectively, for lime-amended soil with and without nanosilica. With W-D cycles, the specimen is observed to become ductile as it is evident from the stress-strain curve corresponding to the 0^{th} and 12^{th} cycle. With subsequent W-D cycles, the strength reduction increased gradually up to the 7^{th} cycle and stabilised after 8 cycles for lime-modified soil. Nabil et al.[11] reported that the strength loss stabilised after 6 cycles when lime-modified soil was subjected to W-D cycles. From the current study, it can be understood that the strength reduction for lime-modified soil reaches equilibrium between 6 to 8 cycles. Addition of nanosilica caused the specimen to reach this equilibrium state after 9 cycles though the percentage reduction in strength was higher than that of the lime-modified soil at this stage. It can be stated that addition of nanosilica has not significantly altered the number of W-D cycles required for the soil specimen to reach stability. After 12 cycles, 66.52 % and 52.41 % strength reductions were observed for lime-modified soil with and without nanosilica respectively.

The CSH gel formation takes place when soil reacts with lime and this process helps maintain the alkalinity of soil essential for further chemical reactions to take place. Addition of nanosilica to this medium results in an additional CSH gel formation leading to further strength gain. The considerable reduction in the UCS of lime-modified soil is due to the disturbances caused to the CSH gel because of moisture variation. Water intrusion into a specimen disrupts the contact between the soil particles and CSH gel, thereby reducing the attractive forces that hold the soil particles together. This further results in a rearrangement of particles and leads to the development of slight cracks in the specimen. It is

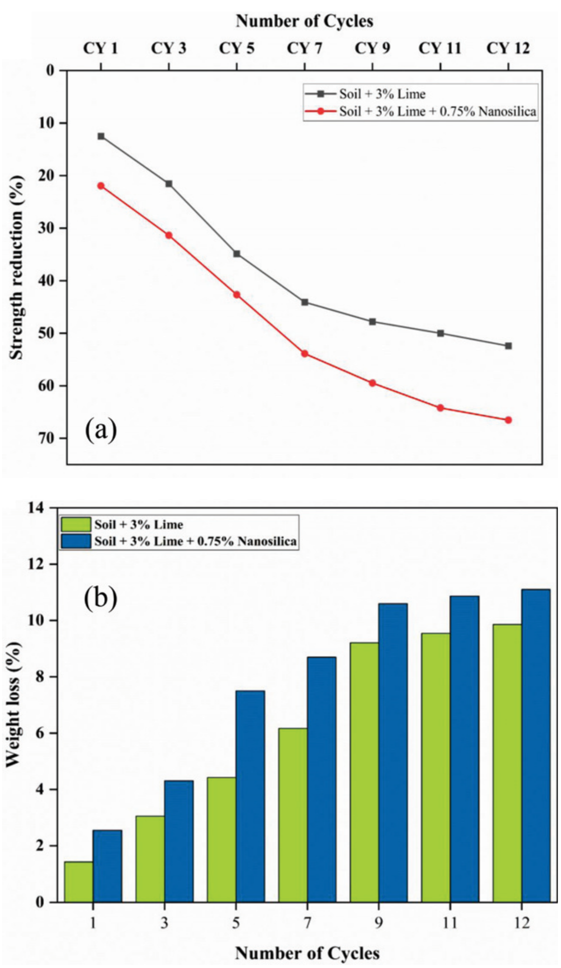

Figure 6: a) Strength reduction with W-D cycles; b) weight loss of the specimen with W-D cycles

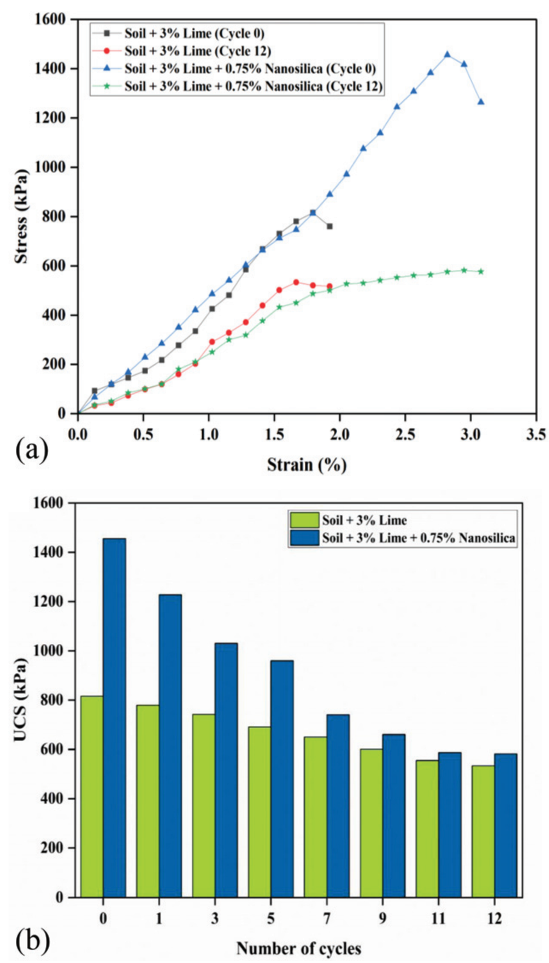

Figure 7: a) Stress-strain curves for modified soil – 0^{th} and 12^{th} cycle of F-T; b) variation in UCS with F-T cycles

also understood that the additional CSH gel formed due to the interaction between nanosilica and lime-modified soil was more susceptible to disruption due to water intervention and hence resulted in further degradation of the strength.[12]

It is also important to understand that though addition of nanosilica resulted in reduced resistance to W-D cycles and more weight loss, the rate of strength reduction after the first cycle is qualitatively better as compared to lime-modified soil. Also, its reduced UCS at the end of 12 W-D cycles is greater than that of lime-modified soil, highlighting the efficacy of nanosilica addition during W-D cycles.

Freeze-thaw cycles – the UCS of lime-modified soil reduced from 815.3 kPa at the 0^{th} cycle to 533.3 kPa at 12^{th} the cycle. Addition of nanosilica to lime-modified soil changed the UCS from 1455.36 kPa at the 0^{th} cycle to 581.58 kPa at the 12^{th} cycle (**Figure 7a**). **Figure 7b** shows variation in the UCS of the lime-modified soil without and with nanosilica, subjected to F-T cycles. The strength reduction and weight loss recorded for F-T cycles are shown in **Figures 8a** and **8b**, respectively. At the end of the first cycle, strength reduction was 4.47 % for lime-modified soil, whereas the addition of nanosilica resulted in a 15.64 % strength reduction while the weight loss was 2.93 % and 3.18 %, respectively. It was observed that the weight loss stabilised after 9 cycles in both cases. At the end of 12 cycles, the weight loss was 14.92 % and 13.05 % for lime-amended soil with and without nanosilica.

As compared to W-D cycles, the weight loss is comparatively higher when a specimen is subjected to F-T cycles. At the end of 12 cycles, the strength reduction for lime-modified soil with and without nanosilica was 60.98 % and 34.58 %, respectively. **Figures 9a** to **9d** explain the mechanism of the strength loss of the modified soil subjected to W-D and F-T cycles.

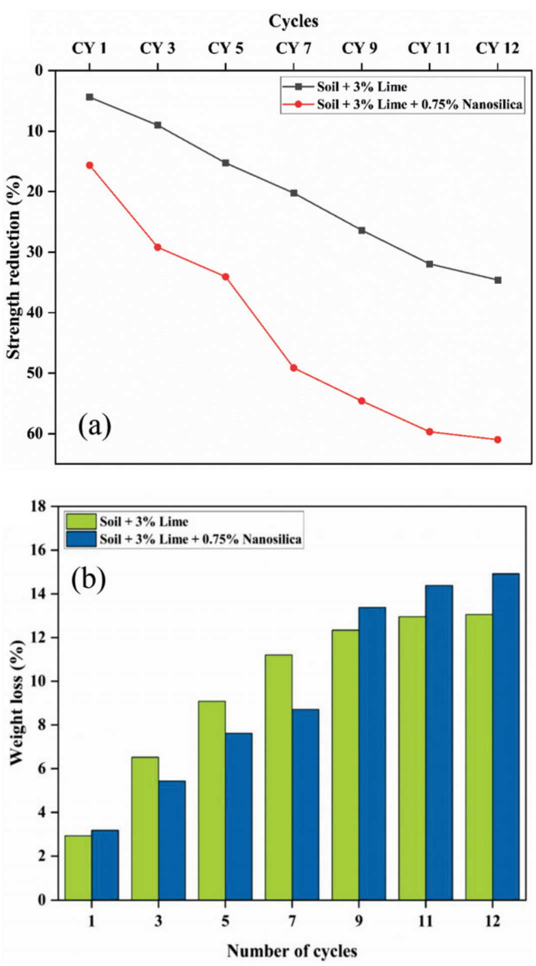

Figure 8: a) Strength reduction with F-T cycles; b) weight loss of the specimen with F-T cycles

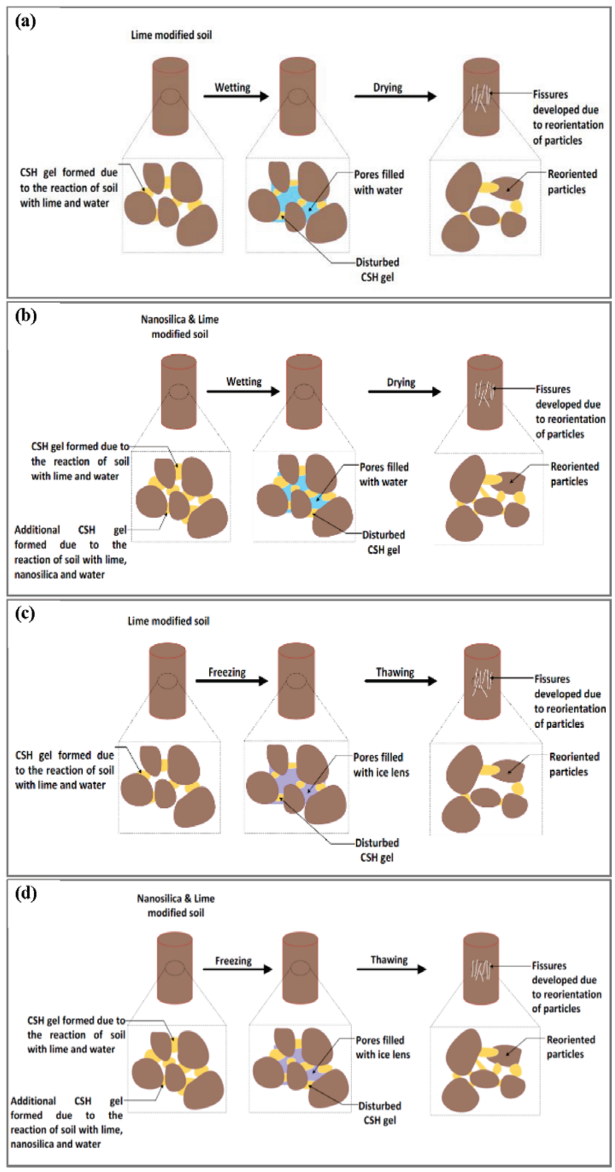

Figure 9: Strength reduction mechanism: a) lime-modified soil subjected to W-D; b) lime- and nanosilica-modified soil subjected to W-D; c) lime-modified soil subjected to F-T; d) lime- and nanosilica-modified soil subjected to F-T

The reduction in the UCS of the lime-modified soil without and with nanosilica occurred because of the disturbances caused to the CSH gel due to the formation of ice lens. In the modified soil, the formation of ice lens occurred parallel to the surface of the specimen and led to the generation of minor fissures inside it (**Figures 9c** and **9d**). The cracks along with the changes in the voids at the aggregate scale resulted in the strength loss of the specimen subjected to F-T cycles.[11]

Addition of nanosilica enabled the specimens to resist F-T cycles more effectively as compared to W-D cycles. Though the weight loss is higher during F-T cycles, the strength reduction is lower indicating that the voids and minor fissures developed in the specimen due to the ice lens formation were fewer than during W-D cycles. The weight loss was identified to occur mostly due to the shredding of soil particles from the surface of the specimen. Also, according to the observations by Roshan et al.,[31] the treated specimens are expected to retain most of their original strength if they lose only 10 % to 15 % of their initial weight when subjected to 12 F-T cycles.

Analogous to the observations of W-D cycles, the UCS of lime-modified soil with nanosilica was higher than that of lime-modified soil after 12 F-T cycles. Hence, nanosilica proved to act as an efficient secondary additive to lime when subjected to W-D and F-T cycles.

3.3 CBR of modified soil

The results from the CBR tests performed on lime-modified soil with and without nanosilica for both soaked and unsoaked condition are shown in **Figure 10**. Usually, the CBR value for the soaked condition corresponding to 2.5 mm penetration is considered critical. The soaked-condition CBR for virgin soil was 2.25 % and it improved to 9.52 % for lime-modified soil. Addition of nanosilica to lime-modified soil resulted the CBR to improve further to 12.08 % indicating a rise in the

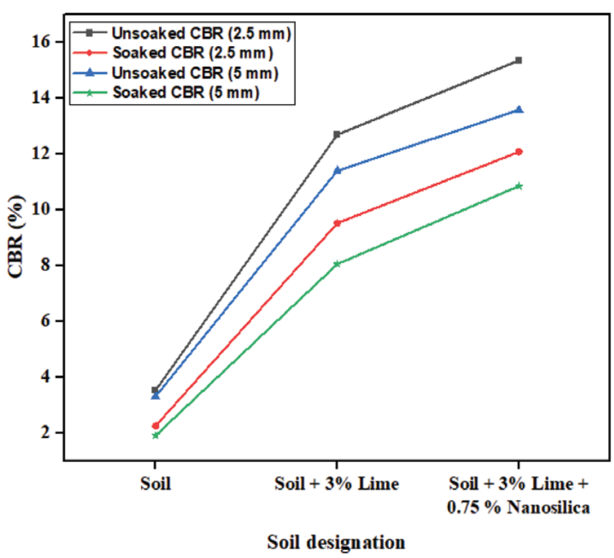

Figure 10: Variation in the CBR with addition of lime and nanosilica

CBR by 26.9 %. Based on IRC 37-2012[32] – for a pavement with a granular base and granular sub-base, with design traffic of 150 million standard axles (msa) – the pavement thicknesses corresponding to CBR values of 9.52 % and 12.08 % are 610 mm and 595 mm, respectively. Addition of nanosilica to the soil-lime mixture therefore resulted in a reduction of pavement thickness of 2.5 %.

4 CONCLUSION

The current study aimed to provide a broader insight into the application of nanosilica as a secondary additive in pavement engineering. Though conventional lime stabilisation has its own benefits, its supplementation with nanosilica resulted in substantial changes in the strength characteristics of the modified soil. Considering long-term curing, addition of nanosilica increased the strength gain of lime-modified soil 1.6 times. Although lime-modified soil exhibits good strength retention as compared to the soil modified with lime and nanosilica, it is noteworthy that at the end of both W-D and F-T cycles, the compressive strength of lime- and nanosilica-modified soil was higher. This explicitly indicates that the safety of roads with respect to cohesion mobilisation is higher in the case of the soil modified with both lime and nanosilica. As compared to W-D cycles, addition of nanosilica resulted in better performance during F-T cycles. Therefore, the present work recommends the additive combination to be employed in the regions highly exposed to the glacier effect.

Addition of nanosilica resulted in an improved CBR of about 3 % as compared to the lime-modified soil, with a 2.5 % reduction in the total thickness of the pavement. Considering immediate and enhanced strength gain along with the ability to withstand extreme climatic conditions, the study unfolds the scope of application of nanosilica as an effective secondary additive to lime.

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