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# Scope of nanomaterial as potential soil stabiliser in pavement engineering

## ABSTRACT

*Present study explores the application of nanosilica in improving the strength of soil subgradeto reduce the pavement thickness. Changes in the plasticity characteristics of soil stabilised with nanosilica was evaluated through Atterberg limit tests. Unconfined compressive strength(UCS) tests were performed on specimen cured for 0, 7, 14 and 28 days to find the optimal percentage of nanosilica for achieving maximum strength. California bearing ratio (CBR) test indicated a substantial reduction in pavement thickness with addition of nanosilica to the soil. Results from Field emission scanning electron microscopy analysisconfirmed the formation of Calcium-Silicate-Hydrate gel responsible for strength improvement of the soil. Thus, inclusion of nanosilica can facilitate the reduction in the quantity of materials requiredfor laying pavement.*

***Keywords:****Clay soil, nanosilica, unconfined compressive strength, California Bearing Ratio*

## 1.INTRODUCTION

Nanomaterials are gaining widespread attention in recent years owing to its ability to alter the physical, chemical and biological properties of materials from atomic level to a higher scale. It finds numerous applications in the field of engineering, food and agricultural science, textile industry, medicine, energy storage & conservation, environment preservation, defence and security and so on [1,2]. It has unfolded a scenario of improved materials, implements, technologies beneficial to the human community. In the field of civil engineering, nanomaterialssuch as nanosilica, alumina, titania, magnesium oxide and iron oxide have been considered as cement additives. The significant attributes of nanoparticles which differ from those of their macro-sized counterparts, are a result of their size range of 1 to 100 nm. In addition to their size effect, nanoparticles possess unique qualities such as large surface area to volume ratio and increased chemical reactivity.Nanosilica is the most researched nanoparticle for cementing applications as it has evidenced to create better cementitious materials with exceptional performance.

Nanosilica has drawn a lot of interest in the field of geotechnical engineering due to its good strength enhancement capabilities for all soil types, easy availability and early strength gain when compared to other nanomaterials. It is to be noted that nanosilica can be sourced by processing various agricultural wastes such as rice, wheat and coffee husk, sugarcane bagasse, corn cob ash and from naturally available quartz and silica sand.It is reported that, nanosilicasupplementation increased the compressive strength and compact ability characteristics of soil while accelerating the pozzolanic reaction resulting in the formation of Calcium- Silicate- Hydrate (CSH) gel [3,4]. Also, the density of the soil increased due to the addition of nanosilicaas itfilledits pores. Consequently, the permeability of the soil reduced considerably [5].SharoandAlawneh[6]hasreported a reduction in the swell potential of the soil due to inclusion of nanomaterial which is one of the most important requirements of soil subgrade. Also, nanomaterials along with other pozzolanic additives have proved to improve the California Bearing Ratio(CBR) of the soil [7] .Though nanosilica can be used as a potential stabiliser, itscontribution in soil stabilisation is still progressing. Thepresent study focused on acquiring the benefits of nanosilica addition to the soil in the development of roads and embankments, as the improved strength of soilsubgradecan eventually contribute to reduction in the thickness of the pavement layer.

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## 2. MATERIALS AND METHODS

### 2.1. Materials

**Soil -**Soil (Fig.1a) is excavated at a depth of 2 m from the ground level at a site in Tiruvallur district, Tamil Nadu, India. To find theindex properties, the soil is air dried and then crushed to specified sizes for performing the tests. The basic properties of the soil are listed in Table 1. The soil is classified as clay of high compressibility (CH) as per IS 1498–1970 [8]. The chemical composition of the soil as obtained fromX-ray fluorescence (XRF) analysis is shown in Table 2.

*Table 1. Properties of the soil*

| Property | Value | IS Code | Reference |
|---|---|---|---|
| Specific Gravity | 2.61 | IS: 2720 Part 3 (1980) | [15] |
| Grain size distribution | | IS: 2720 Part 4 (1985) | [16] |
| Sand (%) | 20 | | |
| Silt (%) | 48 | | |
| Clay (%) | 32 | | |
| Liquid Limit (%) | 54 | IS: 2720 Part 5 (1985) | [17] |
| Plastic Limit (%) | 21.7 | IS: 2720 Part 5 (1985) | [17] |
| Shrinkage limit (%) | 12.6 | IS: 2720 Part 5 (1985) | [17] |
| Plasticity Index (%) | 32.3 | IS: 2720 Part 5 (1985) | |
| Free Swell Index (%) | 80 | IS: 2720 Part 40 (1977) | [18] |
| Maximum dry unit weight, (kN/m$^3$) | 19.8 | IS: 2720 Part 7 (1980) | [19] |
| Optimum moisture content (%) | 18 | IS: 2720 Part 7 (1980) | [19] |
| Unconfined Compressive Strength (UCS) (kPa) | 85 | IS: 2720 Part 10 (1991) | [20] |

*Table 2. Chemical composition of soil*

| Chemical composition | $SiO_2$ | $Al_2O_3$ | CaO | MnO | $Fe_2O_3$ | $SO_3$ | $TiO_2$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|
| Soil | 31.31% | 9.61% | 1.31% | 526.9 ppm | 6.05% | 167.1 ppm | - | 1.55% |

**Nanosilica**- Nanosilica (Fig.1b) with chemical formula $SiO_2$(Silicon oxide), was used as the additive, procured from Astrra Chemicals, Chennai, India. It is a fine, white-coloured powder having a specific surface area of 200 m$^2$/g,withan average particle size of 12 nm and composed of 99.88% of silicon oxide.

a) b)

*Figure 1. (a) Soil (b) Nanosilica*

### 2.2. Methodology

Atterberg limits tests (liquid limit, plastic limit and shrinkagelimit) (Fig.2a)were performed to evaluate the changes in the plasticity characteristics of soil amended with varying proportions of nanosilica – 0, 0.25%, 0.5%, 0.75% and 1% by mass of the soil. Results of these tests providequalitative information on the volume change behaviour (swell and shrink) of soil due to seasonal variations. Clayey soil with higher liquid limit and plasticity index shows higher swell-shrink characteristics. Such soil is not suitable for subgrade and the aim of any soil stabilisation technique is to bring down the plasticity index of the soil to control the volume change behaviour.

To find optimum moisture content (OMC) corresponding to the maximum dry unit weight (MDUW) for all combinations of the additive, mini proctor compaction test was performed [9]. It is to be mentioned thatthe soil demonstrates its maximum strength at its OMC and the strength reduces both above and below OMC.

Unconfined compressive strength (UCS) is defined as the maximum axial compressive stress a cylindrical soil specimen can withstand without any confining pressure.UCS tests (Fig.2b) were conducted on specimen having a diameter of 38 mm and height of 76 mm at a controlled strain rate of 1.25 mm/min. The UCS specimens were prepared at maximum dry density corresponding to the OMC and stored in airtight covers to ensure minimal moisture loss during curing. Wet mix method was adopted for mixing nanosilica with soil.

Homogeneous suspension of nanosilica with water (corresponding to the optimum moisture content of soil + nanosilica) was prepared and mixed using ahigh-speed stirrer at 120 rpm. After ensuring its complete dissolution, it was mixed with soil. This process has been reported to produce uniform dispersion of nanosilica in the soil [3]. Samples were tested for a curing period of 0, 7, 14 and 28 days for all the proportions mentioned above.

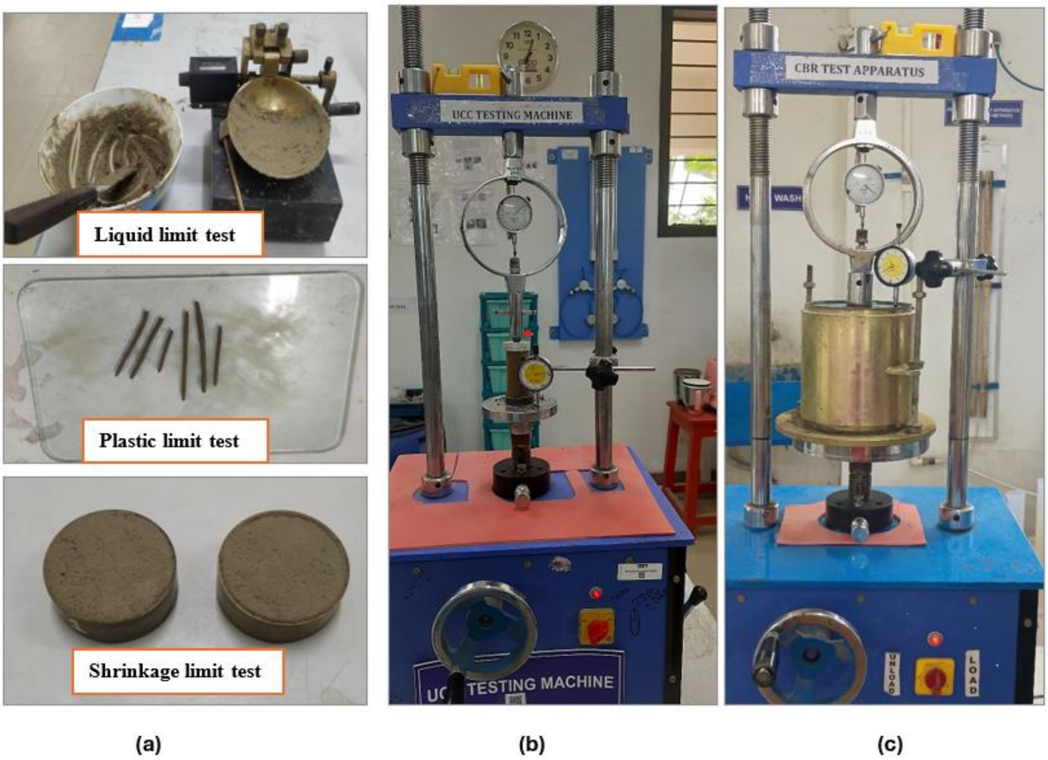


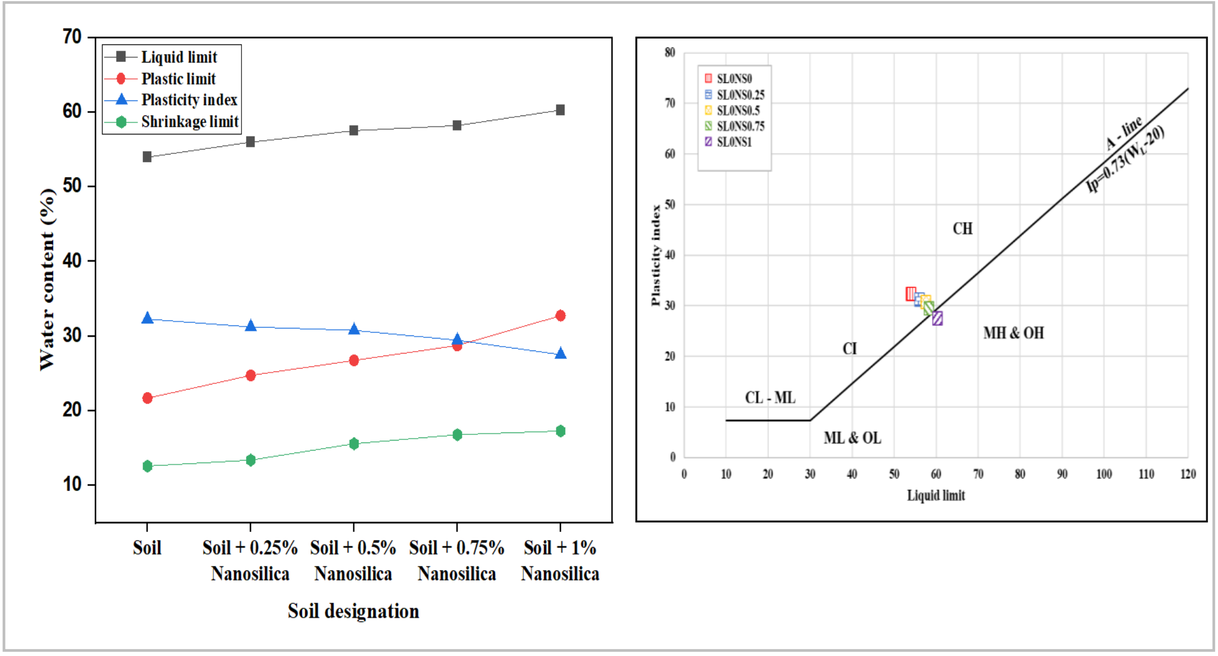
*Figure 2. (a) Atterberg limits test (b) UCS test (c) CBR test*

CBR test (Fig.2c) was performed for virgin soil and soil amended with optimum dosage of nanosilica. A soil subgrade is a layer of natural soil that serves as the basis for a road's pavement. It is composed of compacted earth and aggregate particles that can support the weight and forces transferred from subsequent pavement layers above it. CBR test is usually performed to evaluate the strength of soil subgrade or subsequent pavement layers.It is defined as the ratio of force required to penetrate soil sample to that of the standard material. Usually, the CBR value is measured for 2.5 mm and 5 mm penetration. Higher theCBR ratio stronger is the surface. For the test, specimens were prepared by filling the soil and soil along with optimum proportion of nanosilica at its OMC in the CBRmould having a diameter of 15 cm and height 17.5 cm by adopting light weight compaction. The mould was filled in three layers by giving 56 blows in each layer with a 2.6 kg rammer and 310 mm height of fall. The test was performed on the sample under immediately cured conditions and tested at a constant strain rate of 1.25 mm/min as per IS specifications [10]. CBR test can be performed for both unsoaked and soaked conditions. For the soaked test, the specimenso preparedis soaked in water for 4 days and then tested. Soaked test is performed to consider the effect of water intrusion into the subgrade soil due to ground water fluctuations and seasonal changes.

## 3. RESULTS AND DISCUSSIONS

### *3.1. Effect of nanosilica on Atterberg limits of soil*

Plasticity behaviour of the untreated soil and soil modified with varying percentages of nanosilica – 0.25 %, 0.5 %, 0.75 % and 1 % is evaluated by determining the changes in its liquid limit and plastic limit as shown in Fig. 3a. Plasticity index is deduced by subtracting plastic limit from liquid limit. Addition of nanosilica has resulted in a gradual increase in the liquid limit from 54% (untreated soil) to 60.3 % in case of soil amended with 1% nanosilica. This is due to more absorption of water by nanosilica because of its higher specific surface area. Similar observations were also reported by [11]. For the same additive proportion, plastic limit increased from 21.7 % to 32.76 % but plasticity index decreased from 32.3 % to 27.54 %. Even though the liquid limit increased, the reduction in the plasticity index upheld the efficiency of nanosilica addition to the soil. Fig.3b depicts the changes in soil classification upon addition of nanosilica. Nanosilica supplementation has resulted in the soil classification to shift closer towards the A-line representing the contribution of nanosilica in bringing down the plasticity of the soil.Shrinkage limit increased from 12.6 % to 17.3 % with addition of 1 % nanosilica. It is to be mentioned that as the shrinkage limit increases, the tendency of the soil to undergo volume change behaviourdecreases. Hence it can be stated that the plasticity characteristics of the soil decreased due to the presence of nanosilica. This may be due to the chemical processes that occur between soil and nanosilicaparticles during hydrolysis producing more cementitious compounds, replacing the naturally occurring adsorbed water layer on the surface of soil particles thereby decreasing the thickness of the double layer. This process resulted in the domination of attractive forces between the soil particles outweighing the repulsive forces [12].



*(a)* *(b)*

*Figure 3. (a) Variations in Atterberg limits with addition of nanosilica (b) Changes in soil classification with nanosilica addition*

### *3.2. Effect of nanosilica on UCS of soil*

UCS tests were performed on specimen with varying proportions of nanosilica -0.25 %, 0.5 %, 0.75 % and 1 %. This proportion was considered based on the understanding from the literatures [12], that the quantity of nanosilica required for treatment of CH type of soil is mostly less than 2%. Fig.4 shows the stress strain curve for each proportion of nanosilica for 0, 7, 14 and 28 days of curing. It is observed that soil with 0.75 % of nanosilica resulted in the maximum strength and hence it is considered as the optimum percentage.

The compressive strength reduced beyond the optimum percentage. The increase in the strength of the soil with addition of nanosilica is due to the following mechanisms.

- Void filling and interlocking of soil particles.
- Upon reaction with water, nanosilica forms viscous gel which acts as a medium to bring more soil particles in contact with one another thereby improving its cohesion and interfacial bond strength.
- The chemical composition of the soil obtained from XRF analysis indicated that the soil is composed of 1.31% of calcium oxide (CaO). Upon addition of water, the calcium and hydroxide ions in the soil combine with the silica present in the nanosilica resulting in the formation of cementitiousCSH gel. The gel improved the bonding properties and filled the space between the soil grains [12]. Thus, the increase in density of the soil mass has resulted in strength improvement.

These changes at the microscopic level due to the addition of nanosilicawere traced by carrying out Field emission scanning electron microscopy (FESEM) analysis of as shown in Fig.5 wherein the void space in the virgin soil is filled with white colour precipitate (CSH gel). Addition of nanosilica to the soil beyond 1% caused agglomeration of soil particles resulting in the strength decline. Increase in nanosilica beyond optimum content pushes apart the soil particles and reduces the density resulting in the reduction of its compressive strength.

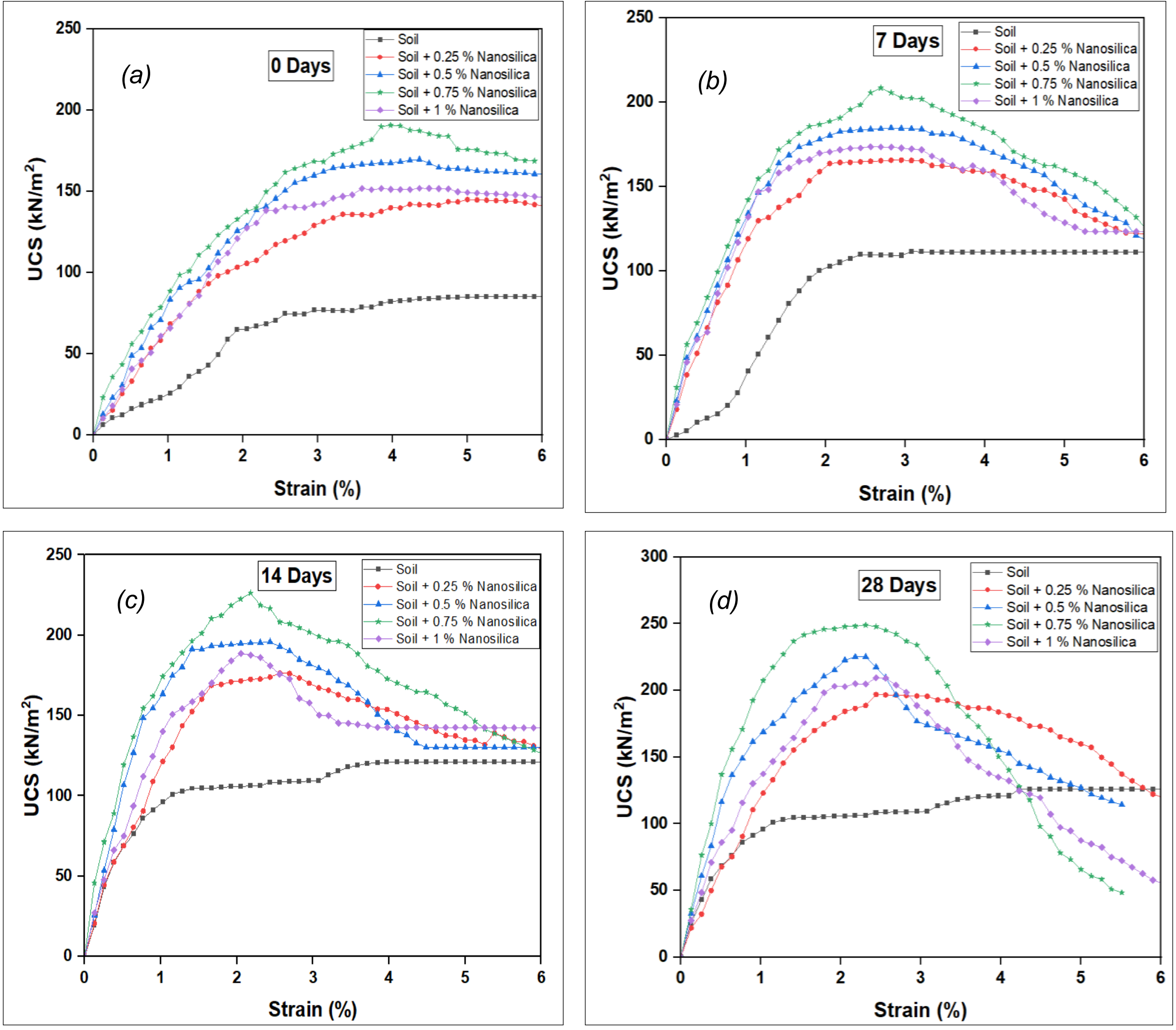


*Figure 4. Stress strain curves for soil amended with varying percentages of nanosilica (a) 0 day (b) 7 days (c) 14 days (d) 28 days*

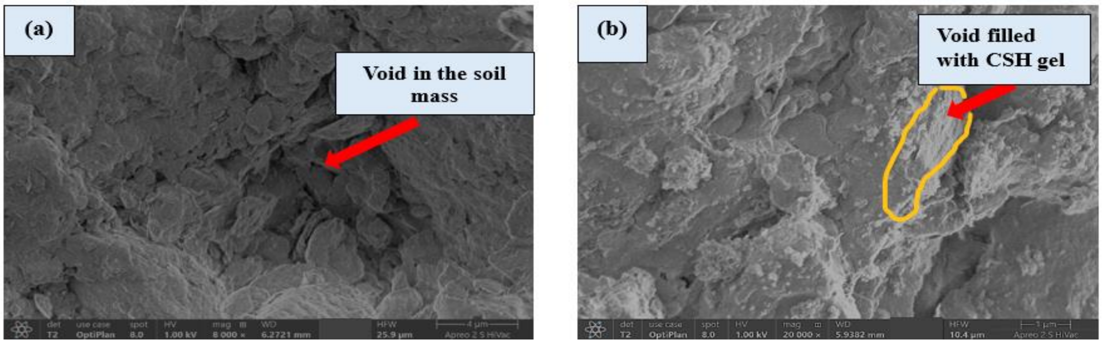


*Figure 5. FESEM images of (a) Untreated soil (b) Soil treated with 0.75 % nanosilica*

The UCS of virgin soil was 85 kPa at its initial curing condition.Soil with 0.75% nanosilica had an UCS of 194.91 kPaat initial curing and it increased to 248.94 kPa at the end of 28 days of curing. To assess the improvement in strength, Strength gain ratio ($S_g$) defined as the ratio of UCS of virgin soil to that of treated soil is introduced (Fig. 6a). With 0.75 % addition of nanosilica, $S_g$is found to be 2.29, 2.45, 2.66 and 2.93 respectively for 0, 7, 14 and 28 days of curing. It is observed that about 83 % of the strength gain is achieved at the end of 7 days of curing itself. The property of early strength gain of nanosilica is one of the primary reasons of this study to find its suitability for application inroadways projects.

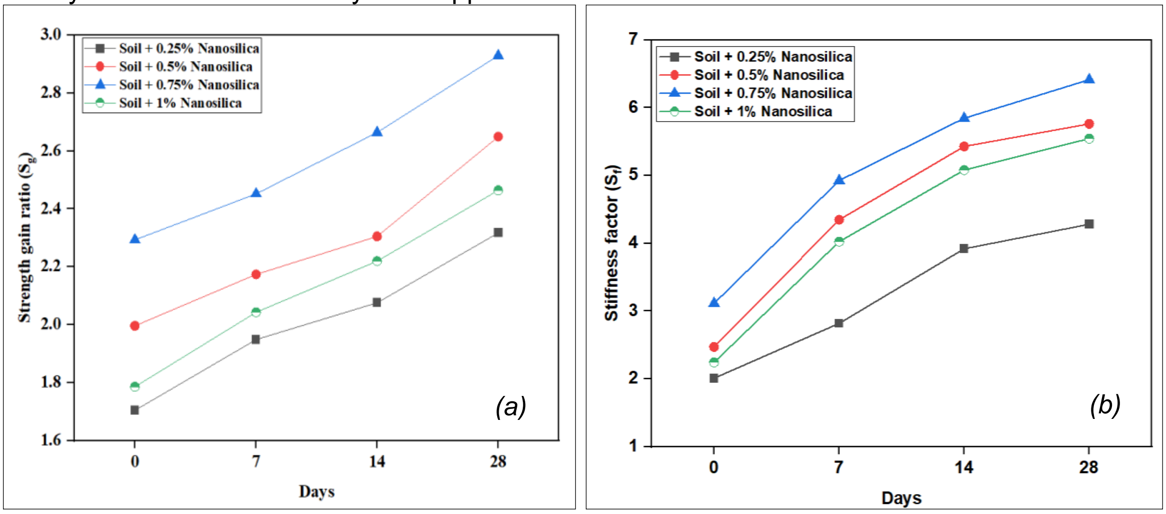


*Figure 6. (a) Strength gain ratio with curing period (b) Stiffness factor with curing period*

Initial tangent modulus is found as the slope of initial portion of each stress strain curve. The modulus of the virgin soil was found to be 3182 kPa. Upon addition of 0.75 % of nanosilica, the modulus increased from 9915 kPa at initial curing to 20411 kPa at the end of 28 days of curing.Stiffness factor ($S_f$) is introduced to measure the ratio of modulus of treated soil with respect to the modulus of virgin soil (Fig. 6b). It is observed that with an increase in nanosilica content and curing period, the stiffness of the soil increased indicating that the material isbecoming stronger and hence the soil will undergo less settlement as compared to the virgin soil.For 0.75 % nanosilica the stiffness increased 3.11, 4.92, 5.84, 6.41 times the virgin soil at the end of 0,7,14 and 28 days of curing. The increase in the stiffness of the treated soil implies that the subgrade material can withstand the load (due to vehicular movement) transferred from the pavement surface more effectively as compared to untreated soil.

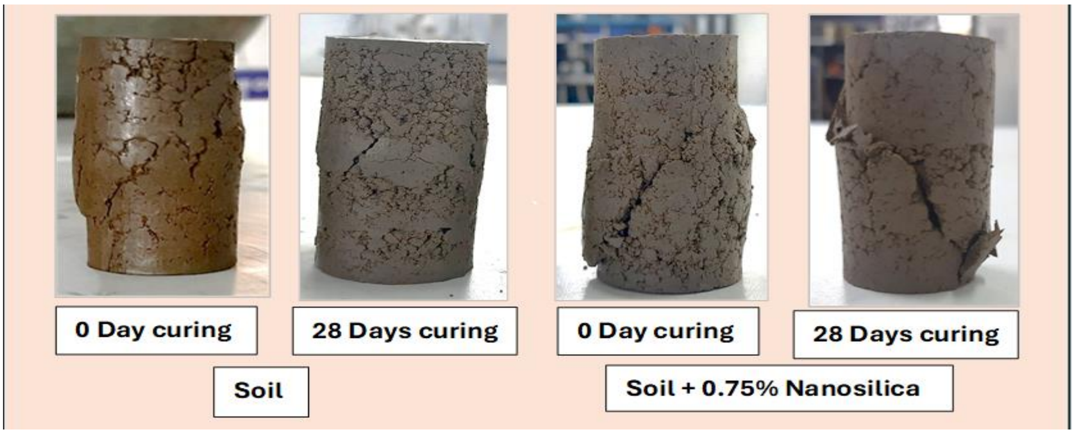


*Figure 7. Comparison of crack pattern in virgin and modified soil*

The failure pattern was captured at the end of all UCS tests to understand the deformation behaviour and the crack pattern developed in treated and untreated soil. At initial curing condition, virgin soil pronounced failure due to bulging. Addition of nanosilica resulted in the development of shear cracks along with bulging. In nanosilica modified soil, with curing the bulging reduced and widening of shear cracks was observed (Fig.7). Thus, addition of nanosilica has made the soil brittle as it is also evident from its stress-strain curve.

### *3.3. Effect of nanosilica on CBR*

CBR test was performed on virgin soil and soil amended with 0.75 % of nanosilica.Fig.8ashows the influence of nanosilica on unsoaked and soaked CBR. It is observed that for soaked case, CBR value increased from 2.2 to 5.03, whereas for unsoaked case it improved from 3.53 to 7.06

indicating a two- fold increase in strength uponaddition of nanosilica. The increase in CBR value can be attributed to the increased density of soil mass resulting in the formation of less compressible material with addition of nanosilica [13]. To estimate the reduction in the pavement thickness due to the enhancedCBR value, chart recommended by Indian Road Congress (IRC:37-1984) [14](Fig. 8b) is used. For a traffic classification (Type D) of 150-450 vehicles per day exceeding 30kN load, the thickness of the pavement for virgin soil with CBR value of 2.2 corresponding to soaked case is 590 mm. Whereas for the similar condition, with nanosilica addition, corresponding to a CBR value of 5.03 the thickness of pavement required is 380 mm implying a 35% reduction. Hence, substantial quantity of pavement materials can be saved due to inclusion of nanosilicafor improving the strength of soil subgrade.

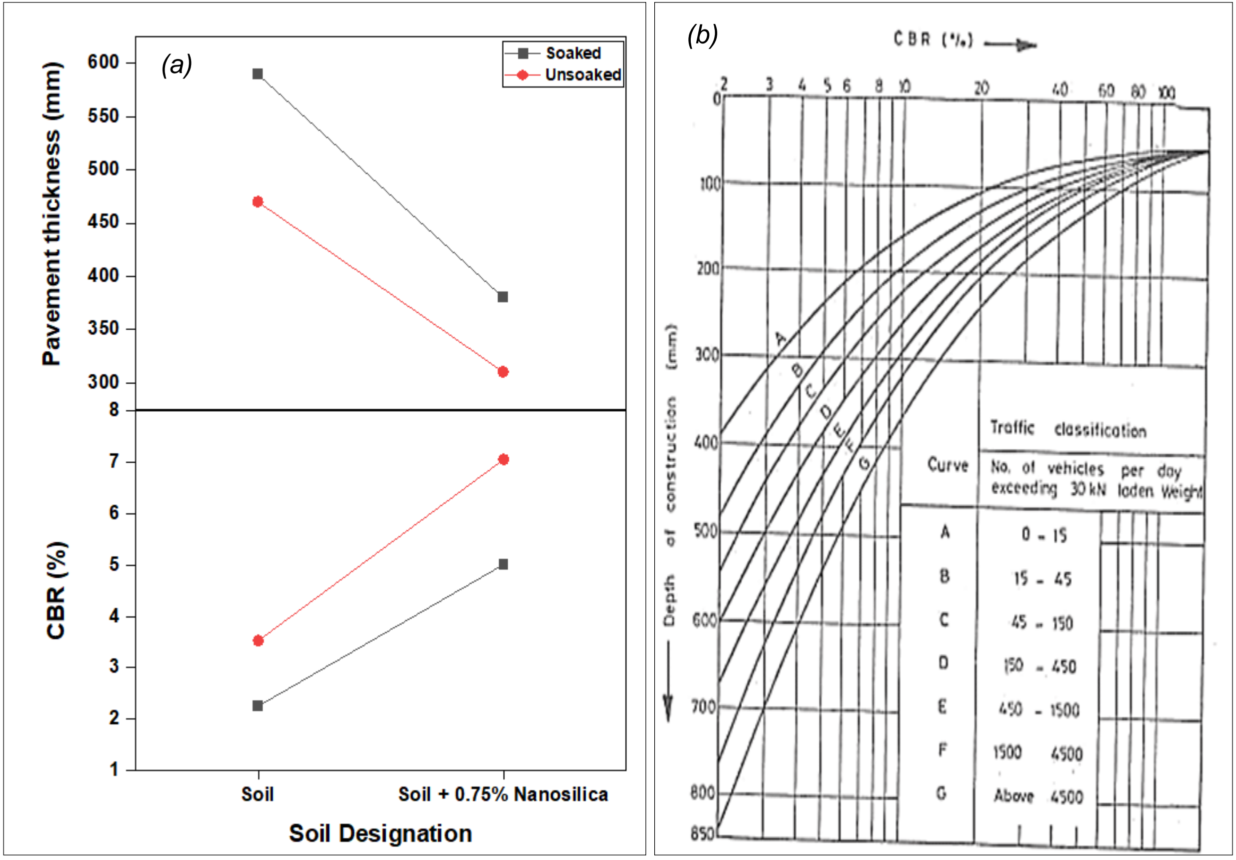


*Figure 8. (a) Effect of nanosilica on CBR and pavement thickness, (b) CBR Design chart recommended by Indian Road Congress*

## 4. CONCLUSION

The study evaluated the viability of nanosilicain improving the strength of soil subgrade. It is concluded that nanosilica can act as a potential soil stabiliseras it contributes to reducing plasticity characteristics of soil and improved compressive strength. For optimal dosage of nanosilica, plasticity index reduced by 8.8 %. For a curing period of 28 days, the UCS and the modulus improved by 2.93 times and 6.41 times the virgin soil respectively. EnhancedCBR valueof the treated soil supports reduction of the pavement thickness by 35% emphasizing the efficacy of nanosilica in application of road development projects.

Cost implications of nanosilica is outweighed considering its early strength gain property alongwith the fact that the quantity of nanosilica required for soil stabilisation (by percentage mass of soil) is less. The production of nanosilicais expected to become cost effective in future due to technological advancements and hence it will prove to be a sustainable soil additive. Assessment of durability characteristics of nanosilicastabilised soil subjected to wetting-drying and freeze-thaw cycles is considered as the future scope of the study as it affects the pavement behaviour significantly.

*Statements and Declarations*

**Declaration of interests -** The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

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## IZVOD

## Obimnanomaterijala kao potencijalnogstabilizatoratla u putarstvu

Ova studija istražuje primenu nanosilicijumdioksida u poboljšanju čvrstoće podloge kako bi se smanjila debljina kolovoza. Promene u karakteristikama plastičnosti tla stabilizovanog nanosilikom procenjene su Aterbergovim graničnim testovima. Ispitivanja čvrstoće neograničenog pritiska (UCS) su izvedenanauzorkukoji je očvršćavao 0, 7, 14 i 28 dana da bi se pronašao optimalni procenat nanosilicijumdioksida za postizanje maksimalne čvrstoće. Test kalifornijskogodnosanosivosti (CBR) pokazao je značajno smanjenje debljine kolovoza uz dodavanje nanosilicijumdioksida u tlo. Rezultati analize polja emisione skenirajuće elektronske mikroskopije potvrdili su formiranje kalcijum-silikat-hidratnog gela odgovornog za poboljšanje čvrstoće tla. Dakle, uključivanje nanosilijuma može olakšati smanjenje količine materijala potrebnih za postavljanje kolovoza.

Ključnereči: Glinenozemljište, nanosilicijum, neograničena tla čnačvrstoća, kalifornijski odnosnosivosti
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