Strengthening Of Weak Soil Using Silica Based Additives.

Dharamveer[1], Dhruv Lodhi[2], Durgesh Mishra[3], Ghulam Murtaza[4], Mr. Ashish Verma[5]
[1,2,3,4]*babu Banarasi das National Institute of Technology & Management (Recognized by AICTE, Govt. of India & Affiliated to Dr. A.P.J. Abdul Kalam Technical University, Lucknow)*
[5]*Assistant Professor at Babu Banarasi das National Institute of Technology & Management (Recognized by AICTE, Govt. of India & Affiliated to Dr. A.P.J. Abdul Kalam Technical University, Lucknow)*

***Abstract*—A Comparative study on the Effect of Silica on Physical, chemical, and Micro structural characteristics of soft soil was investigated. Nano-silica widely used in concrete and cement stabilized soft soil to enhance macro performance. Up to now, the improvement of soft soil using Nano-silica is not completely explored. In this study, a comparison has been done to determine the potential of Nano-silica to stabilize the soil Different experimental work has been performed, especially the standard proctor test, unconfined compressive strength (UCS)and California bearing ratio (CBR) of clay with highly compressible (CH) soil adding Nano-silica. The soil considered here accommodates varying percentages of Nano-silica (0.6%, 0.8%, 1%, 1.5% by weight of soil) and is added for investigation of the relative strength enhance of soil. The present study is to evaluate the Maximum Dry Density, Unconfined Compressive Strength, and California Bearing Ratio of soil using varying percentages of Nano-silica. The test outcomes explain that the shear strength, UCS, CBR value of soil increases by the addition of Nano-silica in soil. The result showed that the addition of Nano-silica with soft soil can accelerate hydration, improve the interfacial zone between soil particles and binder, due to pozzolanic nature and fine particle size. By using Scanning Electron Microscopy (SEM), the interaction at the interface between Nano-silica and soil matrix was analysed. And by Energy-dispersive X-Ray Spectroscopy technique (EDS) the elements and chemical characteristics of soil analysed.**

***Index Terms*—Soil, Stabil Road, Stabilization, Mixture, California bearing ratio (CBR), Unconfined compressive strength (UCS).**

I. INTRODUCTION

In civil engineering soil is one of the most frequently used materials. Nearly all structure usually rests on soil. Presence of weak or soft soil in the construction sites is a major issue for any type of construction. To strengthen the of the Weak soil properties, many methods like stabilization of soil, soil reinforcement, grouting, addition of admixtures etc. are adopted. Addition of admixtures like Lime, fly ash, Cement, bitumen based on type of soil improves the properties of soil to some extent. Use of industrial waste as additives is recently under study, but it arises a question of toxicity.

So, there is a need for finding a new innovative material. Improving the engineering properties soil by using additives, stability and strengthening of the soil increases. One of the new innovative fields Nanotechnology is recently been introduced to Geotechnical Engineering. Nanotechnology is the science that deals with the particles which are less than 100 nm. The sizes of Nano particles have crucial part in behaviour of soil exhibiting different properties.

Soil stabilization is a proven and widely adopted technique to improve the engineering characteristics of problematic soils. Conventional stabilizers such as cement and lime have been extensively used to enhance soil strength and durability; however, their application is associated with high material costs, increased energy consumption, and significant carbon dioxide emissions. In recent years, the focus of geotechnical research has shifted toward the utilization of industrial waste materials and advanced additives as sustainable alternatives for soil stabilization. Marble powder is a by-product generated in large quantities during marble cutting and polishing operations. Improper disposal of marble waste leads to environmental degradation and land pollution. Owing to its fine particle size and high calcium carbonate content, marble powder exhibits potential for use as a soil stabilizing agent by reducing plasticity, filling voids, and improving compaction behavior. The effective utilization of marble powder not only enhances soil properties but also contributes to waste management and sustainable construction practices. Nanomaterials have recently gained considerable attention in geotechnical engineering due to their unique physicochemical properties. Among them, nano-silica is highly reactive and possesses an extremely large specific surface area, which enables it to improve inter-particle bonding at the microstructural level. Nano-silica participates in pozzolanic reactions in the presence of calcium, leading to the formation of calcium-silicate-hydrate (C–S–H) gel, which significantly enhances soil strength and stiffness while reducing permeability and swelling. Although several studies have investigated the individual effects of marble powder and nano-silica on soil stabilization, limited research is available on their combined application for improving the engineering performance of clayey soils. The synergistic interaction between marble powder as a calcium source and nano-silica as a highly reactive pozzolan may result in superior strength development and swelling control. Therefore, the present study aims to evaluate the effectiveness of marble powder and nano-silica as combined stabilizing agents for clayey soil through a comprehensive laboratory investigation. The study focuses on assessing changes in plasticity, compaction characteristics, strength parameters, and swelling behavior, with the objective of identifying an optimum stabilizer combination suitable for pavement subgrade and foundation applications.

II. EXPERIMENTAL WORK AND METHODOLOGY

The different type of material used, preparation of sample and procedure of test has discussed. To analyze the Engineering characteristics of soil various test such as Grain size analysis, "Atterberg's limit test, specific gravity test, compaction test, UCS test, CBR (soaked, unsoaked) test was conducted.

2.1 Material used

Soil: Soil sample used for research work was collected from a site at Gomti river, Lucknow Uttar Pradesh at a depth of 2ft below ground level. The soil was oven dried and lumps were crushed in to small segments and screen by 4.75 mm size sieve to separate pebbles, roots, gravel etc. The soil was categorized according to the IS classification system Silica.

Table 1. Geotechnical properties of soil

Properties	Value
1. Specific Gravity	2.40
2. Liquid Limit (%)	58.01
3. Plastic Limit (%)	24.74
4. Plasticity Index (%)	33.27
5. Classification of soil as per IS 1498	CH
6. Compaction properties	
MDD(g/cc)	1.58
OMC (%)	20.70
7. UCS (kN/m²)	80.54
8. CBR (%)	
Unsoaked	3.46
Soaked	1.81

Silica used in this experimental study was supplied by the Astra Chemicals, Lucknow. The tests were conducted at percentage of silica contents of 0%, 0.6%, 0.8%, 1.0%, and 1.5%. Physical composition and Chemical Characteristics of silica are illustrated in Table no. 2 and 3 respectively.

Table 2. Physical Composition of Nanosilica

Purity (%)	Avg. particle size (nm)	Specific surface area(m²/g)	Specific Gravity	Temped Density(g/l)	Sieve Residue	PH value
99	17	202	2.4	44	0.02	4.12

Table 3. Chemical properties of Nanosilica

Material	Content (%)
SIO_2	99.88
C	0.06
Cl	0.009
Al_2O_3	0.006
TiO_2	0.003
Fe_2O_3	0.001

2.2 Test method

Preparation of sample First the soil was air dried and it was pulverized with the help of wooden hammer. Then it was sieved with 4.75mm I.S sieve. First, they require content of Nano silica have been blended with clayey soil under dry condition. The different Percentage of Nano-silica are 0.6%, 0.8%, 1.0% and 1.5% of by the total soil weight taken for test and variation of OMC, MDD, UCS and CBR values was evaluated.

Specimen preparation for compaction test

The test was carried out by standard Compaction method as per IS2720 (Part VII)1980 to determine the OMC and MDD. The compaction tests were done on the soilNano silica. Different percentage of Nano silica was blended with weighted oven dry soil. The appropriate amount of water was mixed with soil-Nanosilica mixture and also the wet specimen was compacted in proctor mould in 3 layers using 2.6kg of standard proctor rammer.

Specimen preparation for unconfined compression test

For UCS test, samples were prepared as per IS: 2720(Part 10)-1991 at OMC and MDD obtained from compaction test. The Cylindrical specimen used for the test having diameter 3.7mm and height 10.2mm. Mixture filled in mould with three equal lays of having each layer carried 25 numbers of blows. After Compaction the sample taken in extruder of cylindrical stainless tube from mould and placed in load frame machine. The force given should be produce rate of axial strain 0.5 to 2% per minute. Each test was carried out by at least three samples to minimize error and average values were used. The tests were done with soil, soil with Nanosilica.

Specimen preparation for California bearing ratio test

Samples for CBR test were prepared as per IS 2720 ☹ part 16)-1987.The mould used for the test have the diameter of 150mm and height 175 mm. The samples were compacted in 5 lays and each layer carried 55 numbers of blows by 4.5 kg weight rammer with free fall of 450 mm. For soaked CBR test, specimen kept submerged in water for 96 hours before testing. Tests were conducted at a rate of penetration of 1.25mm/min until 12.5 mm penetration. From the test results the Load- penetration curve was plotted and CBR value calculated. By using different percentage of Nano-silica with soil both soaked and unsoaked CBR test were conducted.

2.3 Compaction test

Density and moisture content are the most crucial factors which affect the mechanical behavior of materials. In conformity with the guidelines mentioned in IS 2720 Part-7 [45], heavy compaction test is adopted to reconfirm optimum moisture content (OMC) and maximum dry density (MDD) of the treated soil. Different percentages of cement (by dry weight of soil, i.e., 0 %, 2 %, and 3 %) were added to the soil to achieve the design criteria as per IRC SP 89 [46] on the same type of soil. After determining the optimum cement content for the mixture, varying percentages of the additive (by weight of cement i.e. 0.5 %, 1.0 %, and 1.5 %), were then mixed with the cement and soil at optimum moisture content (OMC) in order to achieve homogenous mixture.

2.4 California bearing ratio (CBR)

California bearing ratio (CBR) is a basic criterion to assess the physical strength and weakness of natural and treated soil for the construction of subgrade. CBR test has been performed according to IS 2720 Part 16 [47] and ASTM D 1883 [48]. In this process, soil mixtures were prepared and compacted in-cylinder mold of diameter 152.4 mm in five layers. The test was performed for samples in both soaked and the un-soaked condition. The soaked samples were tested after 96 h of curing in water. For each condition, three specimens were tested to check reproducibility and variability of the test, and average values were taken for each mix.

2.5 Unconfined compressive strength (UCS)

Unconfined compressive strength test is the most common test used for checking the strength of modified soil mixtures. The standard used for conducting the test is IS: 2720 Part 10 [49], and the mixture prepared was at four additive contents, those were 0 %, 0.5 %, 1.0 %, and 1.5 % of dry cement. For each mixture, three samples were made for determining UCS, after 7 days and 28 days curing by wet gunny bags where average strength was taken to enhance the reproducibility of the treated sample.

III. RESULTS AND DISCUSSION

A Series of experimental work has been performed with combination of Nano-silica in natural soil. There are very limited literature on studies of use of nanosilica on strength of soil. Results of Experiments such as Atterberg's limits, Compaction Test, Unconfined Compressive Strength test, CBR Test (Both soaked and unsoaked) of admixture mixed soil is compared with values of untreated soil. The consequences of Nano-silica on various engineering properties were evaluated. The interaction at the interface between Nano silica and soil matrix is examined by using Scanning Electron Microscopy (SEM). EDS test shows the chemical Composition of materials.

3.1 Compaction test

Effect of Nanosilica on compaction characteristics of soil: The Compaction test on soil treated with varying percentage of Nanosilica by conducting Standard Proctor Test Results graphs has been plotted which has been shown in fig. 1. It is observed that Relative

Proportion of Nanosilica have considerable effects on the OMC and MDD of compacted mix. Increase Nanosilica content from 0 to 1.5%, the MDD Value increases and then decrease at a certain point and OMC value decreases with higher percentages of Nano-silica. In addition of 1% of Nanosilica with soil the OMC value decreased to 16.1 and MDD value increased to 1.71g/cc.

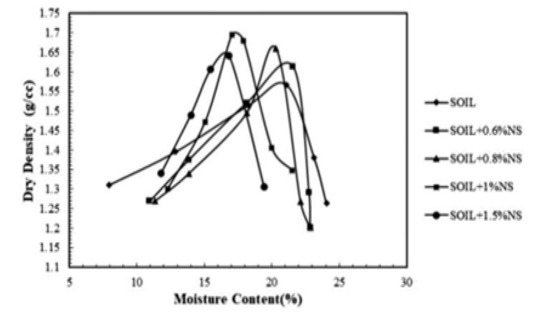


Fig. 1. Variation of compaction curve of soil using different proportion of NanoSilica

3.2 Unconfined compressive strength test

Effect of Nanosilica on UCS of soil

The UCS test was conducted for Nanosilica Mixed soil and the stress- strain results are representing in Fig 2. Result from the study shows that, by increase nanosilica percentage the UCS value increases. So, the Optimum Nano-silica content is Found 1.5% and corresponding UCS value is 208.17 KN/m². The UCS of Optimum Nano silica of 1.5% stabilized soil increased by factor 2.58 when compared with that of natural soil.

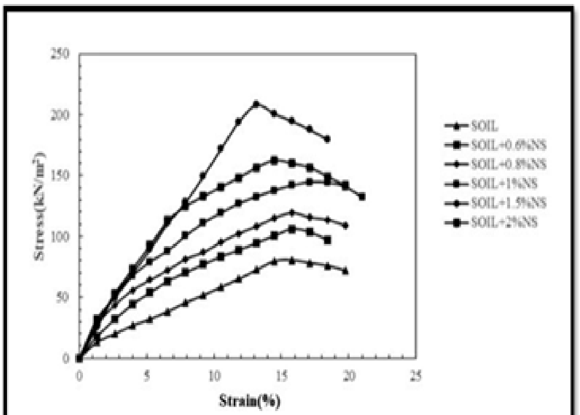


Fig. 2. Stress-strain curve of soil using different content of Nanosilica

3.3 California Bearing Ratio test (CBR)

Effect of Nano silica on CBR of soil Soaked CBR test CBR Value is important engineering parameter to evaluate a sub-base and "sub-grade material for design of pavement". Results shows that addition of Nanosilica, increase the soaked CBR up to Nanosilica Content 1.0%, then the CBR value decreases. The soaked CBR value increases from 1.81% to 3.03%, when 1.0% Nanosilica mixed with soil. Thus, Maximum percentage of Nanosilica for soaked CBR is 1.0%. The load penetration curve for soaked soil sample treated with different percentages of Nano-silica are given in fig 3 and 4.

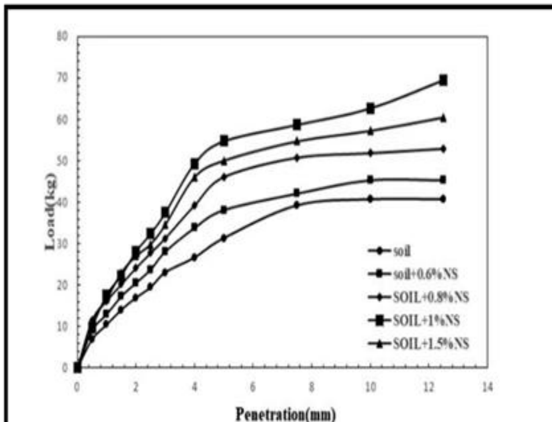


Fig. 3. Load-Penetration Curve for Nano-silica Reinforced Soil Obtained from Soaked CBR test

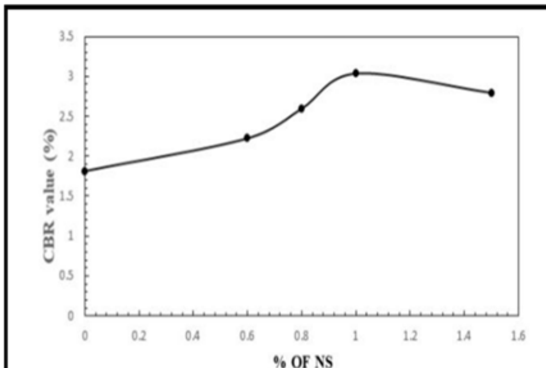


Fig. 4. Effect of Nanosilica on Soaked CBR of Soil

Unsoaked CBR test

The Unsoaked CBR value test results of soft soil treated with different percentage of Nano silica are given below in Fig 5, 6. In addition of different percentages of Nanosilica, increasing Nano-silica content significantly increased the Unsoaked CBR value when compared to virgin soil. The CBR value increases from 3.46% to 9.32%, when 1.0% Nano-silica was added.

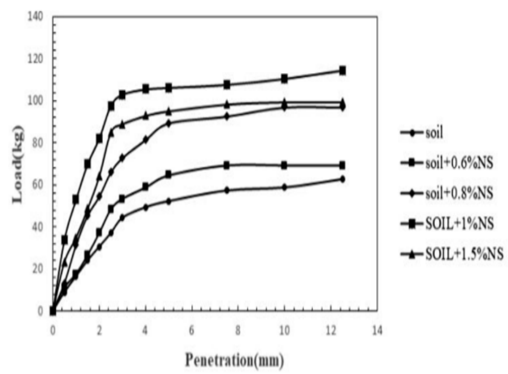


Fig. 5. Load-Penetration Curve for Nano-silica Reinforced Soil Obtained from Unsoaked CBR

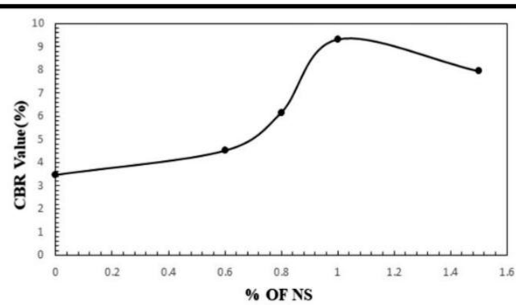


Fig.6. Effect of Nano silica on Unsoaked CBR of soil

3.4 Scanning Electron Microscope (SEM) test

In this samples "were carried out for" SEM test i.e. untreated natural "soil, soil treated with" 1% Nanosilica Which is shown in Fig 5.29 (a), (b). Examining SEM image reveals the Individual particle's surface texture and morphology. According to the results adding Nano-silica to soil may help to improve the shearing resistance. When water is added with nano-soil composite viscous gel is occur because of mixing water with Nanosilica frictional strength between soil particles enhance due to presence of viscous gel. The nano-soil makes the soil particles distances lesser, produce denser soil matrix. It means increasing nano soil results improve effective interfacial contact area between soil contents and enhance the interfacial friction and bond strength.

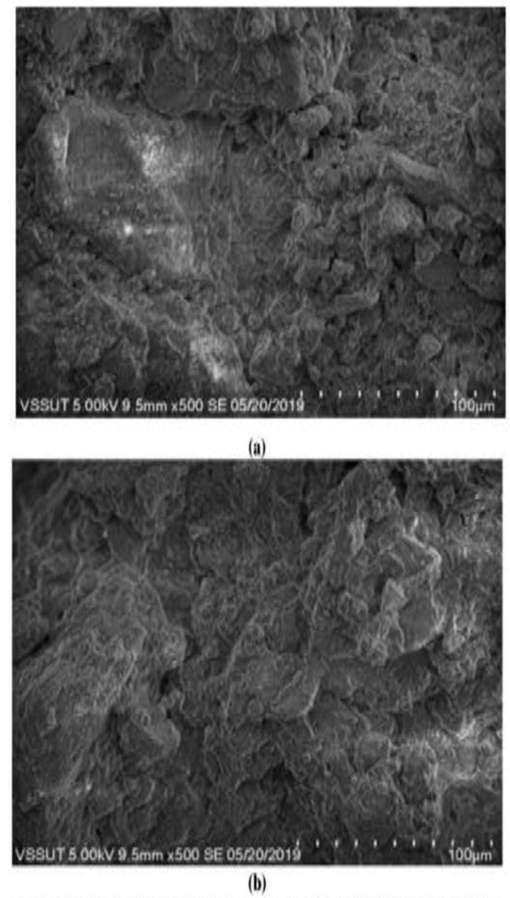
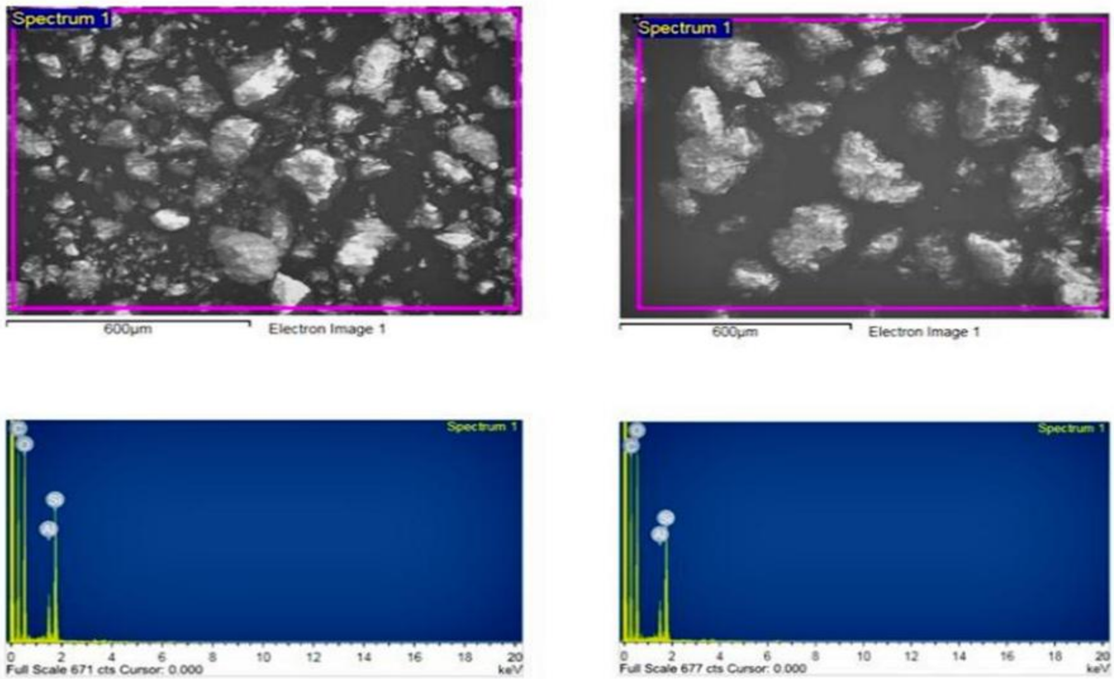


Fig. 7. SEM images of soil specimens (a) untreated soil (b) soil stabilized with Nanosilica

3.5 Energy-Dispersive X-RAY Spectroscopy (EDS)

Fig 8 (a), (b) shows the EDS of soil, soil + Nano-silica, samples. From EDS analysis it is observed that the component of soil nearly equal to the components of soil with Nano-silica mixture, it means Nano-silica cannot do any chemical reaction with soil EDS test is used for analysis of elements and chemical characterization of a sample. It depends on an interaction of few sources of X-Ray excitation and sample. The Basic study of this analysis is to know each element has a unique atomic structure allowing unique set of peaks in its X-Ray emission spectrum.



Elem...	Weight%	Atomic%
C K	43.43	51.81
O K	50.04	44.82
Al K	1.69	0.90
Si K	4.85	2.47
Totals	100.00	

Fig. 8 (a) EDS of soil sample

Elem...	Weight%	Atomic%
C K	45.61	53.89
O K	48.71	43.21
Al K	1.45	0.76
Si K	4.24	2.14
Totals100.00		

Fig. 8(b) EDS of soil + Nano silica

3.6 Compaction characteristics

The variation in the maximum dry density and the optimum moisture at different percentage of cement and additive is illustrated in Figs. 3Fig. 4, Fig. 5 and 6. There were three replicates done to ensure the reproducibility and average value of the MDD and OMC were taken into consideration. It has been noticed that the addition of 3 % cement in the soil led to an increase in the optimum moisture from 11 % to 12 %, whereas the maximum dry density decreased from 1.771 to 1.723 g/cm3. This enhancement in the OMC can be attributed to the increase in specific area, which results in requirement of large amount of water to hydrate the soil particles. Further, the decrease in MDD can be explained due to the flocculation and agglomeration and the cementation of the soil particles, which have been reported in previous works

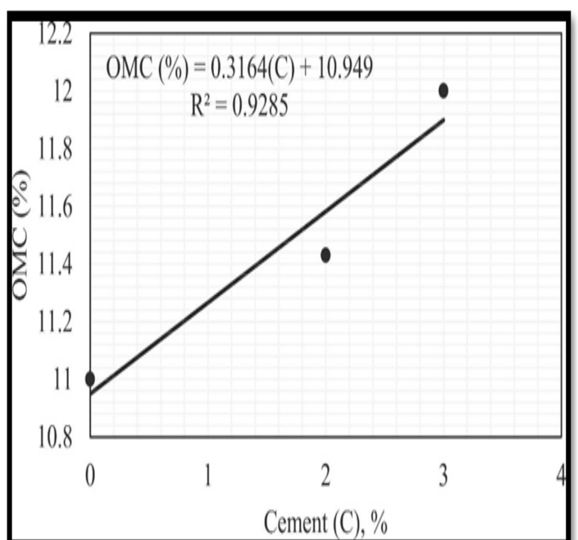


Fig. 3. Optimum moisture content vs cement content.

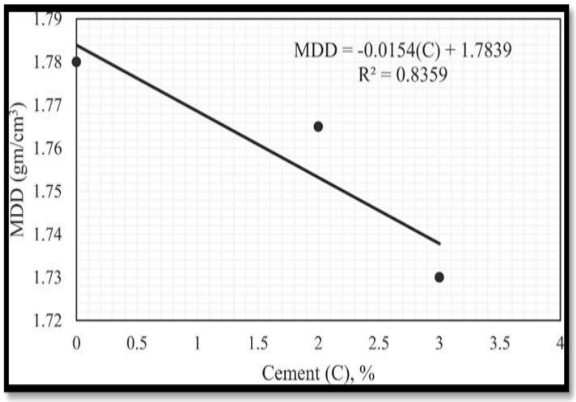


Fig. 4. Maximum dry density vs cement content.

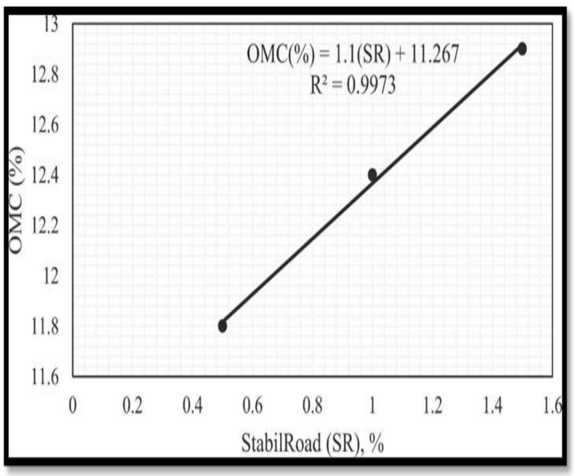


Fig. 5. Optimum moisture content vs additive content.

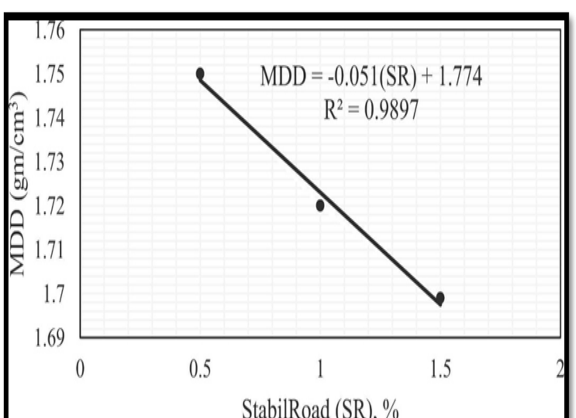


Fig. 6. Maximum dry density vs additive content.

3.7. California bearing ratio

CBR value of the sandy-clayey soil under unsoaked and soaked conditions were tested and found to be 9.0 % and 3.8 %, respectively. On introducing cement to the soil, CBR values increased by 172.22 % and 181.58 %, respectively, which indicates an increase in strength and stiffness of the mixture as shown in Fig. 7. This increase in strength can be attributed due to the attractive forces and the capillary action between the large cluster of cement, clay, and the cement gel [52]. As stated in IRC SP 89 [53], the minimum percentage of cement should be selected, that achieves the minimum specified CBR and it should also incur a lower cost of the subgrade. Therefore, 2 % of cement was chosen as the optimum amount based on these two criteria.

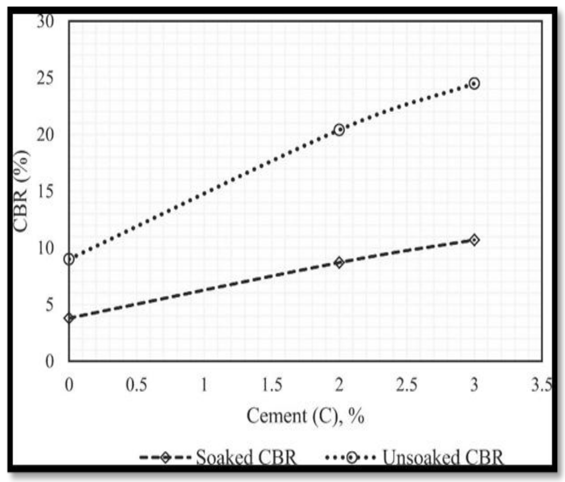


Fig. 7. CBR test results.

3.8. Unconfined compressive strength (UCS)

UCS test has been carried out to assess the effectiveness and contribution of the additive for modifying the strength of soil mixture. The increase in the percentage of the additive on the cement modified soil significantly improved compressive strength of the specimens, as shown in Fig. 9. The compressive strength of soil mixture increased by 70.15 % for 7 days curing period and 88.36 % for 28 days curing period with an increase in the additive content from 0 % to 1.5 %. A significant jump of 23.68 % for 7 days and 42.84 % for 28 days were found as the additive content increased from 0.5 % to 1.0 %, although there was a marginal increase beyond 1 %. This same trend has been exhibited as shown in the CBR test results. Further, the effect of curing time on the specimens containing different percentages of the additive was also observed. It was found that the mixtures attained sufficient strength within the first 7 days of curing. For example, the 1 % additive content treated had a compressive strength of 745.2 kPa, which is 54.77 % more than the compressive strength of the soil-cement mixture. Hence, 1 % additive was chosen as the optimum content to be used in the cement modified soil mixture.

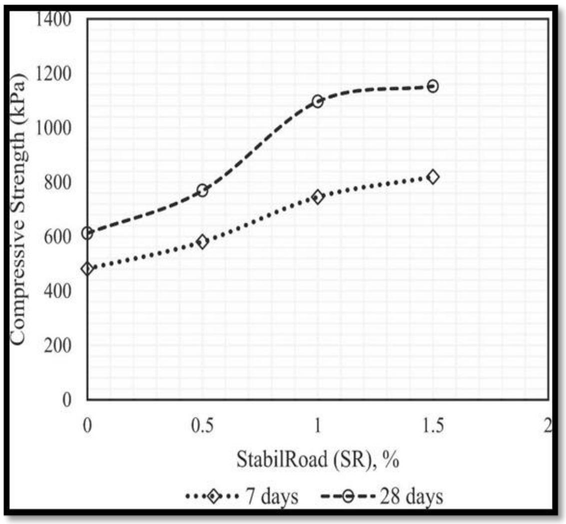


Fig. 9. Unconfined compressive strength test results.

3.9. Economic analysis

The flexible pavement for the rural road sections was designed based upon the soaked CBR values as mentioned in the chart shown in IRC SP 72-2015 [66]. The soaked CBR values taken for study were 3.8 % for soil mixture, 8.7 % for cement modified soil mixture and 15.0 % for Stabil Road cement modified soil mixture. The overall thickness required at different traffic loads varying from 10 to 2000 Equivalent Single Axle Load (measured in thousands) was calculated for each soaked CBR as shown in Fig. 14. It can be clearly seen from the figure that inclusion of cement to the soil mixture resulted in reduction of thickness varying from 26 % to 46 % in comparison with the untreated soil mixture. Furthermore, inclusion of this additive to the cement modified mixture resulted in further reduction varying from 30.43 % to 55.35 % as compared to the soil mixture. As thickness required by the additive mixture is less compared to the other treatments applied, there would be less requirement of materials and less utilization of transportation which ultimately leads in minimizing the carbon footprints.

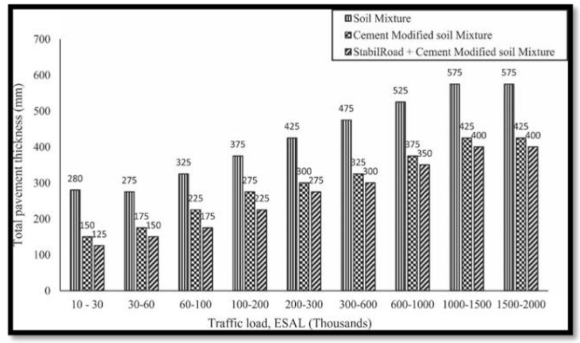


Fig. 14. Total required pavement thickness (mm) at different traffic loads (ESAL).

In order to check the viability of the additive in the cement modified mixture, the cost of the overall pavement was compared. Three types of pavement A–C (as shown in Fig. 15), which were designed using CBR values for untreated soil mixture, 2 % cement modified soil mixture and 2 % cement modified soil mixture containing 1 % additive, were taken into consideration for this study. For the present analysis, traffic load was assumed to be 1000–1500 ESAL and a 7 m width of the pavement carriageway was taken with the length of the section assumed to be 1 km. For determining the cost of pavement, the volume of the material required at each thickness was computed and then it was multiplied by the rates given by CPWD [67] and the price of the additive and its construction cost was taken from its one of the distributors in India [68]. The amount of material required for each thickness, machinery, transportation and labor cost were only taken into consideration for computing the cost of the pavement. As seen from Fig. 16, the pavement with composition C which had StabilRoad in the cement modified soil mixture resulted in saving 42.48 lakhs rupees which is approximately $55,914 per km as compared to the Pavement A which had untreated soil mixture. Further, the Pavement C also had Rs. 6.55 lakhs rupees lower cost which is approximately $8619 cost per km as compared to the Pavement B which had cement modified mixture. The cost comparison indicates that this additive not only results in improving the engineering properties of the soil and reducing the carbon footprints but it also saves the cost of the overall pavement.

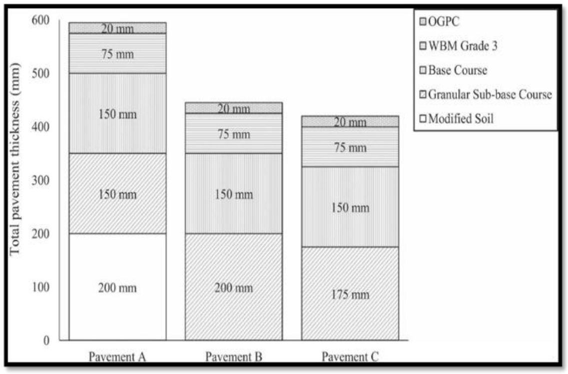


Fig. 16. Overall cost of pavement with and without modified soil mixture.

IV. CONCLUSIONS

Nowadays, Analysis on the application of Nanomaterials has become a large topic follow from economic advantage. To review the result of nano-material on engineering properties of soil, an experimental program was carried out by adding Nanosilica on the soft soil. The following Conclusions can be taken from the Experimental outcomes.

1. "The MDD values of soft soil initially increased with addition of" Nanosilica then decreased after optimum. "The MDD value" increases up to 1% of Nanosilica thereafter its value consistently decreased. In the other hand OMC has continuously decreased" with by using nanosilica in soil.
2. The UCS values of soft soil without curing increases up to 1.5% of Nanosilica and after that decreases.
3. Both the CBR soaked and unsoaked values increases with use of up to 1% nanosilica. Soaked CBR value gives better result for both subgrade and pavement construction."
4. Inclusion of nanosilica to the soil it showed formation of a very dense matrix SEM image in which pores were filled to a large extent and interlock between the particles increases which helps to improve the strength of soft soil.

In this paper, it is noticed that the method of soil stabilized with Nanosilica and is a considerably applied method of ground improvement, which increases the shear strength, UCS, and both soaked and unsoaked CBR of soil. Because of this, it increases the stability of structures, i.e. foundation and roadbed. This improvement technique can be considered as a practical method for improvement of mechanical behaviours of soil in civil engineering project.

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