https://doi.org/10.3311/PPci.23136 | 999
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Periodica Polytechnica Civil Engineering, 68(3), pp. 999–1012, 2024

Laboratory Investigation and Field Performance Evaluation of Chemically Stabilized Cement Treated Subbase

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Received: 05 August 2023, Accepted: 19 March 2024, Published online: 27 May 2024

Abstract

There is a growing concern over the depletion of naturally occurring construction materials for lower unbound pavement layers. Stabilization of locally available materials has attracted considerable research interest. Nanotechnological additives have a good potential in stabilizing materials that are incompatible for pavement construction. The main aim of this research is to evaluate the use of nano-chemical additives on the laboratory and field characteristics of cement treated subbase (CTSB) mixes prepared with locally available soil. Locally available soil, cement, and nano-chemicals were utilized to assess their effect on California bearing ratio (CBR) and unconfined compressive strength (UCS) of chemically treated subbase mixes. The UCS of the soil-aggregate mix treated with cement improved by 103.4% on the addition of nano-chemical additives. The soaked CBR of the mix treated with the optimum dosage of cement and nano-chemical was increased by 219%. The laboratory-based evaluation was followed by construction of field sections utilizing the control subbase (soil-aggregate only), cement-treated subbase, and cement+nano-chemical treated subbase mixes. Deflectometric investigations were performed on the field sections using a light weight deflectometer. X-ray diffraction and scanning electron microscopy tests were carried out to study the microstructure of subbase mixes. Stabilisation using nano chemicals resulted in additional phases of ettringite that caused densification of matrix compared to pristine soil-aggregate mix. Pavement analysis and economic analysis of the different subbase mixes were also performed. The subbase prepared with 3% cement and 1.2 kg/m^3 dosage of nano-chemical additive was found to be the optimum considering laboratory and field performance.

Keywords

cement treated subbase, light weight deflectometer, field evaluation, chemically treated subbase, microstructural analysis

1 Introduction

Unbound pavement layers (subgrade, subbase, and base layers) contribute significantly to the overall pavement performance. Materials with poor quality, if used in unbound pavement layers, may lead to failure of the pavement infrastructure resulting in pavement distresses like rutting and fatigue cracking. Rutting distress can be due to the failure of lower unbound pavement layers, which could be due to the use of incompatible/weak materials. Soil-aggregate mixes or granular materials are mostly used in pavement subbase. Several soil types present in India pose challenges in regard to their use in road construction; for example, black cotton soil has significant swelling and shrinking characteristics [1, 2]. Fine-grained soils like clay and silt can swell and lose strength. To mitigate the problem, proper soil stabilization becomes necessary. In civil engineering, stabilization refers to the techniques used to refine and enhance a material's engineering properties, including strength, compressibility, durability, and permeability.

Naturally occurring materials are depleting at a rapid pace, which results in a high procurement and processing cost of these materials. Stabilization techniques, especially with additives/admixtures, have gained widespread interest in recent decades within the pavement engineering domain. Stabilizing admixtures could be used with locally available materials to improve the properties since total replacement of the inferior material could be economically exorbitant [3]. Earlier studies have shown that the use of cement and fibres has been a usual practice to improve the mechanical and engineering properties of weak soils [4, 5].

Cement treated subbase (CTSB) is being widely used as a subbase in the construction of flexible pavements in India. CTSB generally utilizes locally available soil, which

Cite this article as: Hazim, S., Chopra, T., Pathak, R., Kumar, A. "Laboratory Investigation and Field Performance Evaluation of Chemically Stabilized Cement Treated Subbase", Periodica Polytechnica Civil Engineering, 68(3), pp. 999–1012, 2024. https://doi.org/10.3311/PPci.23136

reduces the cost of construction [6, 7]. Although cement adds to the strength, it is quite important to prevent the intrusion of water in the lower pavement layers. In regions where problems of groundwater intrusion exist, water ingress can cause damage to the lower pavement layers. Water infiltration into soil sublayers through surface cracks, shoulder incursion, and capillary rise are key processes that impact how long pavements last. The resilient modulus of the lower pavement layers is significantly reduced due to such water intrusion, which results in pavement damage during wet seasons. Further, in cold climate water seeps into the ground and freezes. Ice formation can result in frost-heave, and ice thawing can result in spring-thaw. The soil layers can experience severe damage from repeated freezing and thawing cycles. It is thus crucial to keep the lower layers of pavement moisture-free to prolong the pavement's life. Adding certain chemicals to cement-treated soil can be a suitable measure to achieve not only increased strength but also sufficient resistance against moisture penetration, making the layers more stable and durable.

Over the past decade, the field of nanotechnology has gained significant momentum in civil engineering applications. Many studies have reported the use of nanomaterials (or nanomaterial derived additives) in stabilization of lower pavement layers. Nanoparticles of SiO_2 were reported to exhibit high pozzolanic activity due to a high amount of pure amorphous SiO_2 [8, 9]. Laboratory and field studies were conducted on the stabilization of expansive clayey soils and artificial gravel using vinyl acetate homopolymer (VAH) and sodium silicate-based admixture (SSBA) with lime additives [10]. Other materials like Terra-zyme and fly ash have also been used to improve the subbase properties [11]. Kushwaha et al. [12] reported an increase in the California bearing ratio (CBR) and unconfined compressive strength (UCS) values after stabilization with Zycocil.

Field evaluation of stabilized granular materials is crucial as it allows evaluation of the performance of stabilized materials subjected to real-life traffic. In this direction, non-destructive testing (NDT) allows for a highly convenient and quick structural state assessment of flexible pavements [13]. A small and affordable equipment called the light weight deflectometer (LWD) has gained popularity for measuring in-situ reactions, including deflections and surface moduli of thin bound/unbound granular layers and thin asphalt pavements [14]. An LWD is a miniature version of a conventional falling weight deflectometer (FWD) and works on the same principle as the FWD. Previous studies have demonstrated the applicability of LWD as an evaluation device for determining pavement layer modulus in the field [15]. Investigations revealed that LWD played an essential role in determining the layer modulus and performing the design of overlay (in case of low-volume roads) [16].

The main aim of this research is to evaluate the effect of using nano-chemical additives on the laboratory and field characteristics of CTSB mixes prepared with locally available soil. The local soil was mixed with aggregates, nano-chemicals and cement. The need of the study stems from the demand to reduce the proportion of aggregates used in the subbase layer while maintaining the layer's strength. This study investigates the optimum proportion of locally available soil, aggregate, cement, and nano-chemical. The study also examines the chemically stabilised subbase layer using various criteria, including UCS, CBR, microstructural analysis, post-construction field evaluation, and economic analysis. Post-construction assessment was performed on the field sections using the LWD to check compaction during construction and to examine deflections thereafter, from which the modulus was determined. Thus, this research work illustrates the performance of stabilized mix treated with cement and nano-chemical which can be used as a sustainable cement treated subbase layer. Fig. 1 presents the research plan for this study.

2 Characterization of materials

2.1 Soil and aggregates

In this study, soil from Ludhiana, India, was analyzed using [17] protocols to determine its physical properties. Table 1 summarizes the soil's physical and chemical characteristics, while from the XRD pattern the material depicted peaks for calcium carbonate and quartz. The soil was identified as poorly graded sand with silt (SP-SM). Additionally, three stockpiles of aggregates (40 mm, 20 mm, and 10 mm) were obtained from a local quarry and evaluated for bulk specific gravity, water absorption, and impact value. Table 2 provides the properties of these aggregates.

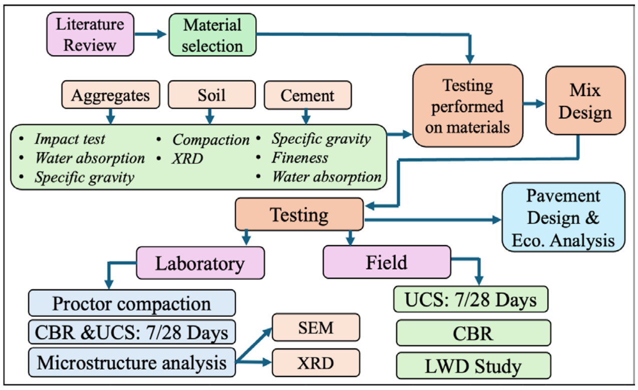


Fig. 1 Research plan for this study

Table 1 Properties of soil

Physical property	Value
Natural water content (%)	3.0
Maximum dry density (g/cm^3)	1.87
Optimum water content (%)	9.30
Specific gravity	2.48
Soil classification	SP-SM
Chemical property	Value (%)
Silica (SiO_2)	70.2
Alumina (Al_2O_3)	16.1
Iron oxide (Fe_2O_3)	5.0
Potash (K_2O)	1.4
Magnesia (MgO)	0.15
Loss on ignition (%)	1.0

Table 2 Properties of coarse aggregates

Aggregate size	Water absorption (%)	Bulk specific gravity	AIV (%)
40 mm	0.39	2.76	13.5
20 mm	0.48	2.70	15.3
10 mm	0.61	2.62	22.8

Note: AIV: Aggregate Impact Value

2.2 Cement

An ordinary Portland cement of grade 43 (OPC-43) was used meeting the requirements of [18] and was obtained from a cement manufacturing industry in Patiala (India). The properties of the cement are given in Table 3.

2.3 Nano-chemicals

The nano-chemicals were obtained from Zydex Industries Pvt. Ltd., Gujarat, India. Two different types of chemicals (ZycoBond and TerraSil) were used in the study. Table 4 presents the properties of the two nano-chemicals. These additives are shown in Fig. 2 and are described further.

TerraSil: It is an organo-silane molecule that combines with soil particles to change their characteristics from hydrophilic to hydrophobic. As a nano-chemical, TerraSil maintains the pores' openness to let vapor escape while preventing water from entering in [3]. This makes the soil less water-sensitive and allows it to be compacted for higher particle interlocking. The additive helps to develop a water-resistant nano-coating on the soils and aggregates. Earlier studies have described the mechanism of formation of 4–6 nm thick alkyl siloxane surface that acts as water repellent nano layer on the aggregate/soil surface [19, 20]. In addition, it works with cement, bitumen emulsions, lime, and other common stabilizers that are used to enhance the properties of soil.

Table 3 Properties of cement (OPC-43 grade)

Physical property	Value
Specific gravity (g/cm^3)	3.12
Fineness (%)	3.0
Water absorption (%)	0.41
Initial setting time (minute)	32
Loss on ignition (%)	1.9

Table 4 Physical and chemical properties of nano-chemicals

Property	TerraSil	Zycobond
Physical state	Liquid	Liquid
Potential usage	Soil modifier (Promotes Hydrophobicity)	Bonding at nano level (80–90 nm flexible acrylic co-polymer)
Colour	White Translucent	Black Translucent
Odour	Faint odour	Faint odour
Boiling point	Approx. 100 °C	Approx. 100 °C
Flash point	>70 °C	>70 °C
Density	0.97–1.02 g/ml	1.00–1.02 g/ml
Solubility	Partly soluble	Partly soluble
Viscosity	20–200 cP @ 30 °C	20–200 cP @ 30 °C
Oxidizing property	Not fire propagating	Not fire propagating

Fig. 2 Nano-chemicals used in the study: (a) Zycobond, and (b) TerraSil

ZycoBond: ZycoBond is an acrylic co-polymer emulsion and nanotechnological additive [21]. It is used for soil stability, topical irrigation, and surface layer sealing as a rolling and dust treatment. It contains nano-polymer having particles less than 90 nm in size. It disperses in the soil, bonding the soil particles and providing erosion resistance, dust control, and fatigue resistance. As recommended by the manufacturer, TerraSil combined with ZycoBond (in 1:1 ratio) was used in this study.

3 Methodology

Different proportions of soil and aggregates (10 mm, 20 mm, and 40 mm) were blended together to check if the resulting overall gradation was in accordance with the MoRTH (2013) specifications for CTSB. Seven gradations were initially chosen and designated as follows: SA_{20} (20% aggregates and 80% soil) to SA_{80} (80% aggregates and 20% soil) with an increment of 10% in the aggregates. Out of the seven gradations, SA_{20} did not meet the MoRTH [22] requirements for CTSB.

The maximum dry density (MDD) and the optimum moisture content (OMC) were determined for remaining six gradations from heavy Proctor compaction tests. Samples were prepared by blending dry soil with different proportions to determine the optimum mix with the highest UCS value meeting the IRC 37 [23] requirements. The samples were tested for UCS, out of which SA_{40} mix was found to have the highest UCS value. The gradation of the mix (SA_{40}) used in this study is shown in Fig. 3. In Fig. 3, the upper and lower gradation limits are specified by [22] specifications for CTSB. The proportions of soil and coarse aggregates (different sizes) resulting in the selected gradation are shown in Table 5.

The optimized soil-aggregate mix (SA_{40}) was then treated with varying cement contents (2%, 3% and 4%) and nano-chemical additives [0.4, 0.8, 1.2, and 1.6 kg/m^3 by weight of mix]. The specimen nomenclature corresponding to the contents of aggregates, cement, and nano-chemicals is illustrated in Fig. 4. For example, the mix $SA_{40}C_4N_{1.2}$ represents soil aggregate mix (40% aggregates and 60% soil) with 4% cement and 1.2 kg/m^3 dosage of nano-chemical additive. The two nano-chemical additives were combined in the ratio of 1:1 for a given content (for example,

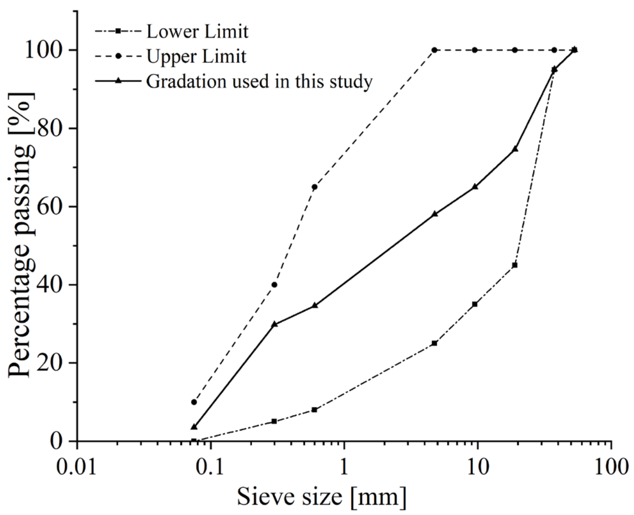


Fig. 3 Soil-aggregate mix (SA_{40}) gradation

Table 5 Proportion of coarse aggregates and soil

Aggregates	10 [mm]	20 [mm]	40 [mm]	Soil
Percentage [%]	15	5	20	60

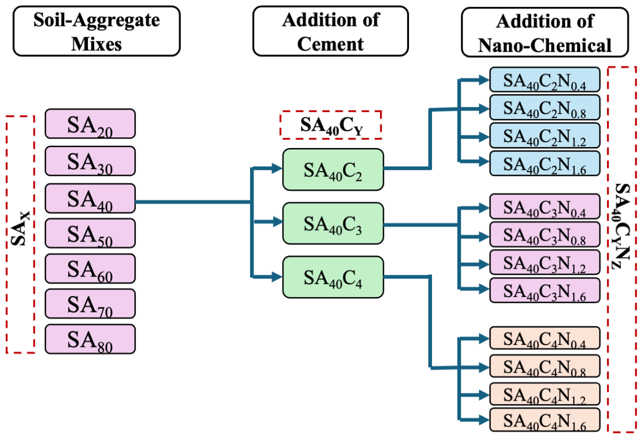


Fig. 4 Nomenclature of subbase mixes with cement and nano-chemicals

0.2 kg/m^3 each of TerraSil and ZycoBond were blended to achieve a nano-chemical dosage of 0.4 kg/m^3). The chemical additives were first blended with water (at the required OMC) and then added to the soil-aggregate-cement mixture. The following experiments were carried out in the laboratory: particle size distribution, Proctor compaction tests, UCS tests, CBR tests, and microstructural analysis by XRD and scanning electron microscopy (SEM). The laboratory tests are described as follows.

The Proctor compaction test, conducted following [24] standards, involved a modified approach to determine the optimum moisture content (OMC) and maximum dry density (MDD) of different soil-aggregate (S-A) and soil-aggregate-cement (S-A-C) mixes. Subsequently, the UCS was determined using an automatic compression testing machine (ACTM) as per IS 516 [25] guidelines. Additionally, the California Bearing Ratio (CBR) test, a widely-used penetration test to assess the strength of unbound pavement materials, was conducted following [26] regulations. The CBR test was carried out on the soil-aggregate-cement mixes after determining their MDD and OMC, and all tests had a soaking period of 96 hours (4 days). Finally, SEM and XRD analyses were performed using a Zeiss Gemini-1 Sigma 500 Emission Scanning Electron Microscope and Rigaku XRD-D1, respectively, on treated and untreated soil-aggregate-cement specimens to gain insights into the underlying mechanisms of cement and nano-chemical effects on various subbase samples.

4 Construction and testing of field sections

In this phase of the study, several field sections were laid with selected dosages of cement and nano-chemicals and were subsequently evaluated using LWD for deflections and moduli. The field sections were located in Ludhiana, India (30°42′N 76°13′E). Six field sections each of length 10 m were identified over a road length of 60 m. One section was the control (Section 1: SA_{40}) without cement and nano-chemicals, three sections contained cement (Section 2: $SA_{40}C_2$, Section 3: $SA_{40}C_3$, Section 4: $SA_{40}C_4$), and the final two sections contained both cement and nano-chemicals (Section 5: $SA_{40}C_2N_{1.2}$, Section 6: $SA_{40}C_3N_{1.2}$). The optimum dosage of nano-chemical was determined as 1.2 kg/m^3 from the laboratory tests (results presented in Section 5), and thus this dosage was used during the construction of field sections. The required quantity of cement was spread in the different sections, followed by spraying the quantity of water corresponding to the OMC. A rotavator was used to mix/blend the soil, aggregate, cement, and water together. To ensure a consistent manual distribution of cement, length and width for spreading the cement bags were marked as shown in Fig. 5. The moisture content of the soil in the field was measured with a moisture meter and was found to be 2.8%. The quantity of water to be added was corrected for the field moisture content. After spreading of cement, the nano-chemical was poured inside the water tanker as shown in Fig. 6 (a).

After proper mixing, samples were taken from each field section for UCS testing, and the molds were filled using a heavyweight and a dry lean concrete (DLC) hammer. The road was ready for compaction after mixing. A three-wheel/drum static road roller was employed for compaction of subbase. To ensure correct compaction at each spot, an LWD was utilized to check the in-situ compaction of soil. After the compaction was completed, the sections were marked for the LWD testing. Four points were chosen in each section, and the LWD test was performed as shown in Fig. 7.

IRC 37 (2018) [22] recommends that the average laboratory strength values should be 1.5 times the field values. The LWD test was performed in the field to check the deflection to ensure proper compaction at the time of laying. LWD is a handy equipment that allows much faster data acquisition and records more properties compared to the conventional sand replacement method, which can only provide field density. After laying the field sections, samples were extracted from the site and brought to the laboratory for UCS testing.

Fig. 5 Spreading of cement on the field sections

(a) (b)

Fig. 6 (a) Adding nano-chemicals, (b) Spraying of water containing nano-chemicals

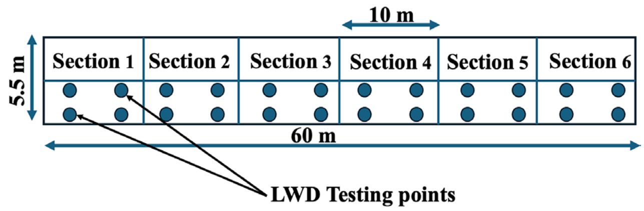


Fig. 7 Plan of road and points for LWD testing

4.1 LWD testing on field sections

LWD test was performed at different points on the six field sections immediately after laying the subbase and after 28 days to compare the modulus and deflection values. The LWD testing locations are shown in Fig. 8. The LWD was used at the time of laying to check the degree of compaction using deflection values. The ratio of the in-situ density to the highest laboratory dry density is used to define the degree of compaction. Testing on each point involved six drops of the base-weight (20 kg). Out of the six drops, the first three were considered as seating loads, and the final drop was used for the evaluation of material properties. Tables 6 and 7 show the average values of different parameters used in LWD testing.

5 Results and discussion

5.1 Compaction curves of S-A and S-A-C mixes

The MDD and OMC values of soil-aggregate (S-A) and soil-aggregate-cement (S-A-C) mixes were determined from heavy Proctor compaction tests. Figs. 9 and 10 show the compaction curves of S-A and S-A-C mixes, respectively. From Fig. 9, it is seen that as the percentage of aggregates increased in an S-A mix, there was an increase in the MDD and decrease in the OMC. Fig. 10 shows that both MDD and OMC increased with the addition of cement. With an increase in cement content, there is an increase in the heat of hydration released, thus increasing the amount of water needed for mixing [27, 28]. The rise in

Fig. 8 Marking of points and conducting the LWD testing

Table 6 Average LWD testing results at the time of laying

Section description	Radius (mm)	Average Load (kN)	Average Stress (kPa)	Average Deflection (μm)	Average E-Mod (MPa)
SA_{40}	150	12.02	169.96	508.86	87.4
$SA_{40}C_2$	150	11.48	162.56	412	118.45
$SA_{40}C_3$	150	12.01	162.93	356.21	129.95
$SA_{40}C_4$	150	12.15	172.04	251	139.15
$SA_{40}C_2N_{1.2}$	150	11.52	162.95	369	123.05
$SA_{40}C_3N_{1.2}$	150	11.31	159.8	361.22	136.85

Table 7 Average LWD testing results after 28 days

Section description	Radius (mm)	Average Load (kN)	Average Stress (kPa)	Average Deflection (μm)	Average E-Mod (MPa)
SA_{40}	150	12.02	169.96	356	128
$SA_{40}C_2$	150	11.48	162.56	274	172
$SA_{40}C_3$	150	12.01	162.93	238	194
$SA_{40}C_4$	150	12.15	172.04	236	195
$SA_{40}C_2N_{1.2}$	150	11.9	172.6	160	283
$SA_{40}C_3N_{1.2}$	150	11.31	172.7	93	488

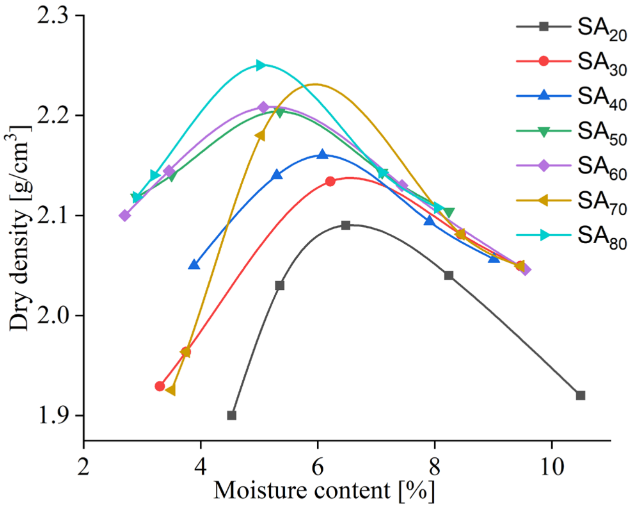


Fig. 9 Compaction curves of SA mixes

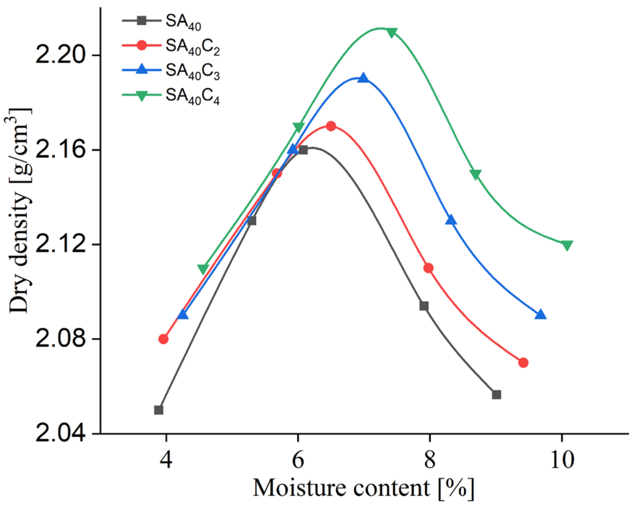


Fig. 10 Compaction curves of S-A mixes at different cement contents

MDD values at higher cement contents are also consistent with the trends reported in past studies [29, 30].

5.2 UCS results

The S-A and S-A-C mixtures with and without nano-chemical additives were tested for UCS, and the results are presented in Figs. 11 to 13. Considering the UCS of S-A mixes (Fig. 11), the maximum UCS was obtained for SA_{40} (soil-aggregate mix with 60% soil and 40% aggregates) at 1.76 MPa. For this reason, the SA_{40} mix was selected for further evaluation with cement and nano-chemical additives.

Fig. 12 shows the UCS values of S-A-C mixes after 7 and 28-days curing. An increase in cement content resulted in a higher UCS value, as also reported in past studies [31, 32]. IRC 37 (2018) specifications require that CTSB should possess 1.5 to 3.0 MPa strength (after 7 days), and therefore there is no need to exceed the cement percentage beyond 3% as it may be uneconomical. The addition of cement from 2% to 4% increased the 7-days UCS from 2.03 MPa to 2.6 MPa which is 28% increase. Comparing 7-days and 28-days UCS, the percentage increase in the strength for mix with 2%, 3% and 4% cement contents was 110%, 112%, and 118%, respectively. An increase in cement content causes greater production of C-S-H gel forming cementitious compounds and thus imparts greater strength to the mixes [33].

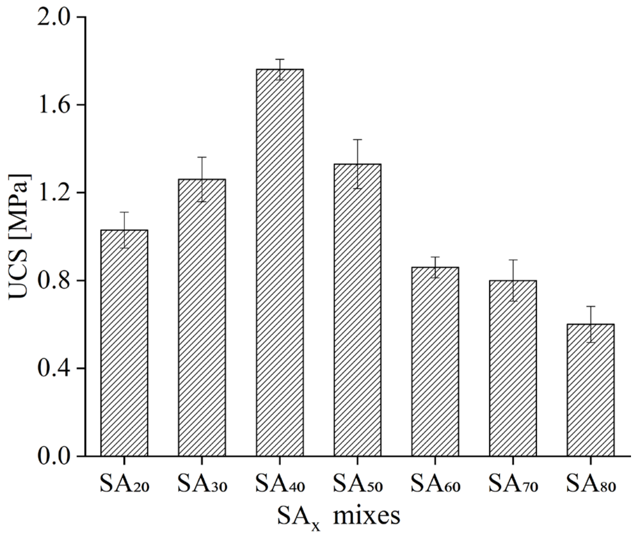


Fig. 11 Average 7-days UCS of SA_x mixes

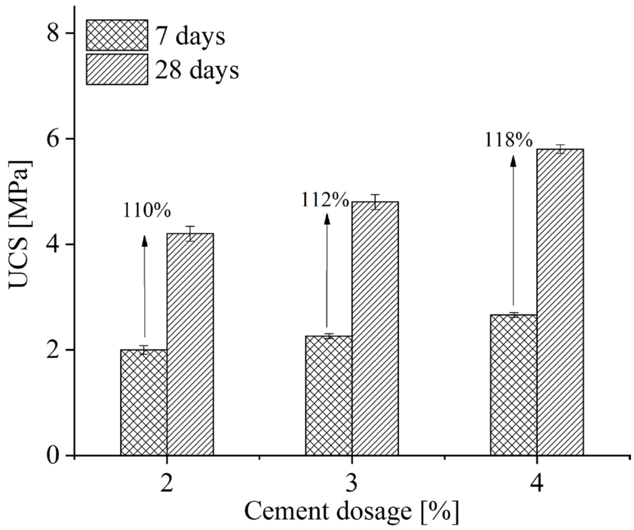


Fig. 12 Variation of average 7 and 28 days UCS of SA_{40} mix with cement content

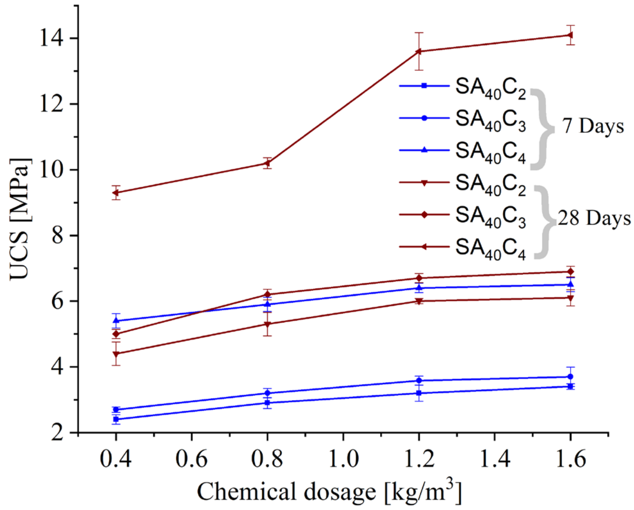


Fig. 13 Variation of 7 and 28 days UCS of S-A_{40} mix with different nano-chemical and cement contents

Fig. 13 presents the UCS values of CTSB mixes with different nano-chemical dosages after 7-days and 28-days curing. The Fig. 13 shows an improvement in the 7-days and 28-days UCS values with an increase in the nano-chemical dosage. The 7-days strength development beyond 1.2 kg/m^3 dosage of nano-chemical was minimal, hence the optimum dosage of nano-chemical was determined as 1.2 kg/m^3. Additionally, sufficient 7-days strength (3.58 MPa to 6.7 MPa) was attained satisfying the IRC 37 (2018) requirements (i.e. 1.5 to 3 MPa after 7 days) using 1.2 kg/m^3 dosage. Hence, there was no need to increase the nano-chemical additive concentration beyond 1.2 kg/m^3 as it would become uneconomical. The minimal improvement in the strength as the dosage of the nano-chemical increased beyond 1.2 kg/m^3 could be due to the agglomeration of nano-chemical particles in the SA_x matrix, which may reduce the rate of strength development. The 7-days UCS values for $SA_{40}C_2N_{1.2}$, $SA_{40}C_3N_{1.2}$ and $SA_{40}C_4N_{1.2}$ were found to be 57.6%, 60.5% and 146.2% higher than $SA_{40}C_2$, $SA_{40}C_3$ and $SA_{40}C_4$, respectively. This shows that the effect of nano-chemical is enhanced at higher cement contents.

5.3 CBR results

Soaked CBR tests (after 96 h soaking) were performed on SA_{40}, $SA_{40}C_2$, $SA_{40}C_3$, $SA_{40}C_4$, $SA_{40}C_2N_{1.2}$, and $SA_{40}C_3N_{1.2}$ mixes. Fig. 14 presents the CBR results. The results show that introducing the nano-chemical additive greatly improved the CBR values. It is further observed that with an increase in cement percentage, the CBR value increased and continued to increase with further addition of nano-chemical. The CBR value for the SA_{40} mix that contained soil and aggregate (60:40) was 18.4%, but with the addition of cement the value increased to 37.2% for $SA_{40}C_4$ which is about 102.2% increase in strength. This increase in the strength could be attributed to the increase in the hydration reaction which reduces the porosity by filling the voids as the cement content increases. After treating the mixes with nano-chemical the value of the CBR continued to increase and reached 58.8% for $SA_{40}C_3N_{1.2}$. The addition of nano-chemical densifies the matrix by forming a very dense C-S-H gel within the soil-aggregate matrix. The findings concur with those from earlier studies [34, 35]. Comparing the CBR of control mix (SA_{40}) with the optimal mix ($SA_{40}C_3N_{1.2}$), the addition of cement and chemical increased the CBR value by 219%.

5.4 UCS results for field sections

After laying the field sections, 150 mm cubical samples were collected and then tested for UCS after 7-days and 28-days curing. Fig. 15 presents the UCS results of the samples collected from field sections. The addition of cement from 2% to 4% increased the 7-days UCS from 1.9 MPa to 2.4 MPa, which is 26.3% improvement in strength.

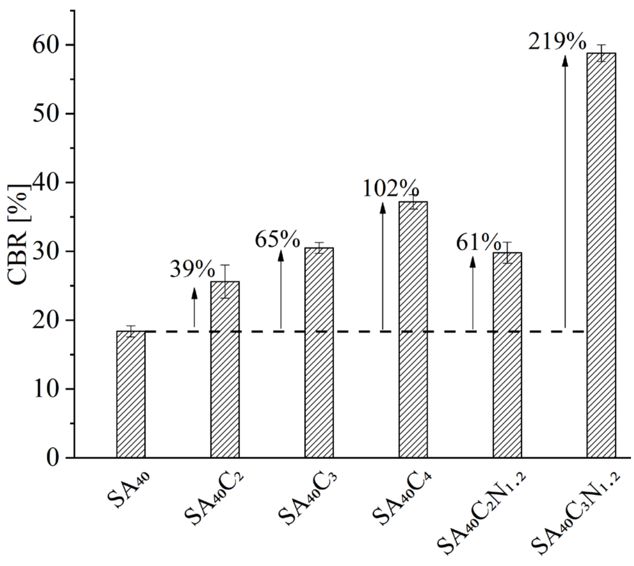


Fig. 14 CBR for different S-A mixes

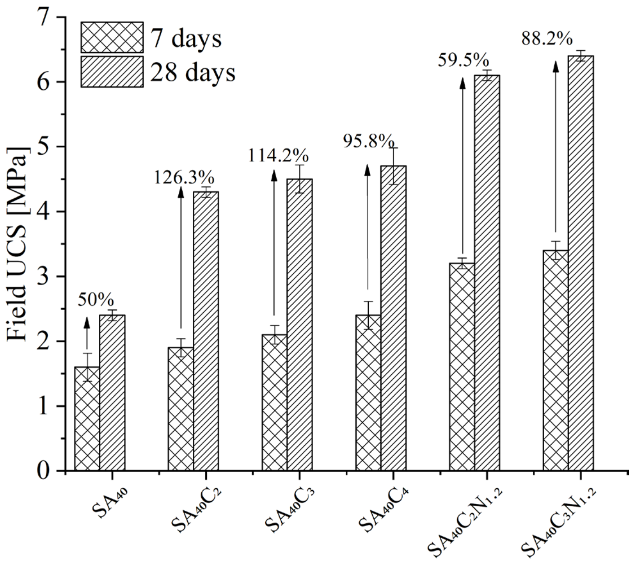


Fig. 15 Field UCS values of S-A mixes

The UCS value increased and continued to improve with the addition of cement and nano-chemical as shown by the 7-days and 28-days UCS. The 7-day UCS for the SA_{40} mix without nano-chemical and cement was 1.6 MPa and it continued to rise to 3.52 MPa for $SA_{40}C_3N_{1.2}$, which is 120% increase in strength. The higher strength is attributed to the availability of nano-chemical for interaction within the soil matrix as compared to the control soil-aggregate mix (SA_{40}). The production of C-S-H gel, which tends to fill the gaps and make the soil aggregate matrix denser may also be responsible for the higher strength.

5.5 LWD testing results for field sections

LWD allows a quick assessment of the compaction quality of soils and unbound pavement layers. The dynamic LWD modulus is empirically associated with the soil's degree of compaction. The LWD modulus values (just after laying and after 28 days) for different field sections are shown in Fig. 16, while Fig. 17 shows the LWD deflection values. The modulus and the deflection are inversely correlated to one another. Figs. 16 and 17 depict that the use of nano-chemical additive enhanced the LWD modulus values and reduced the corresponding deflection. The modulus just after laying of the subbase increased from 87.4 MPa to 139.15 MPa for SA_{40} and $SA_{40}C_4$ respectively, which is a 56.6% improvement. The modulus of $SA_{40}C_3N_{1.2}$ was found to be 136.85 MPa, a little less than that for $SA_{40}C_4$. This could be attributed to a lower content of cement and moreover the effect of nano-chemical might not have been mobilized yet. The 28-days modulus results showed a clear trend with the modulus values rising from 128 MPa to 488 MPa for SA_{40} and $SA_{40}C_3N_{1.2}$,

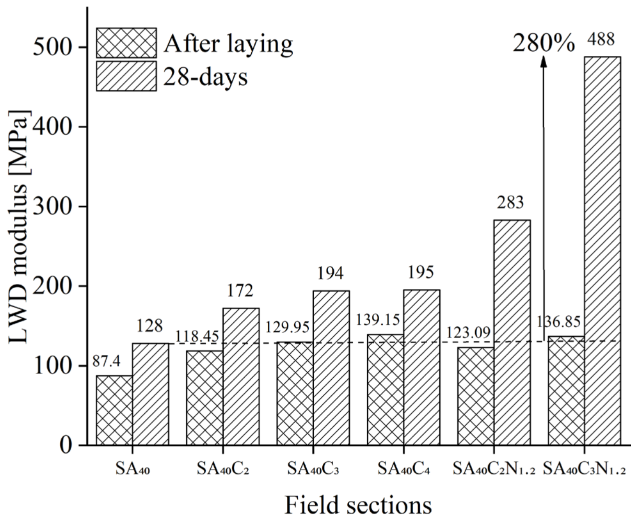


Fig. 16 LWD moduli of field sections at the time of laying and after 28 days

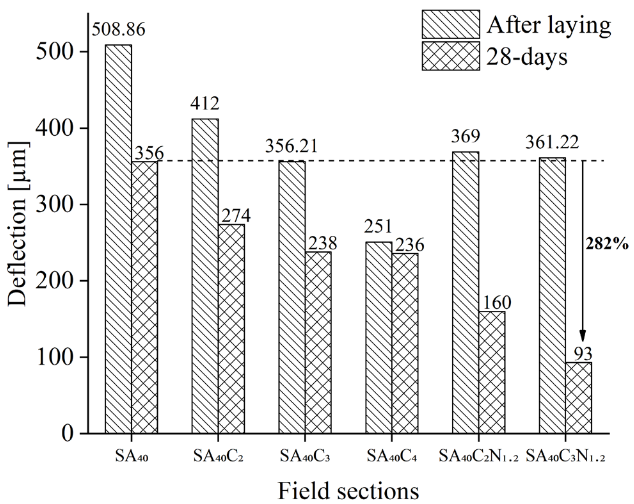


Fig. 17 LWD deflection values of field sections at the time of laying and after 28 days

respectively. The increase in the 28-days modulus value was about 280%. This is because voids in the untreated soil-aggregate mix are filled by cement and the remaining voids are filled by the nano-chemical making the mix denser and ultimately raising the modulus, which is also confirmed by the microstructural analysis (discussed in Section 5.6).

Although the deflection values were measured shortly after laying in order to check the degree of compaction, the highest deflection was observed for SA_{40} field section, which also has the least modulus and the minimum deflection was observed for $SA_{40}C_4$ having the highest modulus. The LWD test was again performed after 28 days. On comparing the modulus and deflection values after 28 days, the mix with the least deflection and highest modulus was found to be $SA_{40}C_3N_{1.2}$, which is considered as the optimum mix in the study.

5.6 Microstructural analysis

The XRD pattern of samples SA_{40}, $SA_{40}C_3$, $SA_{40}C_3N_{1.2}$ are shown in Fig. 18. All samples exhibited SiO_2 as the major phase along with $CaCO_3$. Apart from these crystalline phases, $CaSiAl_2O_6 \cdot H_2O$ phase was also present in $SA_{40}C_3$. With the addition of nano-chemicals in $SA_{40}C_3$ sample, SiO_2 (Q-quartz), $CaCO_3$ (C-calcium carbonate), $CaAl_2Si_2O_8 \cdot 4(H_2O)$ (G-gismondine) and $Ca_6Al_2(SO_4)_3OH_{12} \cdot 26H_2O$ (E-ettringites) phases are observed. Earlier researches have also shown the development of crystalline phases of calcium hydrates, which results in durability and strength [9, 36]. The addition of nanoparticles further enhances the volume fraction of quartz (SiO_2) phase thereby adding more strength to the mix.

The samples were treated with cement (2%, 3% and 4%) and nano-chemicals (1.2 kg/m^3) and SEM analysis was performed after 28 days of curing to understand the morphology of the samples. The SEM images of SA_{40}, $SA_{40}C_3$ and $SA_{40}C_3N_{1.2}$ were taken on the solid samples and are shown in Fig. 19. The Fig. 19 (a) shows that SA_{40} mix contained a large number of pores in the matrix and larger particles of SiO_2 while smaller particles may correspond to $CaCO_3$. It can be observed from Fig. 19 (b) that the addition of cement reduced the samples' porosity and enhanced the binding among the various constituents. The porosity of the soil-aggregate mixture is further decreased by the inclusion of higher concentration of cement and nano-chemical in the matrix as shown in Fig. 19 (c). This might be because of larger concentration of nano-silica available. The cementing action and the formation of C-S-H gel is seen clearly as the cement percentage increased. The development of the cementitious compounds that make up dicalcium and tricalcium silicates may be related to the improvement in the soil-aggregate

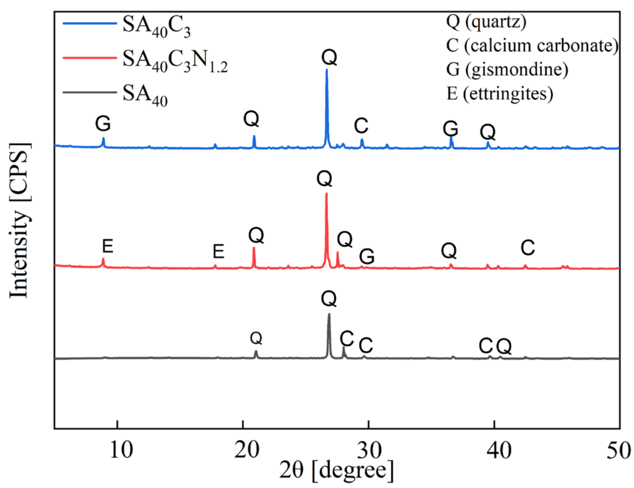
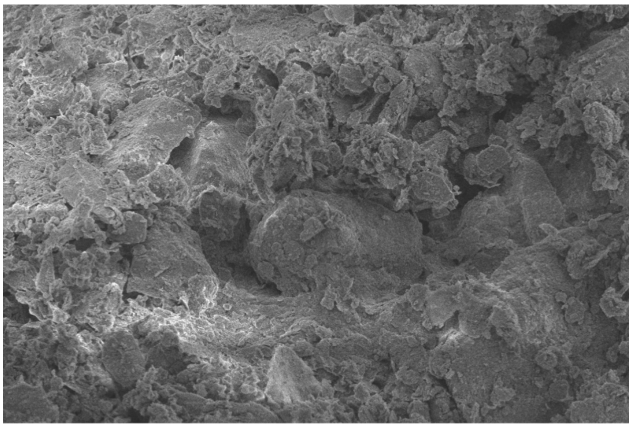
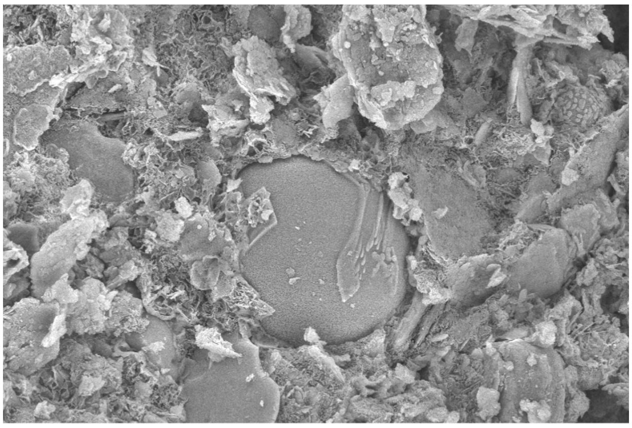


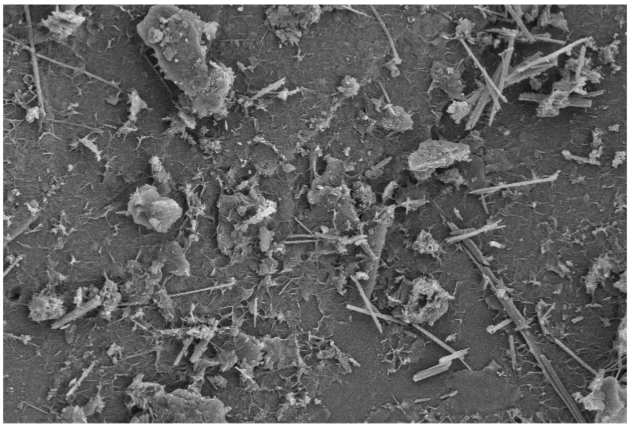
Fig. 18 XRD results for SA_{40}, $SA_{40}C_3$, and $SA_{40}C_3N_{1.2}$



(a)



(b)

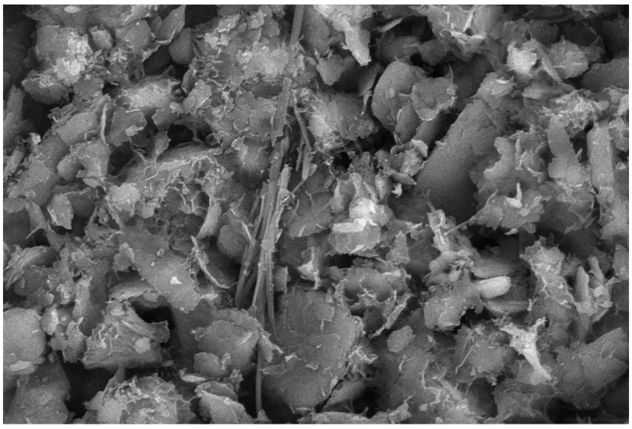


(c)

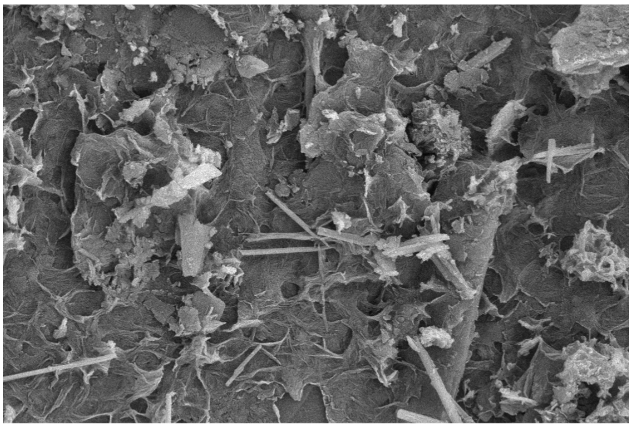
Fig. 19 SEM images of (a) SA_{40}, (b) $SA_{40}C_3$, and (c) $SA_{40}C_3N_{1.2}$

matrix [37]. With the addition of nano-chemicals in $SA_{40}C_3$ a rod type morphology was also observed. It could be related to $Ca_6Al_2(SO_4)_3OH_{12}{\cdot}26H_2O$ (ettringites) crystalline phase. The presence of the nanoparticles tends to fill the pores lowering the matrix's porosity. The highly reactive silica found in nano-chemicals combines with the calcium to create a denser soil matrix through the interlocking of pores which was also seen in the earlier researches [38, 39]. Moreover, adding nano-chemicals along with cement accelerates the hydration reaction, compressing the pores and producing a denser mixture. These results are in a strong agreement with the UCS, CBR and XRD tests presented and discussed earlier.

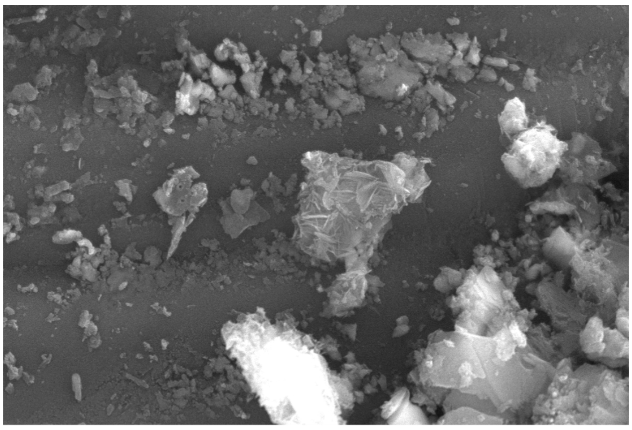
The SEM images show that with an increase in the cement percentage, the densification of the matrix increased, and this is because porosity reduced to a greater extent with the addition of cement. Fig. 20 shows the cement action in presence of nano-chemical. The mix with 4% cement and 1.2 kg/m^3



(a)



(b)



(c)

Fig. 20 SEM images of (a) $SA_{40}C_2N_{1.2}$, (b) $SA_{40}C_3N_{1.2}$, and (c) $SA_{40}C_4N_{1.2}$

nano-chemical ($SA_{40}C_4N_{1.2}$) has a dense composition because of the formation of compounds like SiO_2 and $CaCO_3$ on the surface, which is also reflected from the higher compressive strength (about 126.6% higher than that of $SA_{40}C_2N_{1.2}$).

The addition of cement in SA_{40} increased the mechanical strength of the sample approximately 1.5 times because of the matrix's reduction in porosity, which is clear from the SEM images. Intriguingly, the addition of nano-chemical in $SA_{40}C_3$ sample enhanced the mechanical strength by three times than the SA_{40} sample because of the formation of ettringites that resulted in the densification of the matrix [40].

6 Pavement design and economic analysis

The modulus values obtained from the LWD test were used to analyse the pavement sections using IITPAVE software. IITPAVE is the software used for analysis and design of flexible pavements in India based on mechanistic-empirical philosophy. A design traffic of 5 million standard axles was used to perform the pavement design and analysis. Table 8 shows the allowable and actual strains for different sections obtained from the software. Rutting and fatigue are the two primary distress mechanisms considered in the design of flexible pavements in India. The allowable strains for rutting and fatigue were calculated using the transfer functions proposed in IRC 37 [23]. Results indicate that actual rutting and fatigue strains reduced because the stabilized subbase layer has a higher modulus.

Fig. 21 displays the various layer thicknesses for the conventional design and the designs with stabilized subbases. The conventional section has the highest total pavement crust thickness value compared to other sections. The most optimal section ($SA_{40}C_3N_{1.2}$) has the lowest total thickness and strain values resulting in higher strength. Fig. 22 compares the thickness of the conventional section and the most optimal chemically-stabilized section.

Economic analysis of the pavement sections was also performed in this study. It is desirable that the innovative technologies proposed in the study are relatively economical for ensuing their financial viability for field applications. Inputs used to estimate the cost of a roadway construction project are the road's length, the road's width, the layer's thickness, and the cost of 1 m^3 of the material.

The total thickness for the conventional design came out to be 480 mm and that of the most optimal section was 390 mm, which is a 23% reduction in the thickness. The cost of conventional section was 140.99 lac INR (1 lac INR = 0.1 million INR) and that of the most optimum section ($SA_{40}C_3N_{1.2}$) was 105.9 lac INR which is a reduction of 33% in the cost. Fig. 23 shows the cost comparisons between the conventional design and the most optimal design ($SA_{40}C_3N_{1.2}$). It is evident that the traditional design is quite expensive and the use of cement treated chemically stabilized subbases can lower the cost by 33%.

7 Conclusions

This study assessed subbase materials made with soil-aggregate and soil-aggregate-cement, both with and without nano-chemical additives. Laboratory tests were conducted for compaction characteristics, UCS, and CBR. Field subbase sections were then constructed using the control, cement-treated, and cement+nano-chemical treated mixes, and evaluated with LWD. Pavement design and economic analysis were also conducted. The study's conclusions are presented as follows.

UCS values increased with higher cement and nano-chemical percentages. Optimum dosage was found at 3% cement and 1.2 kg/m^3 nano-chemical. 7-days lab UCS of treated CTSB mix was about 103.4% higher than control. 28-days UCS was approximately 80% higher. 28-days field UCS improved by around 166.7% with 3% cement and 1.2 kg/m^3 nano-chemical in SA_{40} mix.

With the addition of cement and nano-chemical, the CBR value increased from 18.4% for SA_{40} (60% soil and 40% aggregates) mix to 58.8% for $SA_{40}C_3N_{1.2}$ (60% soil and 40% aggregates + 3% cement + 1.2 kg/m^3 chemical). The increase in the percentage of CBR value was 219%.

Table 8 Allowable strains and actual strains for different field sections

Section description	E-Mod (MPa)	Allowable subgrade rutting strain (×10^6)	Allowable fatigue cracking strain (×10^6)	Actual subgrade rutting strain (×10^6)	Actual fatigue cracking strain (×10^6)
Conventional section	186.76			548	318.6
SA_{40}	128			612.3	207
$SA_{40}C_2$	172			611.6	204.4
$SA_{40}C_3$	194	784.3	465	611.1	203.7
$SA_{40}C_4$	195			610.5	203.6
$SA_{40}C_2N_{1.2}$	283			608.1	199.9
$SA_{40}C_3N_{1.2}$	488			566	192.1

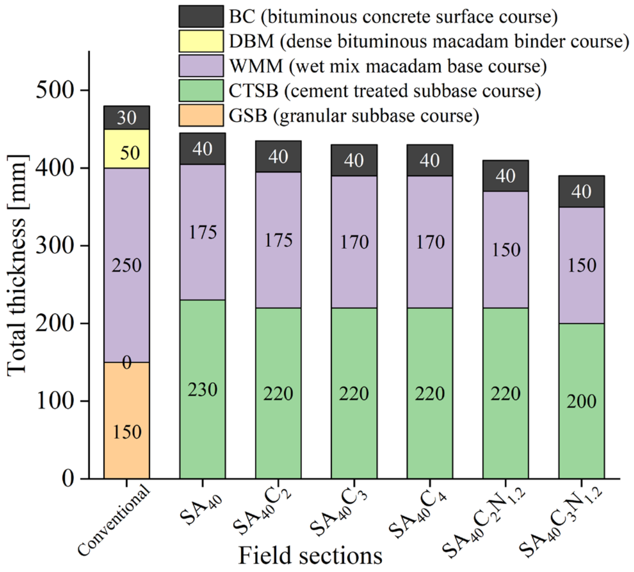


Fig. 21 Pavement design thicknesses for field sections

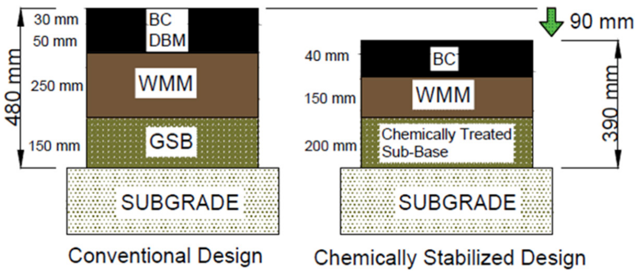


Fig. 22 Thickness comparison of conventional pavement design and design with nano-chemical treated subbase

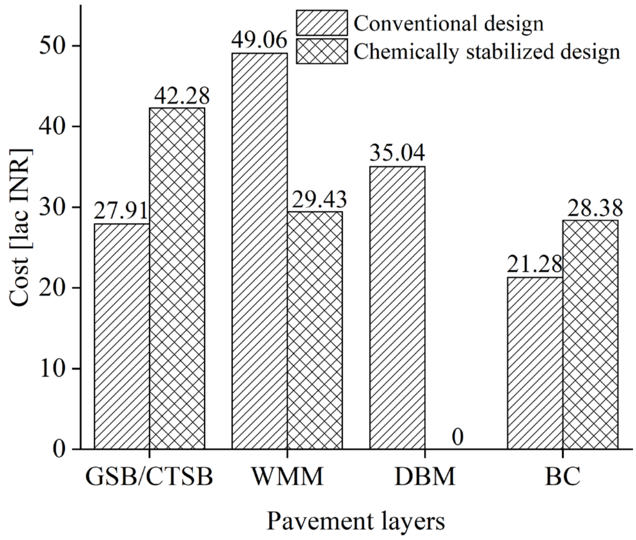


Fig. 23 Cost comparison of conventional and nano-chemical stabilized sections (1 lac INR = 0.1 million INR)

LWD studies showed an increase in the modulus as the nano-chemical and cement dosage increased. The $SA_{40}C_4$ mix had the highest modulus at the time of laying. After 28 days, $SA_{40}C_3N_{1.2}$ mix showed the highest modulus and the least deflection.

Microstructural analysis revealed rod-like structures (ettringites) forming due to the utilization of nano-chemicals, leading to matrix densification. The CSH gel formation's densifying effect was evident in micrographs of soil-aggregate mix treated with cement and nano-particles.

Pavement analysis demonstrated that the optimal sub-base mix $SA_{40}C_3N_{1.2}$ required a 390 mm thickness to support low volume traffic, while the conventional section needed 480 mm. Economic analysis indicated that $SA_{40}C_3N_{1.2}$ was 33% more cost-effective than the conventional pavement for low volume roads.

Future research efforts will focus on a detailed deflectometric study of the field sections using a falling weight deflectometer to assess the material's capability for suitability for use in heavily-trafficked pavements.

Acknowledgments

Nano-chemicals used in this study were sponsored by Zydex Industries Pvt. Ltd. The authors gratefully acknowledge the industry for the nano-chemicals and their cooperation and assistance during the construction of field sections.

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