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Kulkarni and Mandal
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Corresponding Author:
Prasanna P. Kulkarni;
prasanna_kulkarni@iitb.ac.in
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Performance Assessment of Stabilized Soil with Fly Ash- Nano Material Mixes

Prasanna P. Kulkarni
Indian Institute of Technology Bombay, Department of Civil Engineering, Powai, Mumbai, India
Email: prasanna_kulkarni@iitb.ac.in

Jnanendra N. Mandal
Professor, Indian Institute of Technology Bombay, Department of Civil Engineering, Powai, Mumbai, India
Email: cejnm@civil.iitb.ac.in

Abstract

Pavement infrastructure projects require large amount of soil for construction. Very often massive amount of the available soil is found to be weak, highly plastic and expansive in nature, which is unsuitable for constructions. Several studies in the past reveal favorable results for application of problematic soils with additives like lime, cement, fly ash, etc. Since, enormous quantity of fly ash is available from proximity of thermal power stations; the advantage of fly ash can be idealized to stabilize the weak soils. This research paper reports the adequacy of fly ash as an additive in improving the geotechnical properties of medium expansive silty soil in conjunction with nano material. Silty sand was treated with fly ash ranging from 10%, 20%, 30%, 40% and 50% by dry weight of soil. Each proportion was further treated with nano solution with four different dilution ratios of (1:100), (1:225), (1:400) and (1:600) by volume. The CBR properties were found to be highly improved on addition of fly ash and nano material to soil. Similarly, plasticity and hydraulic conductivity properties of the blends were observed to be considerably decreased with the addition of fly ash and nano material. The blends with 30% fly ash and nano solution of (1:100) yielded excellent results. Thus, the soil modified with fly ash and nano material in this research provides a feasible engineered solution to improve the quality and endurance of pavement framework practices and also offers an indubitable contribution towards the problem of fly ash relinquishment and utility.

Keywords: Fly ash, Nano material, Liquid limit, Plastic limit, California Bearing Ratio, Pavements

Acronyms

The following acronyms are used in this technical paper.

CBR = California Bearing Ratio;
CHNS = Carbon-Hydrogen-Nitrogen-Sulphur Analysis;
FA = Fly ash;
FEG-SEM = Field Emission Gun- scanning electron microscope
IRC = Indian Roads Congress;
LL = Liquid limit;
MDD = Maximum Dry Density
MORT&H = Ministry of Roads, Transport and Highways;
Msa = mean standard axles
OMC = optimum moisture content
PS = Powai soil;
PL = Plastic limit;
PI = Plasticity Index;
SAIF = Sophisticated Advanced Instrument facility
Si-OH = Silanol group;
(- Si-O-Si-) = Siloxane bond;
UCS = Unconfined compressive strength;

1. Introduction

The entire growth of any developing nation depends upon a sound pavement infrastructure which will not only improve the economy but also elevate the importance of the nation on a global note. The subgrade which refers to as the foundation soil in roads needs to be properly designed to sustain the vehicular loads coming on to the top of the pavement layers. In this context, the subgrade soil if weak, may pose problems for the overall durability of the pavement structure. Large amount of soil is required for the constructions of roads. Most often, the available soil is found to be weak, highly plastic and expansive in nature which may pose a lot of constructional issues if not treated properly. Therefore, the soil utilized in pavement constructions plays a vital role in deciding the future of safe and durable road networks.

Hence, appropriate treatment of subgrade soil thus becomes prudent for building a good foundation for the roads by resorting to sustainable materials and innovative technology.

Over the past decade, due to rapid industrialization the power generation demands have rose from 1,20,000 MW in 2005 to 2,00,000 MW by 2012 and are expected to reach by 3,00,000MW by 2017 [1]. The combustion of huge quantity of coal utilized for power generation shall not only produce enormous quantity of fly ash but also lead to problems of disposal and applicability in developing nations like India. Fly ash which may contain certain hazardous elements [2, 3, 4] like arsenic, beryllium, strontium, cadmium, mercury, vanadium etc. in trace concentrations may prove to be harmful to human beings when ingested through respiration and cause many diseases like asthma and neurological disorders. If not disposed properly, it can be mobilized to different places and cause severe ecological and terrestrial hazards to mankind. Thus, relinquishment of fly ash is the biggest mission today in light of the environmental panorama which needs to be handled in a skillful manner causing minimal hazards to the society. The potentiality of this material has thus captivated many researchers to adopt it as a backfilling material in various infrastructural applications. Many government bodies and public-sector undertakings since past two decades are enforcing the use of fly ash in day to day practice in the developing countries like India [5].

Many earlier researchers have tried to assess the suitability of fly ash in various applications since past two decades. Stabilization of expansive soils with low calcium and high calcium fly ash with lime as additive reported decrease the plasticity and swelling potential [6]. Shear strength and CBR parameters were reported to be increased with fly ash and cement [7]. Plasticity, hydraulic conductivity and swelling properties were reported to be decreased with increase in fly ash content [8]. Shear strength, CBR and bearing capacity values were increased with fly ash ranging from 9% to 46% [9]. Reduction in plasticity indices in expansive soils were reported with 10% addition of fly ash, with increase in UCS and permeability values [10]. Improvements in CBR values with cement stabilized fly ash with granular blast furnace slag for base and sub base courses in highways were reported in [11]. Increase in UCS values by placing soil -fly ash- soil successive layers and fly ash-soil mixtures stabilized with cement and random polyester fibers [12-13]. Increase in CBR values of silty sand with Class F fly ash mixes were reported in [14].

Several studies of utilization of fly ash related to applications in pavements as sub bases and base materials have also been studied earlier. Increase in UCS values with reference to hydration products and chemical compositions were reported as in [15], strength was reported to be increased to three times whereas plasticity properties and vertical swell indices were reported to be decreased on adding fly ash [16]. UCS, CBR and resilient modulus values were reported to be increased with increase in cement content for fly ash amended soils as base course materials in highways [17], CBR and secant modulus values were reported to be increased on account of addition of waste plastic strips up to 2% to stone dust and fly ash overlying saturated clays [18] Increase in bearing resistance and resilient modulus values were reported to be increased with fly ash reinforced recycled asphalt pavement material (RPM) material significantly [19].

Apart from the conventional materials, the field of nano sciences has gained momentum since the past decade. The importance of nano materials grew all over the globe after the initial talk "There's plenty of room at the bottom- An invitation to enter a new world of physics", where it was investigated of manipulating and controlling things on a smaller scale [20] and thereafter few researchers have tried to analyze the potentiality of these very promising materials in different fields of science and technology. Studies on high volume flyash high strength concrete (SHFAC) using nano silica were discussed as in [21]. The improvements in UCS and CBR behavior using nano composites when added to sewage sludge ash mortar with nano SiO_2 have been presented as in [22]. The effects of flexural fatigue performance of plain cement concrete and concrete containing polypropylene fibers with nano titanium dioxide and nano SiO_2 for pavements have been discussed as in [23]. The general overview of nano particles that exist in soil and fundamental properties that affect the engineering properties of soils were presented in [24]. Few applications of nano technology and nano materials in construction have been presented in [25]. Studies on increase of flexural strength of self-compacting concrete by adding nano zinc oxide have been presented by [26]. Studies on stabilization of cohesive soil using sewage sludge ash/cement with nano aluminum oxide as an additive to improve the subgrade soil have been presented as in [27]. Shrinkage and swelling characteristics of soils were reported to be decreased by doping soil with nano-clay, nano-alumina and nano-copper [28]. Studies on improvement in CBR values and Atterberg limits on Nigerian soils by treating them with organo silane nano material have been presented as in [29]. Improvements in CBR and UCS properties of soils treated with nano silica and cement in applications related to pavements have been reported earlier as in [30- 32]. Studies on improvement in physical properties of weak soils using carbon nano tubes, carbon nano fibers, nano bentonite, laponite etc. have been reported as in [33-34]. The use of nano clay and nano cement in soft soil in improving the compaction characteristics, plastic behavior and strength have been reported as in [35].

The science of nano materials is one such emerging field which has brought revolutionary changes in the field of engineering and technology. Studies on nano materials reveal the diversity of applications in almost all the fields. There is enough evidence of success rates in the cement and concrete industry with the application of nano materials. However, there is still a wide scope in the field of geotechnical engineering and pavement technology, where more research is needed to establish the significance of these contemporary materials by assessing their interaction with different types of soils. Organo silane compound is one such promising material which works on the concept of nano technology and promises to be very effective in stabilization of soils particularly in the road applications [29]. This research is thus an attempt to showcase the potentialities of nanotechnology in conjunction with readily available wastes such as fly ash by conducting simpler laboratory tests and optimizing the proportions, thereby indubitably contributing the nation towards the relinquishment and utility of fly ash.

2. Basic Characterization of Materials

2.1. Fly ash

Fly ash was procured from a thermal power station near Khopoli, in the Raigad district of Maharashtra. The fly ash is being denoted here as 'FA'. Table 1 below represents the physical properties of fly ash.

Table 1: Physical properties of Fly ash

Properties	Values
Specific gravity [36]	2.093
Maximum dry density (gm/cm^3)	1.07
Optimum moisture content (OMC) %	28.5
Coefficient of permeability, k (cm/sec)	1.061 x 10^{-6}
Gravel	--
Sand	26.5%
Silt	70%
Clay	3.5%
D_{10} mm	0.007
D_{30} mm	0.02
D_{60} mm	0.046
Uniformity coefficient (Cu)	6.57
Coefficient of curvature (Cc)	1.24
Group symbol (USCS) [37]	SM
Liquid Limit (%)	Non-Plastic
Plastic Limit (%)	Non-Plastic
Soaked CBR(%)	5.6

The figures below 1 and 2 depict the modified proctor compaction curve and the Particle size distribution curve of Fly ash.

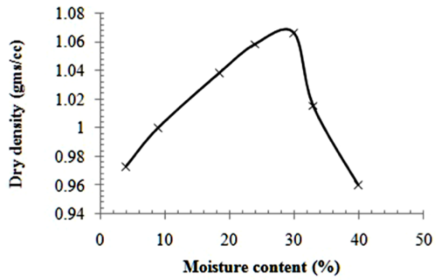


Fig. 1. Modified proctor compaction curve of Fly ash

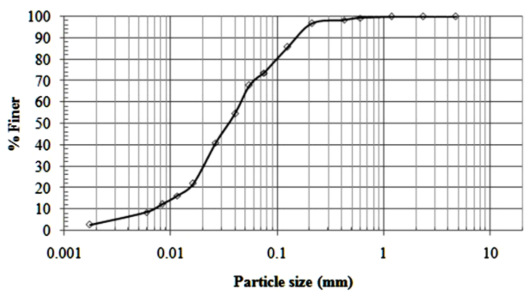
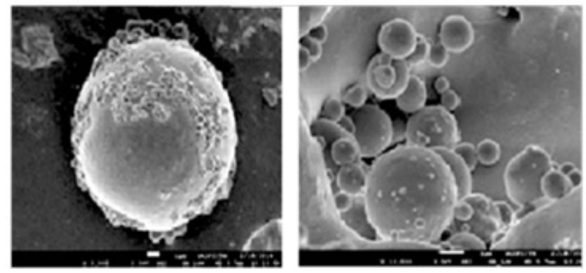


Fig. 2. Particle size distribution curve of Fly ash



(a) (b)

Fig. 3. Scanning Electron Microscope images of Fly ash

The chemical analysis of Fly ash and soil was carried out by X-Ray Fluorescence test (XRF) in the Department of SAIF, IIT Bombay. Table 2 below represents the chemical composition of Fly ash. The Fly ash is seen to be very rich in Silica (SiO_2) of about 62.7% and low Calcium oxide content (CaO) of 0.905%. The Fly ash was classified as Class 'F' Fly ash [38].

The microstructure of Fly ash was studied by performing Field Emission Gun Scanning Electron Microscope (FEG-SEM) tests in the Department of SAIF, IIT Bombay.

Table 2: Chemical composition of Fly ash

Constituent	**(%)**
CaO	0.905
Fe_2O_3	5.152
K_2O	0.927
MnO	0.029
P_2O_5	0.188
SO_3	0.015
SrO	0.056
TiO_2	1.642
Al_2O_3	26.986
BaO	0.068
MgO	0.545
SiO_2	62.799
Na_2O	0.110
LOI	0.578

The images were obtained by SEM model (JSM-7600F) with a resolution of 1.0nm (15kV) under a magnification of x25 to 1000,0000. Fig. 3(a) and 3(b) depict the scanning electron microscope images of Fly ash obtained by Field Emission Gun Scanning Electron Microscope (FEG-SEM).

2.2 Soil

Locally available soil called 'Powai soil' was obtained from the premises of IIT, Bombay. The soil is denoted as 'PS'. Table 3 below represents the physical properties of soil.

Table 3: Physical properties of Soil

Properties	Soil
Specific gravity [36]	2.63
Maximum dry density (gm/cm^3)	1.72
Optimum moisture content (OMC) %	19 %
Gravel	19 %
Sand	35.9 %
Silt	32.8 %
Clay	12.3 %
Liquid Limit (%)	45.4
Plastic limit (%)	30.73
Shrinkage limit (%)	16.23
Plasticity Index (%)	14.67
Group symbol (USCS) [37]	SM
Coefficient of permeability 'k' (cm/sec)	3.457×10^{-5}
Unsoaked CBR (%)	33.36
Soaked CBR (%)	14.07

Fig. 4 and Fig. 5 represent the modified proctor compaction curve and the Particle size distribution curve of Powai soil.

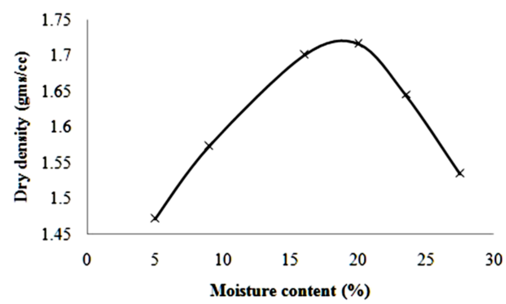


Fig. 4. Modified proctor compaction curve of Powai soil

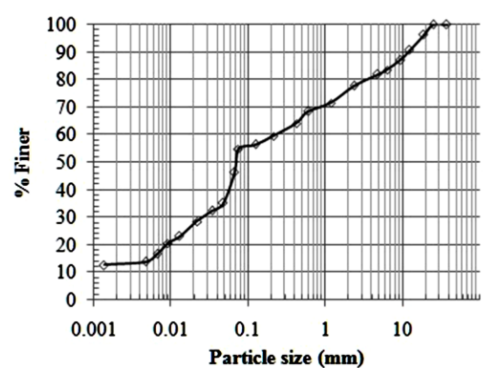


Fig. 5. Particle size distribution curve of Powai soil

The elemental composition of soil was done in the Centre of SAIF at IIT, Bombay by X-Ray Flourescence test (XRF). Table 4 below represents the elemental composition of Powai soil.

Table 4: Elemental composition of Powai soil

Constituent	(%)
Al	4.869
Si	13.346
K	0.354
Ca	2.316
Ti	1.610
Fe	8.643
Ni	49.561 ppm
Zn	127.312 ppm
Na	0.753
Mg	0.619
P	0.048
V	412.350 ppm
Cr	183.889 ppm
Mn	0.162
Sr	67.075 ppm
Cu	116.842 ppm

2.3 Nano material

Nano material, basically an organo silane compound, was obtained from Zydex Industries, Vadodara, Gujarat, India. The material used here is designated as ‘nano material’.

The commercial name of the nano material has been quarantined ensuring the furtiveness of the product. The nano material is a pale yellowish viscous liquid which can be dissolved in water. Nano material is basically an Organo silane compound, nonfunctional organic R (alkyl) group and tri alkoxy groups. RnSi(OR)4-n is the basic structure of organosilanes with "R" being an alkyl, aryl, or organofunctional group and "OR" being a methoxy, ethoxy, or acetoxy group. The compound on reacting with water i.e. hydrolysis forms silanol (Si-OH) groups. These silanol groups have a greater affinity towards oxygen and can form siloxane (= Si-O-Si=) bonds with the surface silanol groups of silica containing substrates like soil, stone, aggregate etc. [39]. Figure 6 below depicts the nano material sample used in the study.

Fig. 6. Nano material sample

The Carbon-Hydrogen-Nitrogen-Sulphur analysis was carried out in the Department of SAIF, IIT Bombay. Table 5 below represents the CHNS analysis of nano material.

Table 5: CHNS Analysis of Nano material

Constituent	Percentage (%)
Carbon	64.173
Hydrogen	9.669
Nitrogen	3.945
Sulphur	-
Losses on Ignition	22.213

2.3.1 Chemical Interaction of soil with nano material

When the nano material mixed with water reacts with the soil, hydrolysis reaction takes place. Nano siliconizes the surfaces i.e. coats the soil particle with silicon by converting water absorbing silanol groups to water repellent alkyl siloxane surfaces. Hence due to the further affinity towards oxygen more and more siloxane (= Si-O-Si=) bonds containing long alkyl chains are formed which form a thin hydrophobic film at the molecular level treated surfaces [29]. This thin hydrophobic film formed on the surface of the soil represents water repelling alkyl siloxane bond which makes the soil impermeable and water proofs it thereby causing a significant improvement in its geotechnical properties including CBR and plasticity indices.

3. Sample Preparation and Methodology

Oven dried fly ash was mixed to the soil in increasing proportions by 0%,10%,20%,30%,40% and 50% by dry weight of the soil. Further each sample was treated with nano solution (nano material diluted in water) in four different dilution ratios of (1:100), (1:225), (1:400) and (1:600) by volume. The laboratory tests included grain size sieve analysis, modified proctor compaction tests, modified California bearing ratio tests, liquid limit (LL), plastic limit (PL) and falling head permeability tests. Table 6 below represents the proposed test variations considered in the testing program.

Table 6: Test variations considered in the testing program

Series	Sample details
Series I	90% PS + 10% FA
	90% PS + 10% FA + (1:100) nano solution
	90% PS + 10% FA + (1:225) nano solution
	90% PS + 10% FA + (1:400) nano solution
	90% PS + 10% FA + (1:600) nano solution
Series II	80% PS + 20% FA
	80% PS + 20% FA + (1:100) nano solution
	80% PS + 20% FA + (1:225) nano solution
	80% PS + 20% FA + (1:400) nano solution
	80% PS + 20% FA + (1:600) nano solution
Series III	70% PS + 30% FA
	70% PS + 30% FA + (1:100) nano solution
	70% PS + 30% FA + (1:225) nano solution
	70% PS + 30% FA + (1:400) nano solution
	70% PS + 30% FA + (1:600) nano solution
Series IV	60% PS+ 40% FA
	60% PS + 40% FA + (1:100) nano solution
	60% PS + 40% FA + (1:225) nano solution
	60% PS + 40% FA + (1:400) nano solution
	60% PS + 40% FA + (1:600) nano solution
Series V	50% PS+50% FA
	50% PS + 50% FA + (1:100) nano solution
	50% PS + 50% FA + (1:225) nano solution
	50% PS + 50% FA + (1:400) nano solution
	50% PS + 50% FA + (1:600) nano solution

3.1 Test methodology: Modified proctor compaction

Modified proctor densities (simulating the heavy compaction in field) were established initially as a prerequisite for conducting the modified CBR tests. The densities were obtained by mixing soil with increasing proportions of fly ash i.e. 90% soil with 10% fly ash, 80% soil with 20% fly ash, 70% soil with 30% fly ash, 60% soil with 40% fly ash and 50% soil with 50% fly ash by dry weight of soil. Further each proportion was treated with nano solution (nano material diluted in water) with four different dilution ratios of (1:100), (1:225), (1:400) and (1:600) by volume. The water treated with nano material i.e nano solution was used to conduct the modified proctor tests for all variations. The tests were carried out in accordance with [40].

3.2 Test methodology: Modified California Bearing Ratio Test

The modified proctor compaction tests were initially conducted on all the test variations as an imperative requirement for all the successive tests and the respective dry densities and optimum moisture contents were determined. The samples were placed on a polythene sheet, covered and left about 8 hours to interact with the nano solution. The CBR moulds were compacted to the respective modified proctor densities and then were left to air dry for four days. The unsoaked CBR tests were performed after 4 days of air drying. The moulds were then submerged in water for four days. The soaked CBR tests were then conducted after four days of submergence in water. Load was applied by means of a load cell mounted on the top of the frame with its lower end attached to the plunger. Penetrations up to 10 mm were measured by dial gauge fitted to the frame resting on the annular weight placed on the top of the mould. The load was measured by a digital output configured with the load cell. The samples were tested for Modified California bearing ratio in accordance with [41]. Figure 7 below depicts the Modified CBR set up in the laboratory.

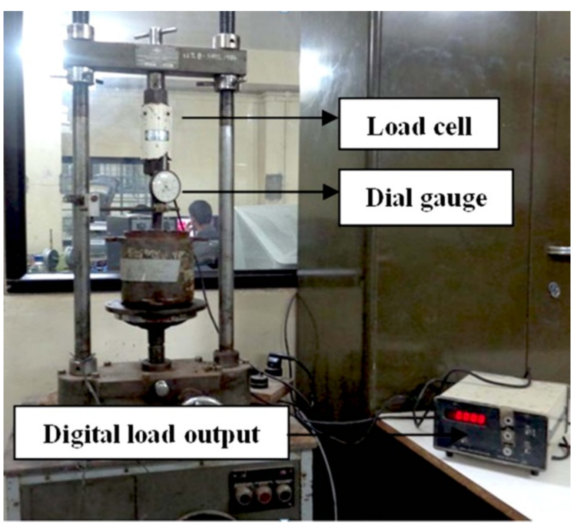


Fig. 7. Modified CBR test set up

3.3 Test methodology: Liquid Limit and plastic limit

The samples were prepared in the same manner as that of modified CBR tests as discussed above. Treated samples with nano solution were then covered in a polythene sheet were left to interact with the soil for 8 hours. After the interaction time the samples were then oven dried and the liquid limit and plastic limit tests were conducted on all the test variations in accordance with [42].

3.4 Test methodology: Falling head permeability test

The samples were prepared in the same manner as that of modified CBR tests as discussed above. Treated samples with nano solution were then covered in a polythene sheet were left to interact with the soil for 8 hours. The samples were then oven dried and the falling head permeability tests were conducted only on the optimized proportions of fly ash and nano solutions based on the modified CBR results. The tests were conducted in accordance with [43].

4. Results and Discussions

4.1 Modified Proctor compaction tests

Table 7 below represents the modified proctor compaction test results.

Table 7: Modified Proctor compaction test results

Sample details	MDD (gm/cm^3)	OMC (%)
PS (neat soil)	1.72	19
90% PS + 10% FA	1.715	18.5
90% PS + 10% FA + (1:100) nano solution	1.725	18.7
90% PS + 10% FA + (1:225) nano solution	1.723	18.6
90% PS + 10% FA + (1:400) nano solution	1.710	18.8
90% PS + 10% FA + (1:600) nano solution	1.705	18.7
80% PS + 20% FA	1.70	18.1
80% PS + 20% FA + (1:100) nano solution	1.718	18.0
80% PS + 20% FA + (1:225) nano solution	1.713	17.9
80% PS + 20% FA + (1:400) nano solution	1.697	18.2
80% PS + 20% FA + (1:600) nano solution	1.695	18.3
70% PS + 30% FA	1.68	19
70% PS + 30% FA + (1:100) nano solution	1.695	18.1
70% PS + 30% FA + (1:225) nano solution	1.69	18.4
70% PS + 30% FA + (1:400) nano solution	1.683	18.6
70% PS + 30% FA + (1:600) nano solution	1.675	18.7
60% PS+ 40% FA	1.65	18.5
60% PS + 40% FA + (1:100) nano solution	1.664	18.3
60% PS + 40% FA + (1:225) nano solution	1.66	18.4
60% PS + 40% FA + (1:400) nano solution	1.64	18.6
60% PS + 40% FA + (1:600) nano solution	1.63	18.7
50% PS+50% FA	1.602	19.1
50% PS + 50% FA + (1:100) nano solution	1.615	18.8
50% PS + 50% FA + (1:225) nano solution	1.610	18.9
50% PS + 50% FA + (1:400) nano solution	1.605	19.0
50% PS + 50% FA + (1:600) nano solution	1.596	19.2

It is observed that soil becomes lighter on account of addition of fly ash. Since the specific gravity of fly ash is less than that of the soil, the mix so formed is light in weight. The dry densities were therefore observed to be decreased with increase in the percentage of fly ash. Similar results were reported in earlier research [14]. However, there is a little variation seen in the optimum moisture contents. On treating the soil with nano solution the maximum dry densities are observed to be slightly increased with a little decrease in moisture content. The densities were observed to be slightly greater in samples treated with dilution ratios of (1:100) and (1:225) i.e. (more concentrated samples) as compared to the samples treated with dilution ratios of (1:400) and (1:600) (less concentrated samples). This can be attributed to the formation of siloxane bonds which start imparting hydrophobicity to the soil on reacting with nano material and rearrangement of its molecules under the heavy compaction effort. However, since the proctor compaction tests were immediately carried out after mixing the soil with nano solution there was hardly any reaction time available for the nano material to react with the soil. Hence the densities were not seen to be changed much. (Ref: Table 6 Series I to V)

4.2 Modified California Bearing Ratio (CBR) tests

Both un-soaked and soaked modified CBR tests were conducted on all the test variations considered in the program to ascertain the improvement in the CBR properties of soil treated with fly ash and nano solution and to check its suitability for the construction of subgrade and subbases in pavement related applications.
Figures 8 to 12 represent the Stress penetration curves for unsoaked CBR samples for Series I to V.

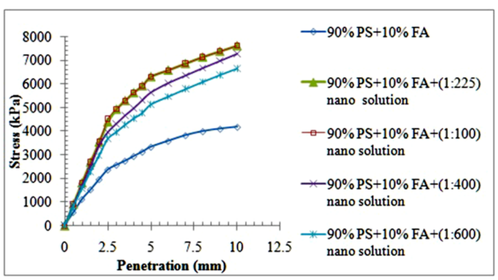


Fig. 8. Stress penetration curves of Unsoaked CBR samples of series I

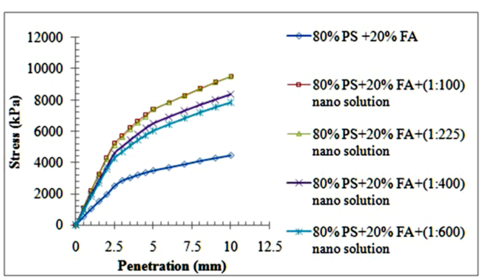


Fig. 9. Stress penetration curves of Unsoaked CBR samples f series II

For all the stress penetration curves the soaked CBR values were observed to be lesser as compared to the unsoaked values on account of submergence of soil in water for four days. Both unsoaked and soaked CBR values were observed to be increased with the addition of fly ash to the soil. The CBR values were observed to be improved up to addition of 30% of fly ash to the soil. On adding 30% of fly ash the un-soaked CBR value of soil increases from 33.36% to 37.22 % thereby indicating an increase of 1.11 times in the value. Similarly, the soaked CBR value increases from 14.07% to 24.1% thus improving the value by 1.71 times respectively.

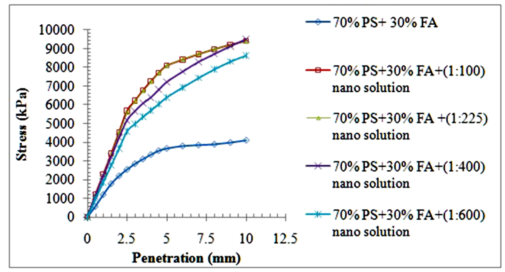


Fig. 10. Stress penetration curves of Unsoaked CBR samples of series III

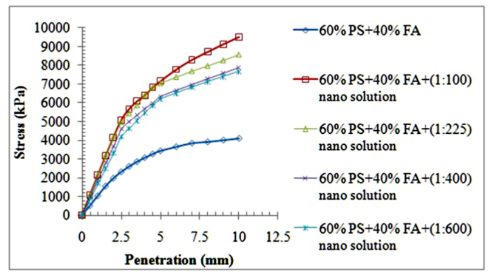


Fig. 11. Stress penetration curves of Unsoaked CBR samples of series IV

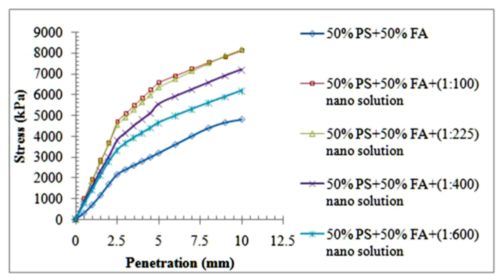


Fig. 12. Stress penetration curves of Unsoaked CBR samples of series V

Further the CBR values were observed to be decreased beyond 30% addition of fly ash. The increase in CBR values may be attributed due to the increase in silica percentage due to increase in fly ash content up to 30%. Beyond addition of 30% of fly ash it can be interpreted that the blend tends to become more cohesionless and the soil-fly ash mix thereby starts losing its cohesion due to addition of more fly ash i.e. (>30%). As a result, the CBR values beyond 30% of addition of fly ash were observed to be decreased.
Figures 13 to 17 represent the Stress penetration curves for soaked CBR samples for Series I to V.
On further treating the samples with nano solution in four different dilutions of (1:100), (1:225), (1:400) and (1:600) the CBR values were observed to be significantly improved. The CBR values of both unsoaked and soaked tests are seen to be higher for the dilution ratios of (1:100) and (1:225) (higher in concentration) as compared to the dilution ratios of (1:400) and (1:600) (lesser in concentration). Maximum improvements were observed in samples of (70% PS + 30% fly ash) and nano solution with dilution ratios of (1:100) and (1:225). For the dilution ration of (1:100) the un-soaked CBR values were observed to be increased from 37.22% to 87.22% thereby indicating an increase of 2.34 times and for dilution ratio of (1:225) the unsoaked CBR values were observed to be increased from 37.22 % to 81.57% indicating an increase by 2.19 times.

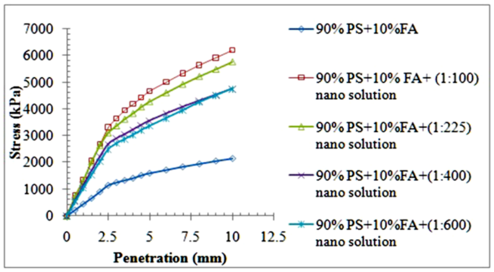


Fig. 13. Stress penetration curves of soaked CBR samples of series I

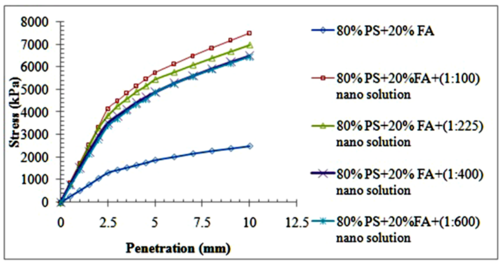


Fig. 14. Stress penetration curves of soaked CBR samples of series II

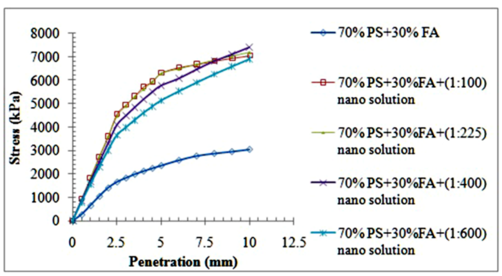


Fig. 15. Stress penetration curves of soaked CBR samples of series III

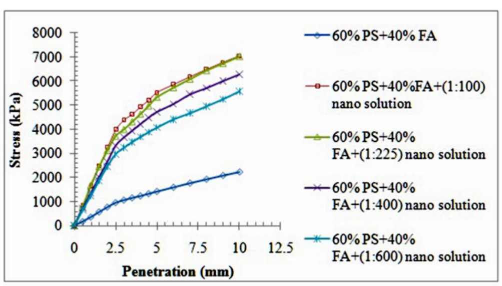


Fig. 16. Stress penetration curves of soaked CBR samples of series IV

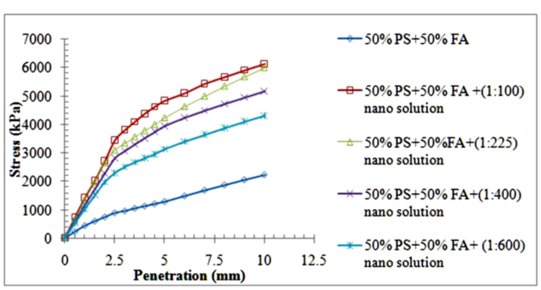


Fig. 17. Stress penetration curves of soaked CBR samples of series V

Similarly, the soaked CBR values with the dilution ratio of (1:100) were drastically improved from 24.1% to 66.52% thereby improving the value by 2.76 times and that for the dilution ration of (1:225) the soaked CBR values were improved from 24.1% to 65.37% thus indicating an improvement by 2.71 times when compared with (70% PS + 30% fly ash) sample. Hence in all the samples of tests series I to V it was observed that the dilution ratio of the nano solution played a vital role in improvement of CBR values. All the samples recorded maximum CBR values for both dilution ratios of (1:100) and (1:225). It was also observed that there was an insignificant difference in the CBR values of samples treated with dilution ratios of (1:100) and (1:225). A parallel improvement was seen in the samples treated with both these dilution ratios. Table 8 summarizes both unsoaked and soaked CBR values for test series I to V. The results were similar to the earlier studies conducted on soils [29]. Fig. 18 depicts the graphical representation of both unsoaked and soaked CBR values for all test series I to V.

The drastic improvement in CBR values can be attributed to the formation of strong siloxane (Si-O-Si) bonds when the soils come in contact with the nano solution. The stronger long chain (Si-O-Si) bonds are formed as the Si-OH bonds are broken on hydrolysis. Since silica has more affinity towards oxygen it attracts all the electrons present on Oxygen, as a result of which the electron density on oxygen decreases. It therefore causes the proton (H+) to be acidic in nature which easily breaks and detaches the (OH) group from Silica. This breaking of (OH) group from silica makes the Oxygen molecules to acquire negative charge. Now again due to the affinity of silica towards the oxygen more and more Si-O-Si bonds are formed which will become stronger and stronger thereby making the soil denser and imparting a good hydrophobicity to the soil surface. Also, as the Class 'F' fly ash being used in this research is very rich in silica (62.79%) (Referred in Table 7), the soil- fly ash- nano solution mixture makes more silica available for reaction with the silanol groups present in the nano solution. Hence there is more formation of Si-O-Si bonds within the soil mass thereby forming water repelling zone in the form of a thin film above the surface of soil. The film so formed is the water repelling alkyl siloxane bond which makes the soil impermeable and water proofs it thereby attributing significant improvement in its CBR properties.

4.3 Liquid Limit and Plastic limit tests

There is a significant decrease observed in the liquid limit and plastic limit values on treating the soil with fly ash. It was observed that the liquid limit and plastic limit values drop down to 1.69 times and 1.65 times respectively on treating the soil with 30% fly ash when compared with the neat soil. Further the reduction in LL and PL values was observed to be comparatively less beyond addition of 30% of fly ash. On treating the soil further with nano solution in four different dilutions of (1:100), (1:225), (1:400) and (1:600) the LL, PL and PI values were observed to be reduced consistently. It was observed that the LL value for (70% PS+30% FA) sample reduces by 1.67 times when treated with (1:100) dilution ratio and reduces by 1.58 times when treated with (1:225) dilution ratio. Similarly, the plastic limit values were observed to be reduced by 1.88 times on treating with a dilution ratio of (1:100) and were reduced by 1.79 times on treating the samples with (1:225) dilution ratio. Maximum reduction in the values of LL and PL were observed with the dilution ratios of (1:100).

Table 8: Unsoaked and soaked CBR results for test series I to V.

Sample no	Sample details	Unsoaked CBR (%)	Soaked CBR (%)
	PS (neat soil)	33.36	14.07
Series I	90% PS + 10% FA	34.31	16.58
	90% PS + 10% FA + (1:100) nano solution	65.94	48.2
	90% PS + 10% FA + (1:225) nano solution	64.01	45.11
	90% PS + 10% FA + (1:400) nano solution	57.45	39.14
	90% PS + 10% FA + (1:600) nano solution	53.21	36.24
Series II	80% PS + 20% FA	36.24	19.27
	80% PS + 20% FA + (1:100) nano solution	76.35	57.45
	80% PS + 20% FA + (1:225) nano solution	74.04	56.11
	80% PS + 20% FA + (1:400) nano solution	67.1	51.1
	80% PS + 20% FA + (1:600) nano solution	62.28	49.35
Series III	70% PS + 30% FA	37.22	24.1
	70% PS + 30% FA + (1:100) nano solution	82.72	66.52
	70% PS + 30% FA + (1:225) nano solution	81.57	65.37
	70% PS + 30% FA + (1:400) nano solution	75.4	59.58
	70% PS + 30% FA + (1:600) nano solution	66.71	53.21
Series IV	60% PS+ 40% FA	33.94	13.88
	60% PS + 40% FA + (1:100) nano solution	74.04	59.58
	60% PS + 40% FA + (1:225) nano solution	72.31	54.18
	60% PS + 40% FA + (1:400) nano solution	67.1	48.4
	60% PS + 40% FA + (1:600) nano solution	61.12	43.2
Series V	50% PS+50% FA	31.24	12.92
	50% PS + 50% FA + (1:100) nano solution	68.07	50.14
	50% PS + 50% FA + (1:225) nano solution	66.14	48.21
	50% PS + 50% FA + (1:400) nano solution	55.15	41.07
	50% PS + 50% FA + (1:600) nano solution	48.4	33.35

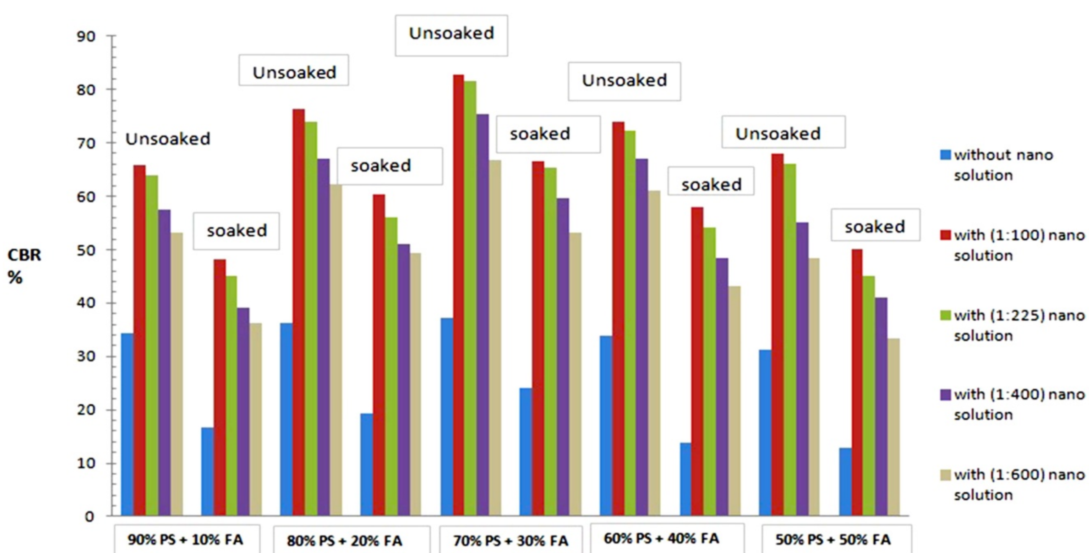


Fig. 18. Graphical representation of Un-soaked and Soaked CBR samples of test series I to V

Parallel improvements in the reduction of LL, PL and PI values were observed with both the dilution ratios of (1:100) and (1:225). The value reductions were observed to be lesser in the samples treated with lesser concentrations i.e (1:400) and (1:600) dilution ratios which thereby clearly help to validate the significance of dilution of nano material in water. Table 9 summarizes the liquid limit and plastic limit results for test series I to V.

The improvement in plasticity of soils can be attributed to the formation of strong siloxane (Si-O-Si) bonds when the soils come in contact with nano solution. The advantage of rich siliceous content of fly ash clearly demonstrates the additional availability of silica for the reaction with the silanol groups of the nano solution. The stronger long chain (Si-O-Si) bonds are formed as the Si-OH bonds are broken on hydrolysis thereby imparting hydrophobicity to the soil and making it more water repelling. The new siloxane bonds so formed neutralize the net negative charge on the silt and clay particles [29] thereby reducing the plasticity of soil. As a result, the plasticity indices also are seen to be reduced which enable the soil in reducing the plasticity characteristics to a great extent, thereby making it more compatible to be handled on site. Thus, the treated soil used in the study was observed to be transformed from 'silts and clays of medium compressibility' (LL between 35%-50%) to 'silts and clays of low compressibility' (LL less than 35%) [44] pertaining to the Indian sub-continent conditions.

4.4 Falling head Permeability tests

Table 10 summarizes the results of falling head permeability tests. Based on the above results of modified CBR tests and plasticity tests it was observed that optimum results could be obtained adopting 30% of fly ash and nano solution ratios of (1:100) and (1:225). It was observed that when soil was mixed with 30% of fly ash the permeability was reduced by 7.25 times as compared to the neat soil. Further on treating with nano solution ratio of (1:100) the permeability value was observed to be decreased by 137.31 times. Also on treating with nano solution ratio of (1:225) the permeability value was decreased by 139.49 times.

The drastic reduction in permeability values can be attributed to the formation of strong siloxane (Si-O-Si) bonds when the soils come in contact with the nano solution. The stronger long chain (Si-O-Si) bonds are formed as the Si-OH bonds are broken on hydrolysis. Since silica has more affinity towards oxygen it attracts all the electrons present on Oxygen, as a result of which the electron density on oxygen decreases. It therefore causes the proton (H+) to be acidic in nature which easily breaks and detaches the (OH) group from Silica. This breaking of (OH) group from silica makes the Oxygen molecules to acquire negative charge. Now again due to the affinity of silica towards the oxygen more and more Si-O-Si bonds are formed which will become stronger and stronger thus counterbalancing the negative charge of silt and clay particles thereby making the soil denser and imparting a good hydrophobicity to the soil surface. The soil- fly ash- nano solution mixture makes more silica available for reaction with the silanol groups present in the nano solution. Hence there is more formation of Si-O-Si bonds within the soil mass by forming thin water repelling zone above the surface of soil, thereby making the soil more impervious in nature and contributing to a significant reduction in the permeability values.

Table 9: Liquid Limit and Plastic Limit results for test series I to V

Sample no	Sample details	LL (%)	% decrease	PL (%)	% decrease	PI (I_p) (%)
Series I	PS (neat soil)	45.4	-	30.7	-	14.7
	90% PS + 10% FA	34.3	24.4	22.9	25.4	11.4
	90% PS + 10% FA +(1:100) nano solution	30.5	32.8	18.6	39.4	11.9
	90% PS + 10% FA + (1:225) nano solution	31.6	30.4	19.3	37.1	12.3
	90% PS + 10% FA + (1:400) nano solution	33.7	25.8	20.6	32.9	13.1
	90% PS + 10% FA + (1:600) nano solution	34	25.1	21.8	29.0	12.2
Series II	80% PS + 20% FA	29.7	34.6	20.5	33.2	9.2
	80% PS + 20% FA + (1:100) nano solution	22.9	49.6	15.6	49.1	7.3
	80% PS + 20% FA + (1:225) nano solution	23.4	48.5	16.7	45.6	6.7
	80% PS + 20% FA + (1:400) nano solution	25.6	43.6	18.4	40.0	7.2
	80% PS + 20% FA + (1:600) nano solution	26.5	41.6	19.1	37.7	7.4
Series III	70% PS + 30% FA	26.8	41.0	18.5	39.7	8.3
	70% PS + 30% FA + (1:100) nano solution	16.0	64.8	9.8	68.1	6.2
	70% PS + 30% FA + (1:225) nano solution	16.9	62.8	10.3	66.4	6.6
	70% PS + 30% FA + (1:400) nano solution	19.3	57.5	13.7	55.4	5.6
	70% PS + 30% FA + (1:600) nano solution	22.1	51.3	16.4	46.6	5.7
Series IV	60% PS+ 40% FA	25.9	43.0	17.7	42.3	8.2
	60% PS + 40% FA + (1:100) nano solution	18.4	59.5	12.3	59.9	6.1
	60% PS + 40% FA + (1:225) nano solution	19.2	57.7	13.1	57.3	6.1
	60% PS + 40% FA + (1:400) nano solution	21.4	52.9	14.6	52.4	6.8
	60% PS + 40% FA + (1:600) nano solution	23.1	49.1	16.2	47.2	6.9
Series V	50% PS+50% FA	25.8	43.2	17.5	43.0	8.3
	50% PS + 50% FA + (1:100) nano solution	20.1	55.7	12.3	59.9	7.8
	50% PS + 50% FA + (1:225) nano solution	20.7	54.4	12.9	58.0	7.8
	50% PS + 50% FA + (1:400) nano solution	23.6	48.0	15.2	50.5	8.4
	50% PS + 50% FA + (1:600) nano solution	24.3	46.5	16.1	47.6	8.2

Table 10: Falling head permeability test results

Sample details	**Coefficient of Permeability 'k' (cm/sec)**	**% decrease**
PS (neat soil)	3.457×10^{-5}	--
70% PS + 30% FA	4.765×10^{-6}	86.21
70% PS + 30% FA + (1:100) nano solution	3.470×10^{-8}	99.89
70% PS + 30% FA + (1:225) nano solution	3.416×10^{-8}	99.90
70% PS + 30% FA + (1:400) nano solution	9.876×10^{-7}	97.14
70% PS + 30% FA + (1:600) nano solution	7.766×10^{-6}	77.53

4.5 Suitability as a good subgrade / subbase material

The soil when treated with fly ash and nano material is seen to improve its CBR properties to a great extent
thereby satisfying the criteria for 'good subgrade' and 'subbase' in the design of flexible pavements pertaining to the Indian subcontinent.
As per IRC: 37-2012 specifications "good subgrade" should possess a soaked CBR of 8% [45]. Also, the sub base should possess a soaked CBR of 15% with liquid limit and plasticity index not exceeding 25% and 6 respectively. [46]. It also satisfies the criteria of a "good subbase" of having a CBR of 20% for cumulative traffic up to 2msa and CBR of 30% for cumulative traffic exceeding 2 msa. [47- 48]. The stabilized soil with fly ash and nano material thus satisfies the required criteria for a 'good subgrade and sub base' in the design of flexible pavements.

5. Conclusions

An experimental study was carried out to investigate the effect of addition of fly ash and organo silane nano material on soil properties including Modified California bearing Ratio tests, liquid limit, plastic limit tests and falling head permeability tests. Tests were conducted on silty sand mixed with increasing percentages of fly ash from 0 to 50% with four different nano solution ratios of (1:100), (1:225), (1:400) and (1:600). The quantitative results obtained from the modified CBR tests are based on laboratory CBR values which can be helpful in giving a proper direction to achieve the desired degree of CBR in the field by adopting suitable proportions optimized in the present study.
The following conclusions can be drawn from the present study.

1. The dry density of soil goes on decreasing with the increase in fly ash content with less variation in the optimum moisture contents. The densities slightly increase with a little decrease in optimum moisture contents on the addition of nano material. The variation is slightly higher for nano solution dilution ratios of (1:100) and (1:225).
2. The unsoaked as well as soaked CBR values increase with the increase in fly ash content. Maximum values are observed on adding 30% of fly ash. The CBR values are observed to be decreased beyond 30% of addition of fly ash. The soaked CBR is improved by 1.71 times with addition of 30% of fly ash to the soil. Thus, proportion of 30% fly ash is optimized in the study which envisages successful usage of 30% of fly ash to be adopted in subgrades and subbase courses in flexible pavements.

3. The CBR values were observed to be further enhanced on treating the soil with nano solution. Soaked CBR values with the dilution ratio of (1:100) were drastically improved from 24.1% to 66.52% thereby improving the value by 2.76 times and that for the dilution ration of (1:225) the soaked CBR values were improved from 24.1% to 65.37% thus indicating an improvement by 2.71 times when compared with (70% PS + 30% fly ash).

4. All the test variations reported higher unsoaked as well as soaked CBR values for dilution ratios of (1:100) and (1:225) i.e. (higher concentrated samples) as compared to dilution ratios of (1:400) and (1:600) i.e. (lesser concentrated samples). The dilution role of nano material in water plays a significant role in improving the CBR properties.

5. It was observed that the liquid limit and plastic limit values drop down to 1.69 times and 1.65 times respectively on treating the soil with 30% fly ash when compared with the neat soil. On treating the soil further with nano solution in four different dilutions of (1:100), (1:225), (1:400) and (1:600) the LL, PL and PI values were observed to be reduced consistently. The LL value for (70% PS+30% FA) sample reduces by 1.67 times when treated with (1:100) dilution ratio. Similarly, the plastic limit values were observed to be reduced by 1.88 times on treating with a dilution ratio of (1:100) thus transforming the soil as silts and clays of medium compressibility to silt and clays of low compressibility [44].

6. It was observed that when soil was mixed with 30% of fly ash the permeability was reduced by 86%. Further on treating with nano solution ratio of (1:100) the permeability value was observed to be decreased by 99.89%.
7. The stabilized soil with fly ash and nano material satisfies the criteria for 'good subgrade' and 'subbase' in the design of flexible pavements conforming to the codes pertaining to the Indian sub-continent.

The research work reported emphasizes on relevance of wastes such as fly ash and nano technology to be adopted as basic construction materials for the construction of subgrade and subbase in pavement related applications. Despite the fact that the present study presumes the laboratory based analysis it emboldens the use of waste fly ash to improvise the geotechnical parameters as a whole, thereby indubitably contributing the nation towards the problem of its relinquishment and utility. However, the results need to be extrapolated on the field before adopting suitable proportions of the considered mixes in the laboratory testing. The research is an attempt made for the first time by combining soil with waste fly ash in conjunction with the innovative nano technological approach that promises an engineered solution predicated by applied sciences that has acquired significance globally.

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