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Numerical & Experimental Analysis for Soil Subgrade Strength Improvement Using Geosynthetics

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Abstract

The construction sector widely utilizes soil, a substance known for its adaptability. All civil engineering constructions rely on soil for support, whether they rest on it or immerse in it. Soil poses significant obstacles during construction due to its great compressibility and diversity of characteristics. External materials like geosynthetics frequently implement soil stabilization to tackle these problems. The loading process has an impact on the soil's microstructure, which affects the performance of structures. The purpose of this study is to investigate how soil foundations behave in different situations, focusing on how stress is distributed and how structures change shape, with and without geosynthetic material. In this context, computational techniques are used, specifically Abaqus FEM software, to simulate soil foundations and analyse various scenarios that involve boundary conditions, mechanical loading, and stress distribution. Initial findings suggest that using geosynthetic materials in the soil subgrade results in enhanced stress distribution and less deformation.

Keywords: Bearing capacity, Soil Stabilization, Geosynthetics, Finite Element Analysis

Introduction

Subgrade stabilisation becomes essential when the available local soil is not strong enough to support the traffic loads [1]. Subgrade stabilisation can be achieved by mechanical or chemical means, both of which need expensive machinery and skilled labour. Geosynthetics have been more and more well-liked as a dependable technique for fortifying soil in recent years [2]. Geosynthetic materials are used in pavements nowadays for many different functions, such as separation, filtration, lateral drainage, and reinforcing. Numerous researchers claim that geosynthetic reinforcement can enhance pavement performance [3]. Geosynthetics have the potential to improve a road's performance over its entire design life and provide long-term advantages, even in cases where the stabilising application is chosen primarily during initial construction. Enhancements to pavement life [4], lower construction costs, and fewer requirements for aggregate thickness are only a few of the numerous uses for geosynthetics in road building. Applications for geosynthetic pavement include geotextiles, geogrids, and other materials.

The impacts of using geotextile and geogrid to enhance pavement systems have been extensively studied [5]. Many of them conducted tests on laboratory models in addition to extensive field investigations. Many researchers have also conducted laboratory experiments to understand the effects of geosynthetic as a reinforcing material for subgrades. The results indicate that the use of geosynthetic as a reinforcement can greatly improve the strength qualities of the subgrade [6].

That being said, the main focus of this study is on the interaction between geotextile and subgrade reinforcement. Studies have indicated that the best subgrades to use geotextiles as reinforcement are those with a California Bearing Ratio (CBR) of less than 3%. The best geotextiles for subgrade reinforcement are those with a high tensile strength, according to numerous studies. [7] One crucial element influencing the carrying capacity of reinforced soil is the location of the geosynthetic reinforcement. Researchers have generally discovered in [8] that a larger bearing capacity on lab specimens is obtained when the geosynthetic is positioned in the upper part of the sample. A great deal of research has been done recently on the behaviour of soil reinforced with geotextile. Researchers have used both computational and experimental methods to examine how geotextile reinforcement affects granular soil carrying capacity. [9] They tested the compressive strength (CBR) of loose soil separated by a non-woven geotextile and covered in sand. Furthermore, [10] they used the PLAXIS programme to do FE analysis in order to reassess the CBR test results. The geotextile layer is mainly used in studies as a separator, particularly at the interface where the subgrade and sub-base layers meet. Only a few studies have used the geotextile layer as a single-layer reinforcing element within subgrade soil [12], and there is some debate about where to use it.

This study looks at the effects of geotextile in single and multiple layer configurations at different placement levels on two different types of soil: clayey and sandy. Additionally, the experimental results are validated using numerical modelling with the FEM-based programme ABAQUS. [13]Finite element modelling (FEM) analysis results are utilised to investigate the reinforced subgrade's load transmission mechanism.

Research Gaps

1. The research reveals a lack of comprehensive studies that integrate both numerical simulations and experimental validations to thoroughly assess the efficacy of geosynthetics in improving soil subgrade strength. Additionally, existing literature often overlooks the influence of varying soil types and conditions on the performance of geosynthetic reinforcements, leading to gaps in understanding their applicability across different geotechnical scenarios.
2. Moreover, while some studies focus on immediate strength improvements, there is insufficient data on the long-term durability and performance of geosynthetics under realistic environmental conditions and cyclic loading. This issue is compounded by the absence of sufficient guidelines and recommendations derived from rigorous numerical and experimental analyses, which hinders the optimal design and implementation of geosynthetic-reinforced soil subgrades in real-world projects.

Research Objectives

1. To evaluate the effect of using different geosynthetics with different orientations on CBR strength and permeability properties of the soils.
2. To perform finite element investigations for flexible pavement sections impregnated with geosynthetics with the help of ABAQUS finite element software.

Finite Element Analysis

Finite element material is a numerical technique used to perform analysis on the performance of physical prototype. As it is necessary to quantify and physical phenomena such as stress, distribution, thermal transportation, wave propagation, fluid behaviour and load application [14].

The whole structure is divided into sub elements and structural sections which are inter-connected to finite number of nodes and point. An important feature of finite element method is that it set apart from other numerical method is its ability to formulate solution for individual element before the entire problem [15].

Advantages of FEM

Finite element method generates the physical response of a mortal at any desired location and conditions [16]. It allows easier modelling of complex shapes of both interior and exterior and can be used to determine the failure pattern.

- Can analyse physical stress, high degree of accuracy.
- Can be used for certain time dependent constraints.
- Boundary conditions also can be defined for the model to get the accurate result as per the physical conditions.
- Stress strain analysis.
- Fluid dynamics, heat, transfer and temperature variation.
- It can solve equation of linear domain.
- Complex problems with closed mathematical solution.
- Low investment with rapid calculations.

Materials Used

- **Soil**

For this study, clay soil classified as CL and CL-ML was collected from the Delhi Katra Expressway near Kansala village in Rohtak, Haryana, with a soaked California Bearing Ratio (CBR) value of 2.7%.

Table 1.1 Properties of Soil

Properties of Soil	
Properties	CL
Specific Gravity	2.47

Liquid Limit %	26.38
Plastic Limit %	15.61
Plasticity Index	10.77
OMC (Std Proctor) %	13.13
Maximum Dry Density (Std Proctor)	18.74
CBR %	2.17
KN/Cum	218.19
Permeability (cm/sec)	4.34×10^{-8}

The geosynthetic materials used are woven and non-woven geotextiles, which act as major reinforcement in the soil subgrade [17]. These materials serve multiple functions, including reinforcement, separation, filtration, and drainage. Various tests were conducted on the geotextile materials to determine their properties

Table 1.2 Getextile Properties

Geotextile Properties			
Properties	**Test Method**	**Unit**	**Woven (TF15100)**
Grab Strength	ASTM D4632	N	890
Grab Elongation		%	15
Burst Strength	ASTM D3786	kPa	2750
Tensile Strength	ASTM D4595	KN/M	
Puncture Resistance	ASTM D6241	N	
Index Puncture Resistance	ASTM D4833	N	422
Trapezoidal Shear Strength	ASTM D4533	N	330
AOS	ASTM D4751	mm	0.425
UV Resistance	ASTM D4355	-	70%
Permittivity	ASTM D449	sec^{-1}	0.05

METHODOLOGY

Sampling/Test Procedure

The particle size distribution was evaluated using wet sieve analysis, with a hydrometer test conducted specifically for particles smaller than 0.075 mm. The soil was categorised based on the Indian Standard Classification System IS: 1498 (1970), which corresponds to the Unified Soil Classification System (USCS). The soil's specific gravity, Atterberg limits, and strength characteristics were established and are outlined in Table 1.1, showcasing many geotechnical qualities. The soil's optimum moisture content (OMC) and maximum dry density (MDD) were determined using a Standard Proctor test, which adheres to the specifications outlined in IS: 2720 (Part 7). For this experiment, dirt was compressed in a mould with a volume of 1000cc. The compression was done in three separate layers, with each layer being subjected to 25 impacts from a rammer weighing 2.6 kg. The rammer was dropped from a height of 310 mm. The Maximum Dry Density (MDD) was determined to be 18.74 kilonewtons per cubic metre (kN/m³), whereas the Optimum Moisture Content (OMC) was measured at 13.13%.

Two distinct categories of geotextiles were employed: woven and non-woven [17]. Woven geotextiles are produced by interlacing threads through a traditional weaving method, resulting in a uniform textile structure that exhibits exceptional tensile strength. Non-woven geotextiles are produced by bonding randomly arranged fibres together using methods such as partial melting, needle punching, or chemical agents. This creates a random pattern and results in a lower tensile strength compared to woven geotextiles. The manufacturer has provided thorough information about the physical features of these geotextiles, which can be found in Table 1.2.

The unreinforced and reinforced samples were each compacted in three layers, with each layer getting 56 impacts from the rammer in order to obtain the target dry density. In the soaked CBR test, the samples were immersed in water with a 4.6 kg additional load under controlled conditions (27°C) for a duration of 96 hours. Following the time of immersion, CBR tests were carried out in accordance with the IS-2720 (Part-16) regulations. The positioning of geotextile at different locations within the CBR mould was recorded, and several combinations were observed for the purpose of comparative analysis, as shown in the figure.

This approach entails the preparation of clay soil samples, both without reinforcement and with reinforcement using woven and non-woven geotextiles. These samples are then subjected to established testing techniques to assess the effect on CBR (California Bearing Ratio) values. The tests were conducted to investigate the impact of various placements and types of geotextiles on soil stabilisation and bearing capacity. The obtained experimental data were further utilised for conducting numerical simulations in order to further assess the efficacy of geotextiles in soil reinforcing.

Simulation Methodology

The initial step in the simulation involves creating a model prototype, which can be either two-dimensional or three-dimensional with a deformable/solid shape. Abaqus is a unitless software, allowing parts to be created directly within the software or imported from other files. Nodes are assigned in this module to define the geometry and mesh of the model. The prototype created for this study is rectangular, with dimensions 5 x 10 x 20 units.

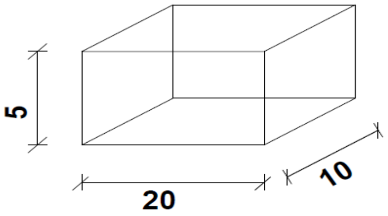


Figure 1.1 prototype

Materials Parameters

This model incorporates the identified properties of both the soil and geosynthetic materials to simulate their behaviour under various loading conditions. The numerical simulations are conducted using Abaqus to analyse and predict the performance of the soil-geosynthetic system, ultimately guiding the design and optimization for enhanced stability and bearing capacity.

Table 1.3 Material Parameters

Materials (kg/m³)	Elastic Modulus(Kpa)	Poisson's Ratio	Cohesion (Kpa)	Friction Angle	Density
Clay	1.8×10^4	0.35	32	14	2

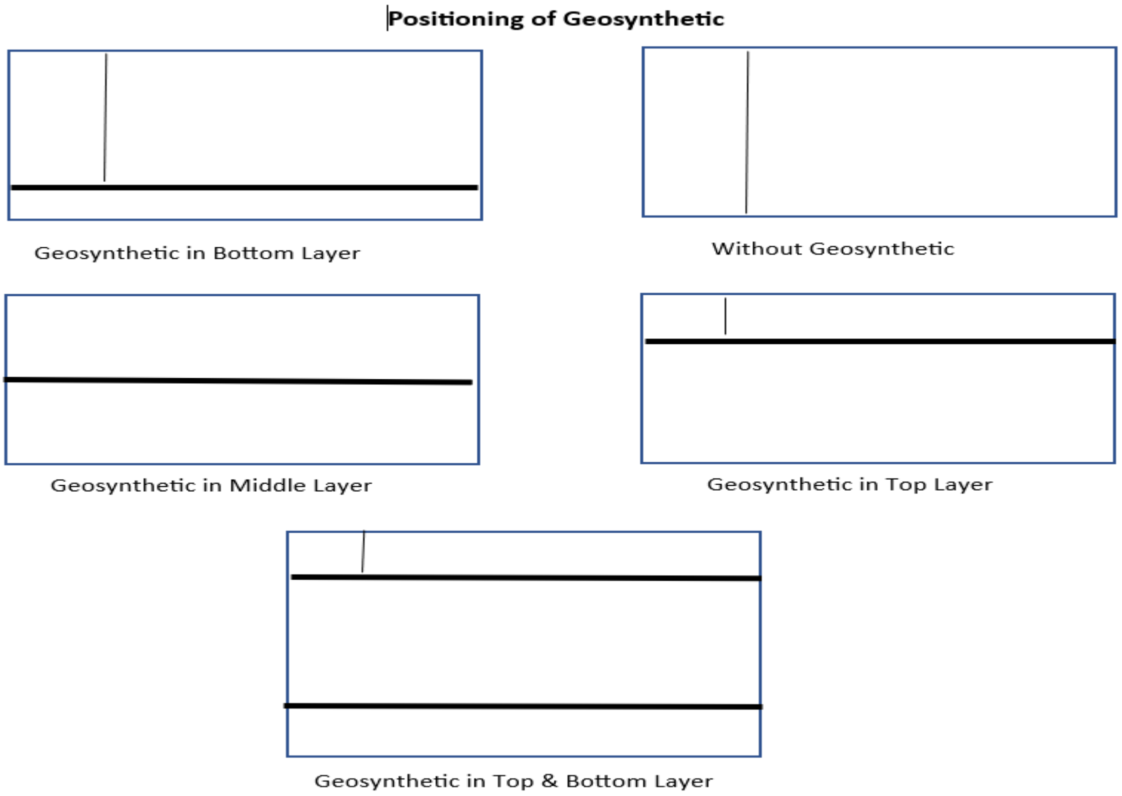


Figure 1.2 Positioning of geotextile (GT)

Results

Stress distribution

The placement of geosynthetic material is essential, as it facilitates the even distribution of stress across a large area. This work involved the creation of ABAQUS CAE models under two distinct loading conditions: one with a uniform distribution of load across the top surface, and another with a concentrated force applied to a single node on the top surface. These parameters enabled the examination of the impact of stress distribution on the prototype that was developed. The applied load on the soil model creates stress, which has a substantial effect on the subgrade's strength.

The even distribution of stress under an evenly distributed load is achieved by using geosynthetics in both the top and bottom layers. After that, the geosynthetics are only placed in the upper and middle layers. Geosynthetic installation in the soil model, whether in the bottom layer or elsewhere, has no discernible effect on the stress distribution within the models.

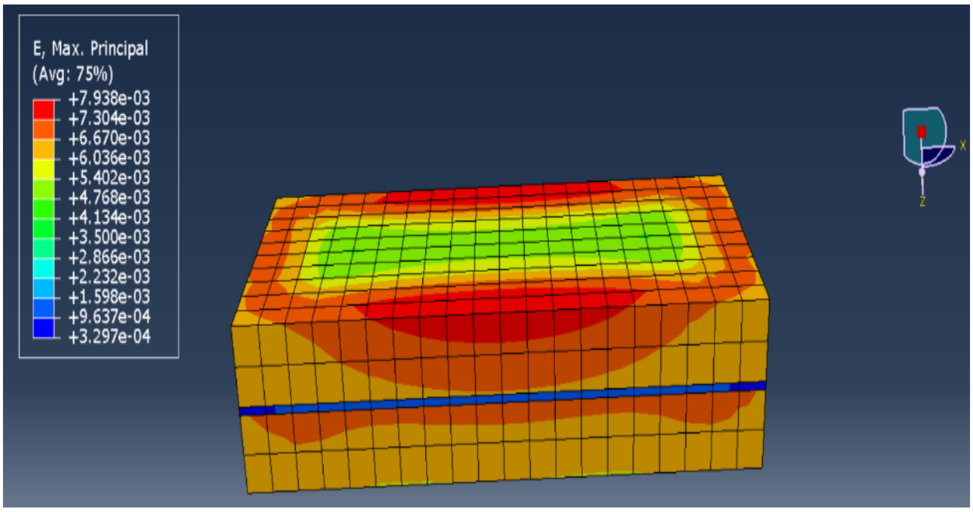


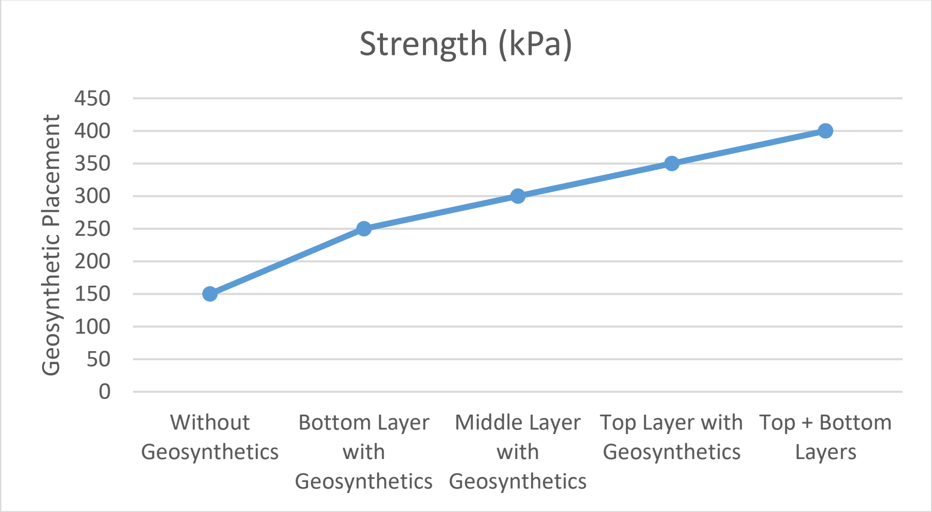
Figure 1.3 Stress Distribution (After geosynthetic Placement).

The strength results from the tri-axial test for different geosynthetic placements are presented below.

Experimental Results (Tri-axial Test)

Table 1.4 Strength Results of Triaxial Test

Geosynthetic Placement	Strength (kPa)
Without Geosynthetics	150
Bottom Layer with Geosynthetics	250
Middle Layer with Geosynthetics	300
Top Layer with Geosynthetics	350
Top & Bottom Layers	400

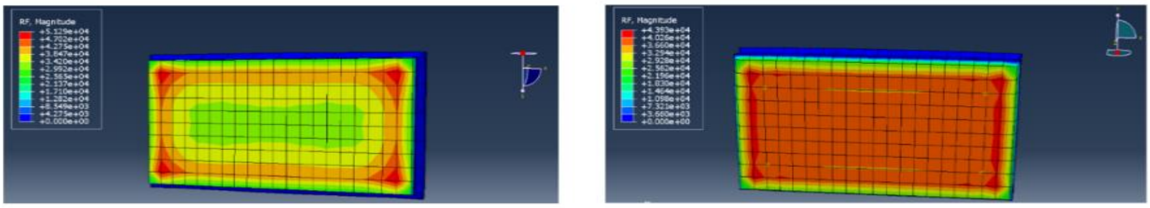


Graph 1.1 Strength (kPa) for different geotextile positions.

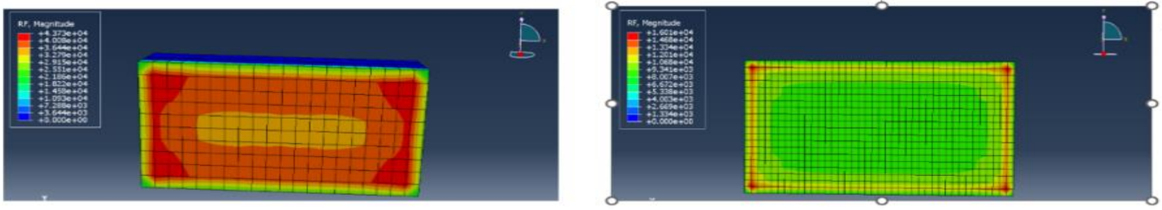
The experimental stress distribution results show that geosynthetics improve the even distribution of stress over a large area. The placement of geosynthetics plays a crucial role:

Load Application (Numerical Analysis)

- **Uniformly Distributed Load:** The stress distribution is most even with top and bottom placement of geosynthetics, followed by placement only on the top layer, middle layer, and lastly, the bottom layer. Models without geosynthetics show the least improvement.



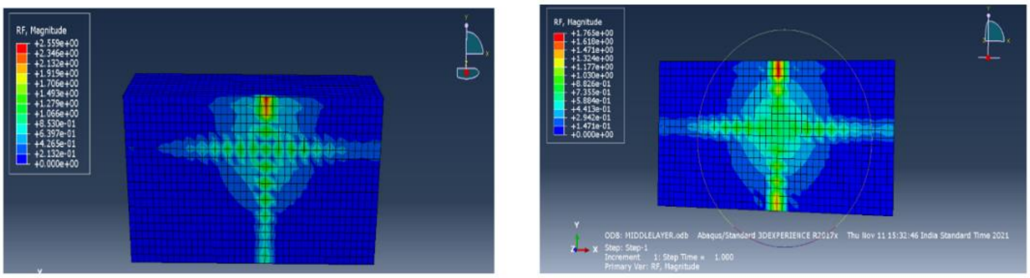
Without Geosynthetic Material Geosynthetic Material in Bottom Layer



Geosynthetic Material in Middle Layer Geosynthetic Material in Top Layer

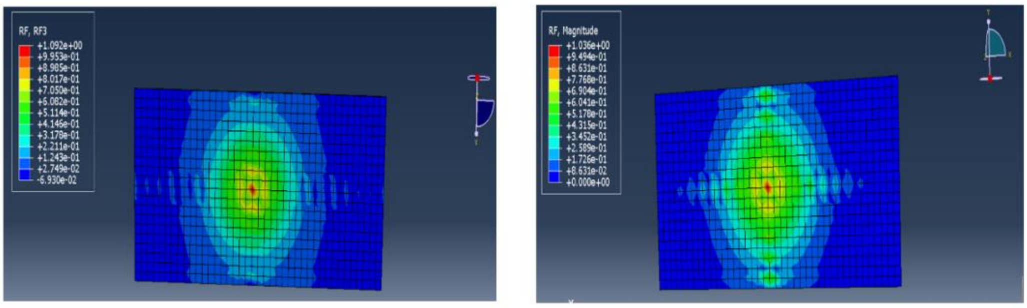
Figure 1.3 Stress Distribution in lower layers after application of conc. Load.

- **Concentrated Load:** The pattern is similar to the uniformly distributed load, with top and bottom placement showing the best stress distribution, followed by top, middle, and bottom layers, respectively.



Without Geosynthetic Material

Geosynthetic Material in Bottom Layer



Geosynthetic Material in Middle Layer

Geosynthetic Material in Top Layer

Fig 1.4– Stress distribution in lower layers after application of Conc. load.

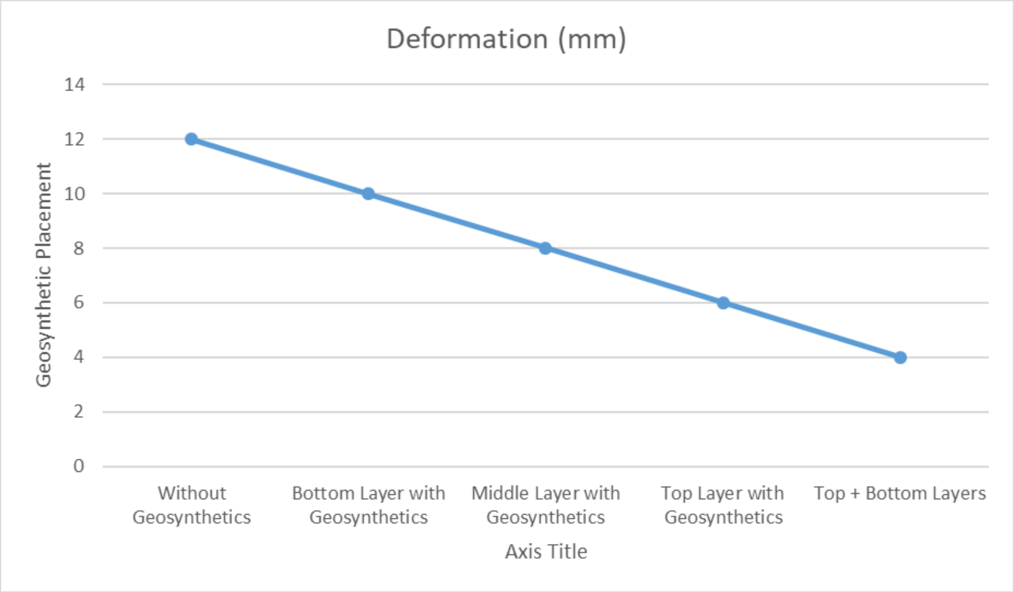
Deformation (Oedometer Test)

A soil mass undergoes deformation when it shifts vertically or laterally in response to an external force, altering its volume or changing its shape. The geosynthetic material that is part of the soil subgrade serves to disperse the stress and lessen soil deformation when a load is applied to the soil. It was not found that placing geosynthetic material toward the bottom significantly improved the reduction of deformation. On the other hand, geosynthetic material works best when placed close to the surface, where loads are exerted. By positioning the geosynthetic material in the middle layers rather than the bottom, deformation can be minimized in the reinforced sample. Below are the deformation findings obtained from the oedometer test for various geosynthetic locations.

Fig 1.5– Test Apparatus Oedometer Testing.T

Table 1.5 Deformation Results of Oedometer Test

Geosynthetic Placement	Deformation (mm)
Without Geosynthetics	12
Bottom Layer with Geosynthetics	10
Middle Layer with Geosynthetics	8
Top Layer with Geosynthetics	6
Top & Bottom Layers	4



Graph 1.2 Deformation (mm) for different geotextile positions.

Experimental Results

Experimental observations on deformation indicate that

- **Without Geosynthetics:** Shows the highest deformation.
- **Bottom Layer with Geosynthetics:** Shows some reduction in deformation but not significant.
- **Middle Layer with Geosynthetics:** Shows better reduction in deformation compared to the bottom layer.
- **Top Layer with Geosynthetics:** Shows even less deformation.
- **Top & Bottom Layers:** Shows the least deformation, indicating the best reinforcement.

Discussion

Geosynthetic materials in soil subgrades evenly distributes stress and reduces deformation. Numerical models using Abaqus FEM software and experimental data showed that geosynthetics worked well in a range of loading conditions and placements.

The top and bottom soil subgrade layers with geosynthetics had the most even stress distribution under uniform loads [16]. This was consistent across numerical and experimental investigations. Geosynthetics in the top layer improved stress distribution more than in the intermediate or bottom layers [18]. The soil model without geosynthetic reinforcement had an unequal stress distribution and higher stress concentrations, making it the least effective [19].

Concentrated loads had a stress distribution similar to that of uniformly distributed loads [20]. The top and bottom layer placements again distributed stress equally over the soil subgrade. Strategic geosynthetic deployment may alleviate the negative effects of concentrated loads on high-stress concentrations [21].

Deformation research showed that geosynthetics significantly reduced soil deformation under load. [22] Quantitative results showed that geosynthetics placed at the bottom, middle, top, and top-bottom layers minimized deformation. Deformation was lowest when geosynthetics were near the surface or in the top and bottom layers, according to experiments [23]
Geosynthetics distribute loads more uniformly [24], minimizing soil vertical and lateral movements while improving deformation. This benefits applications in which soil stability is critical for structural integrity [25].

Conclusion

Geosynthetic materials in soil subgrades have many benefits, as shown by this study. Geosynthetics increase soil mechanical characteristics, reducing stress distribution and deformation, according to computer calculations and laboratory experiments. The conclusions drawn are as follows:

1. Improved Stress Distribution: The top and bottom layers' geosynthetics ensure homogeneous stress distribution under both scattered and concentrated loads.
2. Reduced Deformation: Geosynthetics effectively minimize soil deformation, particularly near the surface or in both the top and bottom layers.
3. Strategic Geosynthetic Placement: Top and bottom layer placements consistently achieved the optimum stress distribution and deformation reduction.

Limitations and Future Scope

The primary limitation of this study is the controlled laboratory conditions under which tests were conducted. Field conditions may introduce variables not accounted for in the laboratory. Therefore, future work should focus on field experiments to validate these findings in real-world conditions. Additionally, the study could be expanded to explore the long-term durability and performance of geosynthetics in subgrade stabilization, considering factors such as environmental exposure and load variations over time.

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