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COMPARATIVE EVALUATION OF NATURAL AND SYNTHETIC GEOTEXTILE REINFORCEMENT IN SAND USING SCPT AND DCPT

ABSTRACT

The use of geotextile reinforcement has been increasingly adopted as a practical and economic approach for improving the mechanical response of non-cohesive (granular) soils in unpaved and lightly trafficked pavement systems. The synthetic geotextiles have been extensively studied and widely implemented owing to the high tensile strength and durability. The natural geotextiles namely, jute and coir offer sustainable and environmentally favourable alternatives. In the present study, a laboratory based experimental work was undertaken to examine the reinforcing behaviour of natural geotextiles (jute and coir) in compared to a synthetic geotextile placed over a sandy subgrade. Static Cone Penetration Tests (SCPT) and Dynamic Cone Penetration Tests (DCPT) were employed to evaluate the influence of reinforcement type, tensile stiffness, placement depth, and layering configuration on penetration resistance, stiffness mobilisation, and confinement behaviour. A digital SCPT device was used to obtain detailed penetration resistance profiles under controlled conditions, while DCPT provided complementary insights into the response of the reinforced system under dynamic loading. The comparative charts prepared using experimental results show that the inclusion of geotextile reinforcement leads to a significant improvement in cone resistance and penetration characteristics of the sand. Synthetic geotextiles exhibit higher peak resistance, primarily due to their greater tensile modulus, whereas natural geotextiles demonstrate significant improvement in near-surface stiffness through enhanced frictional interlock and confinement effects. The observed experimental response indicates that, under appropriate placement conditions, natural geotextiles are capable of delivering meaningful reinforcement benefits in unpaved pavement systems.

Keywords: geosynthetics; coir and jute geotextiles; SCPT; DCPT; unpaved pavements; sandy subgrade.

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CHAPTER 1

INTRODUCTION

Unpaved and low-volume rural roads make a major portion of the transportation infrastructure in developing countries like India. They serve as essential links for social, economic, agricultural, and emergency activities. In India, despite continuous development of non-urban roads through national initiatives such as the Pradhan Mantri Gram Sadak Yojana (PMGSY), 30% of the rural road network is still unpaved as of 2024 [1]. These pavements typically consist of a compacted soil sub-grade with a granular base layer. These are often constructed in regions where the sub-grade soil is weak, loose, or highly moisture sensitive. Due to inadequate drainage conditions and seasonal wetting, unpaved pavements frequently experience excessive rutting, progressive loss of serviceability, and premature deterioration when subjected to repeated vehicular loading. Such performance issues are particularly found in low-volume and rural road networks, where maintenance interventions are often limited.

Geosynthetics, over the last few decades, have been increasingly adopted as an effective means of improving the mechanical response and service life of unpaved pavements. Their primary functions include providing lateral confinement to the granular layer, improving load distribution, reducing shear stress concentrations, and limiting permanent deformation under the static and dynamic loadings. The beneficial effects of geosynthetic reinforcement have been documented in several international design guidelines and supported by field investigations, especially in situations where long-term performance considerations justify the initial investment in material costs[2],[3]. Despite these advantages, the use of synthetic geosynthetics in rural or resource-constrained regions remains limited. This is largely due to higher material and transportation costs, limited local availability, and concerns associated with their non-biodegradable nature, which raises issues related to long-term environmental impact and disposal [4].

Natural geotextiles such as jute and coir offer an alternative that directly addresses many of these constraints. These materials are locally available in several regions of India, derived from renewable resources, biodegradable, and generally more economical. Jute geotextiles possess relatively high initial tensile strength and favourable frictional properties. These properties make them suitable for short-term reinforcement applications where gradual biodegradation can be accommodated [5]. In contrast, coir geotextiles, with higher lignin content, exhibit slower degradation rates and can therefore provide reinforcement over a comparatively longer

duration [6]. The utilisation of such materials also aligns well with the objectives of Sustainable Development Goals (SDGs), especially those concerned with environmentally responsible infrastructure development and the use of indigenous resources.

Although the advantages of natural geotextiles are well recognised, their reinforcing behaviour in granular soils, especially sand—which is one of the most commonly used subgrade and base materials—has not been fully understood. A considerable proportion of existing studies emphasise synthetic geosynthetics or employ laboratory testing approaches that do not adequately capture localised soil–fabric interaction under traffic-induced stresses. In particular, the penetration behaviour of sand reinforced with natural and synthetic geotextiles remains insufficiently examined using penetration-based testing methods.

Static Cone Penetration Test (SCPT) and Dynamic Cone Penetration Test (DCPT) are highly effective techniques for assessing near-surface strength, stiffness variation, and localized confinement effects. SCPT provides high-resolution cone resistance profiles under controlled penetration, while DCPT offers a rapid and practical assessment of dynamic resistance relevant to field conditions. However, comparative assessments of natural and synthetic geotextiles using both SCPT and DCPT under identical boundary conditions are limited, leaving a critical knowledge gap.

In view of this gap, the present work seeks to evaluate and compare the reinforcement efficacy of natural geotextiles (jute and coir) and a synthetic geotextile placed within a sandy medium using SCPT and DCPT as the primary experimental tools. Controlled laboratory investigations were carried out to examine strength enhancement, deformation resistance, load transfer mechanisms, and the influence of reinforcement type and placement depth on penetration behaviour. This experimental approach enables a detailed assessment of soil–reinforcement interaction at a local scale and facilitates a clearer distinction between the mechanisms mobilised by natural and synthetic geotextiles. The experimental results of this study are expected to provide useful insights into the applicability, advantages, and limitations of natural geotextiles for unpaved rural road applications. The findings may contribute to informed material selection and practical design considerations for reinforced sand layers. It may support the development of economically viable, durable, and environmentally sustainable rural transportation infrastructure.

CHAPTER 2

LITERATURE REVIEW

The reinforcement of granular soils using geosynthetics have been investigated extensively over the last several decades, primarily because of its proven ability to provide improved strength, stiffness, and deformation resistance in pavement and geotechnical applications. Early studies by Giroud and Noiray [7], Bender and Barenberg [8], and Berg et al. [9] laid the conceptual foundation for reinforcement mechanisms such as membrane action, lateral restraint, and stress redistribution in unpaved road systems. These studies provided the basis for understanding how geosynthetic(reinforcement) layers interact with overlying granular materials to improve load distribution. Further investigations by Perkins [10], Hass et al. [11], and Shukla [12] advanced this understanding by examining soil–fabric interaction in reinforced pavement sections, particularly for geotextiles and geogrids positioned at the interface between the subgrade and base layers. Research focusing on synthetic geotextiles consistently highlights their high tensile modulus, resistance to creep, and durability under environmental loading, which makes them suitable for long-term reinforcement applications. In this context, pavement studies incorporating geogrids and geocells, including the reports provided by Tang et al. [13], Yang et al. [14], Hufenus et al. [15], and Al-Qadi et al. [16], demonstrate notable reductions in rutting and improvements in load distribution under cyclic and accelerated loading conditions. Design guidelines such as IRC: SP:59–2019 [17] and FHWA technical reports [3] formalise these findings by emphasising parameters such as stiffness compatibility, aperture geometry, and interface friction. Alongside synthetic materials, increasing attention has been given to natural geotextiles, particularly jute and coir, because of their biodegradable and sustainable characteristics. Coir geotextiles, due to their relatively high lignin content, show improved durability compared to jute and provide improved interfacial friction resulting from their rough surface texture, as reported by Visvanathan et al. [18]. Experimental studies by Hegde and Sitharam [19], Beena and Banerjee [20], and Rao and Dutta [21] shows that natural geotextiles can bring about significant improvement in the the short-term bearing capacity and stiffness of granular soils, especially in low-volume road applications. Investigations on multi-layer reinforcement systems, such as those by Rashidian et al. [22], suggest that most of the performance improvement is mobilised by the uppermost reinforcement layer, highlighting the importance of shallow embedment. Accelerated pavement testing involving natural geotextiles has also shown measurable

reductions in rut depth and surface deformation. For example, Kermani and Xiao [23] reported that on the application of a geotextile as a separator, fines migration was reduced by approximately 70% and rutting by nearly 30% under MMLS3 loading conditions. Studies focusing on jute-reinforced sand by Sharma et al. [24] and Ahmed and Ramamurthy [25] further emphasise the relevance of biodegradability, stiffness compatibility, and strain characteristics in natural fibre reinforcement. Penetration-based testing techniques such as **Static Cone Penetration Test (SCPT) and Dynamic Cone Penetration Test (DCPT)** have been increasingly used to analyse localised stiffness improvement and confinement effects due to geotextile reinforcement. SCPT enables the development of continuous cone resistance profiles that are sensitive to changes in confinement induced by reinforcement layers. Studies involving SCPT on geotextile-reinforced sand, including digital SCPT investigations reported by Boban et al.[26], show clear increases in cone resistance at optimal reinforcement depths. DCPT, which is widely employed for field evaluation, has been shown to capture reductions in dynamic penetration index in reinforced sections. This can be analysed from the reported literatures of Visvanathan et al. [12], Aiban et al. [27], and Alobaidi and Hoare [28]. Even after the availability of extensive body of literature on both synthetic and natural geotextile reinforcement, controlled and direct comparisons between natural and synthetic materials using both SCPT and DCPT under identical boundary conditions remain limited. Consequently, the influence of reinforcement type on confinement behaviour, stiffness mobilisation, and penetration resistance in sand is not yet fully understood. The present experimental work tries to overcome this limitation by systematically evaluating jute, coir, and synthetic geotextiles under comparable laboratory conditions to analyse differences in soil–fabric interaction mechanisms.

2.1 Research Gap and Problem Statement

Unpaved rural roads constructed over sandy or weak subgrades are particularly susceptible to rutting and early loss of serviceability, underscoring the need for effective and economically viable reinforcement solutions. Although synthetic geotextiles have been widely studied and implemented, natural alternatives such as jute and coir remain comparatively under-explored, despite their sustainability, low cost, and local availability. A key limitation in the existing literature is the absence of systematic, side-by-side comparisons between natural and synthetic geotextiles under identical experimental conditions, especially in sandy soils where load transfer and confinement mechanisms differ from those in non-granular soils. Moreover, the

localised reinforcement mechanisms mobilised under penetration loading are not well established, as relatively few studies have employed SCPT and DCPT to quantify stiffness enhancement and penetration resistance in reinforced sand. The limited availability of combined SCPT–DCPT datasets and the lack of clarity regarding the factors like influence of reinforcement type, tensile stiffness, and placement depth contribute to a significant research gap. In view of the limitations stated above, the present work aims to investigate the reinforcing behaviour of natural geotextiles placed over sandy subgrades and to examine their interaction with unpaved pavement systems under both static and dynamic penetration loading. The performance of natural geotextiles is evaluated and compared with that of a synthetic geotextile and an unreinforced system, with particular emphasis on penetration resistance, stiffness mobilisation, and near-surface confinement behaviour.

2.2 Objectives

The following objectives have been planned for the proposed experimentation:

- a. To perform the comparative analysis between unreinforced and geosynthetic (natural and synthetic) reinforced unpaved test sections using the SCPT test
- b. To perform the comparative analysis between unreinforced and geosynthetic (natural and synthetic) reinforced unpaved test sections using the DCPT test

Scope of this study

The scope of the work at hand is confined to experimental investigations on sand reinforced with jute, coir, and synthetic geotextiles. The research focuses primarily on the short-term load response and deformation characteristics under controlled laboratory conditions. The experimental program includes conducting SCPT and DCPT tests on both set-ups, without reinforcement and with reinforced sand beds with provision of geotextiles at varying depths of embedment. A comparative analysis of different materials is carried out to assess the relative effectiveness of natural and synthetic reinforcements, and an empirical or semi-empirical relation is co-related from the DCPT results. The scope of this study, however, does not extend to investigating the degradation behaviour of geotextiles in long run or the effects of environmental variability.

CHAPTER 3

MATERIALS AND THEIR PROPERTIES

3.1 Cohesion-less soils and geosynthetic reinforcements are commonly used in the development of low-trafficked roads and other transportation systems. In these materials, inter-particle friction and grain-interlocking mainly contribute to shear strength of the geomaterials, since there is no inherent electrochemical bonding between the individual soil particles. As a result, the mechanical response of such materials is largely determined by factors including grain size distribution, angularity, relative density, compaction effort, and prevailing moisture condition. When put to use in unpaved pavement sections, these geo-materials function as the principal load-distributing layer, facilitating the transfer of vehicle-induced stresses to the underlying subgrade while ensuring overall structural stability of the pavement system.

3.2 Method

To characterise the geomaterial used in the present study and assess its usability for unpaved pavement systems, corresponding index property tests were performed. Grain size distribution analysis was done to determine the gradation properties of the material and its deformation resisting potential under traffic loading. The results obtained from these basic characterisation tests formed the basis for subsequent evaluation of reinforced soil behaviour under penetration loading. All index property tests in this study were conducted as per the relevant IS code specifications, and the list of tests performed for soil characterization is shown below in Table 1.

Table 1: List of Experiments conducted for the determination of basic index

S. No.	Experiments	Properties	Indian Standards
1.	Grain size distribution	Soil Gradation	IS 2720: part 4 (1985)
2.	Standard proctor test	OMC and MDD	IS 2720: Part 7 (1980)

3.2.1 Particle Size Distribution

The gradation characteristics of the geomaterial were determined by sieve analysis in accordance with *IS 2720 (Part 4, 1985)*. The representative oven-dried soil sample was passed through a sequence of standard IS sieves arranged in the order of decreasing aperture size. In the process of sieving, approximately 1 kg of the soil sample (oven dried) was taken. It was placed on the top sieve of the combination of sieves (arranged as shown in the figure 3.1 below), and the entire assembly was subjected to mechanical shaking.

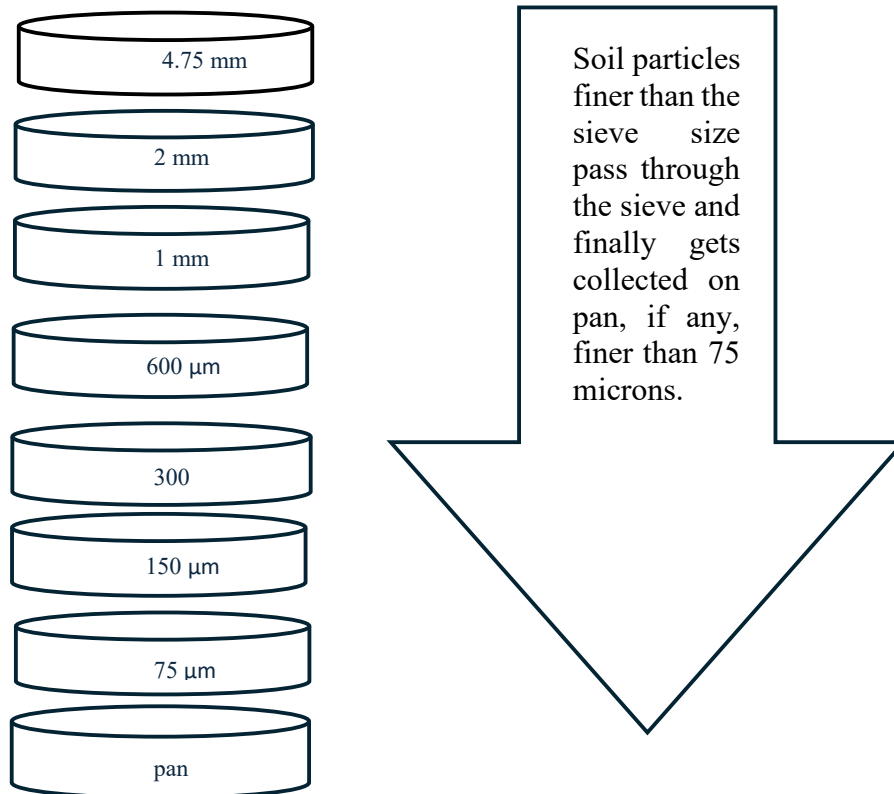


Figure 3.1 Grain Size Analysis of Geomaterials

After completion of sieving, the quantity of soil retained on different sieves was measured on weighing scale. These weights were used to determine the retained percentage and passing percentage corresponding to each sieve size, which describes the distribution of particle sizes within the geomaterial.

47

$$\text{Percentage retained (\% retained)} = \left(\frac{\text{weigh of soil retained}}{\text{Total sample weigh}} \right) \times 100 \quad (1)$$

$$\text{Percentage Passing} = 100 \% - \text{Cumulative Retained (in percentage)} \quad (2)$$

17 54 A particle size distribution (PSD) curve was plotted. The X-axis represents grain size (on a logarithmic scale) and the percentage passing is represented by Y-axis. With the help of PSD Curve gradation characteristics can be evaluated which helps in determining the coefficient of uniformity (C_u) and coefficient of curvature (C_c). These parameters facilitates in assessing the spread and shape of the PSD.

$$C_u = \frac{D_{60}}{D_{10}} \quad (3)$$

$$C_c = \frac{(D_{30})^2}{D_{60} * D_{10}} \quad (4)$$

Where: D_{60} , D_{30} , and D_{10} denotes the particle diameters with respect to 60%, 30%, and 10% passing, respectively, obtained from the PSD curve.

3.2.2 Standard Proctor Compaction Test

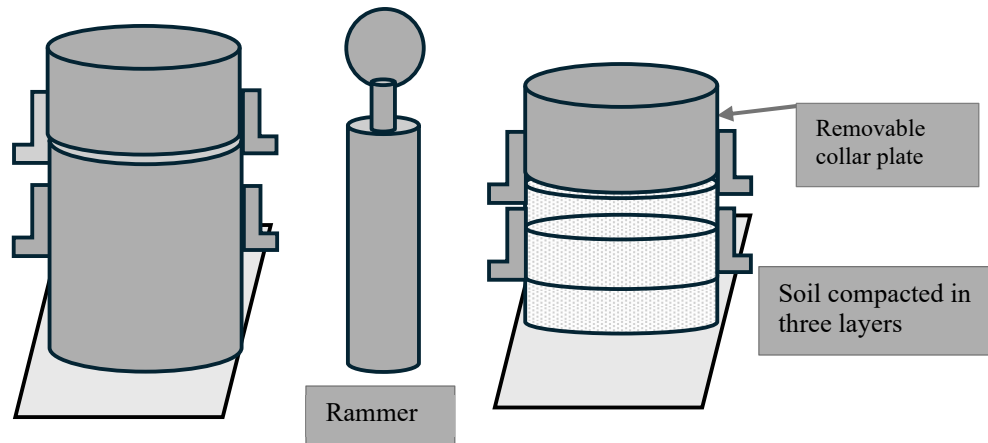


Figure 3.2 The standard mould and rammer assembly used in the compaction process

The Standard Proctor Compaction Test was done to evaluate the Optimum Moisture Content (OMC) and subsequently Maximum Dry Density (MDD) of the geomaterial in accordance with IS 2720 (Part 7): 1980. Typical setup for this test involves a 1000 cc mould(also known as Proctor mould). After placing the soil in the mould, it is compacted by a 2.6 kg rammer(standard specified weight). Each fall of the rammer was free fall and from the height of 310 mm(standard specified height). Following the similar steps soil was compacted into three layers. For successive trials, the moisture content of the soil was varied, and the compacted specimen mass was noted after each compaction. Following compaction, for every trial, representative sample of the test specimen was collected to determine its moisture content. Subsequently, the related quantities were calculated using the following relationships:

$$\gamma = W/V \quad (5)$$

$$\gamma_d = \frac{\gamma}{1+w} \quad (6)$$

where:

γ = bulk unit weight (compacted soil)

γ_d = dry unit weight

W = weight of soil specimen (compacted)

V = volume of the Proctor mould

w = moisture content of the soil

A scatter curve was plotted with moisture content(w) along x- axis and dry density(γ_d) along y-axis. From the plot, two important compaction parameters viz. maximum dry density, MDD

(maximum recorded value along y- axis) and corresponding moisture content (recorded on x-axis) knowns as optimum moisture content (OMC) were recorded.

3.3 Reinforcement Materials (Geotextiles)

Three types of geotextiles of different materials were procured for this experimental program to understand their reinforcing behaviour in unpaved conditions under repeated loading and penetration resistance.

(a) Jute Geotextile (Natural): Jute geotextile was selected as a biodegradable and environmentally friendly natural reinforcement. It was obtained from a certified supplier and had a plain-woven structure.

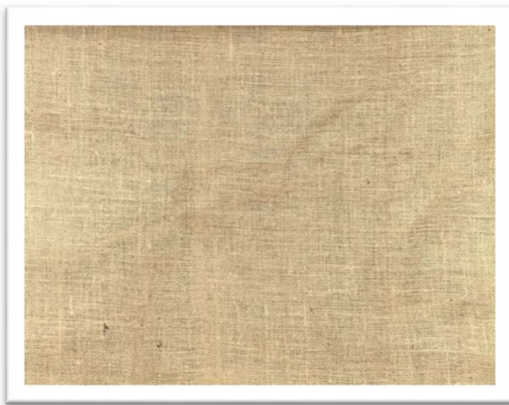


Figure 3.3 (a) Jute Textile^a



(b) Jute Textile^b

(b) Coir Geotextile (Natural): Coir geotextile, made from coconut fibres, was also used due to its high durability and slow biodegradation rate compared to jute. It was obtained in a woven form.



Figure 3.4 Coir textile



Figure 3.5 Synthetic Geotextile

(c) Synthetic Geotextile (Woven Polypropylene) A woven synthetic geotextile made of polypropylene fibres was used for comparison with the natural alternatives. It was characterized by high tensile strength, low elongation, and long-term durability.

Property	Jute Geotextile ^{a,b}	Coir Geotextile
GSM (g/m ²) ^{[31], [35],[36]}	650–750 g/m ²	300–1300 g/m ²
Thickness (mm) ^{[32], [35],[36]}	1.3–1.5 mm	6–14 mm (nonwoven); 6–10 mm (woven)
Apparent Opening Size (AOS, mm) ^{[34], [35],[36]}	0.23–0.26 mm	0.3–0.6 mm
Wide-width tensile strength (kN/m) ^{[33],[35],[36]}	MD: 19–25; CMD : 21–25	MD: 1.7–31.5; CMD : 0.7–12.7
Elongation at break (%) ^{[33],[35],[36]}	MD: 11–13; CMD: 8–9	MD: 11–42; CMD : 10–32
Initial tangent modulus ^{[33],[36]}	300–450 MPa equivalent	10–100 kN/m (coir mats)
Puncture resistance ^{[37], [38]}	Moderate; increases with gsm	High for coir due to thickness

Table 2 General Engineering properties of natural geotextile

Table 3 Properties of Synthetic geotextile [41]

Property	Value	Test Method
Tensile strength(kN/m)	45 x 34 (MD x CMD)	ASTM D4595
Puncture Strength(N)	480	ASTM D4833
Apparent opening size(mm)	0.075 mm	ASTM D4751
Mass per unit area of fabric(g/m ²)	200	ASTM D5261

MD denotes Machine direction , CMD denotes Cross- Machine direction

CHAPTER 4

METHODOLOGY

This experimental work was undertaken to analyse the reinforcement performance of natural geotextile (jute and coir) and synthetic geotextiles in sand under varying modes of loading. The investigation comprised of two main components: the Static Cone Penetration Test (SCPT) and the Dynamic Cone Penetration Test (DCPT). These tests were conducted in the present work to evaluate the enhancement in static and dynamic bearing resistance of sand sub grade on strengthening using geotextile reinforcement. The penetration responses obtained from these tests were subsequently used to assess the relative improvement in bearing resistance under reinforced and unreinforced conditions.

4.1 Static Cone Penetration Test

The Static Cone Penetration Test is a widely recognised as a simple, cost-effective, and reliable technique for subsurface exploration, estimation of pavement layer thickness, and assessment

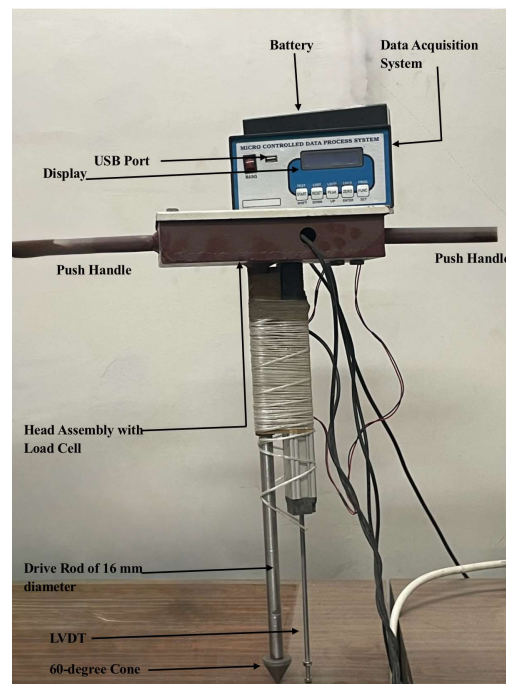


Figure 4.1 Digital Static Cone Penetrometer Device

of in-situ strength characteristics. In the present investigation, a digital variety of Static Cone Penetrometer (SCP) device was used for penetration testing. The apparatus comprises of a measuring body fitted with a drive rod of 16 mm diameter and 498 mm length, two push handles and a 60° steel cone attached at the lower end. The system is instrumented with a linear

variable displacement transducer (LVDT) having a measurement run of 0–200 mm, a load cell having a capacity of 300 kg, and a unit to acquire data is provided with a USB output module, as shown in Fig. 4.1. The digital version of SCP is a portable, hand-operated device which can be pushed to penetrate sub-base and sub-grade layers with relative ease.

During testing, particular attention was paid to maintaining the penetration rod in a vertical alignment. Sudden jerks and abrupt movements were carefully avoided in order to ensure that the recorded measurements were not affected by operator-induced disturbances. In conventional SCP testing, the instrument (cone) is advanced into the soil specimen at a fairly constant rate of penetration and the corresponding resistance offered to cone is measured [41]. In the present study, a uniform penetration load was applied manually by exerting body weight through the push handle system, which allowed controlled advancement of the cone into the soil. The load cell along with the transducer operated simultaneously throughout the test. The load cell recorded the penetration force applied, while the transducer continuously measured the corresponding penetration of cone. The electrical signals generated in the process were recorded by sensors and transmitted to the system used for acquiring of data, where the analogue signals were converted into digital form. The load and penetration data were automatically stored in a connected USB device in a two-column tabular format for subsequent processing and analysis.

Common Test Tank: A test tank of dimensions 650 mm × 460 mm × 400 mm (L x B x H) was prepared and filled with sand compacted using rammers into layers of 50 mm thickness so as to achieve a relative density of approximately 50%. The reinforcement layers comprising jute, coir, and synthetic geotextiles were positioned at predetermined depths of 50mm, 100mm, and 150mm.

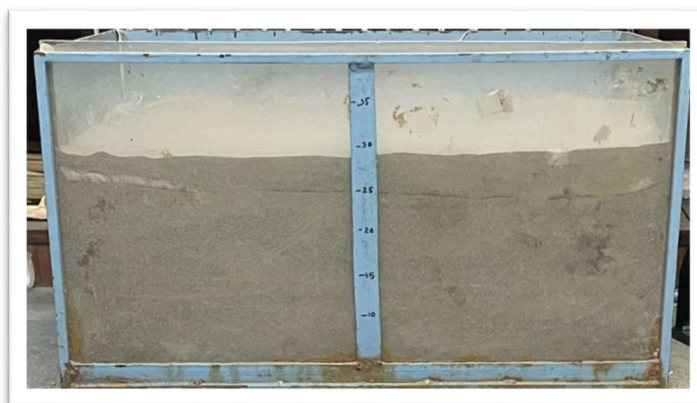


Figure 4.2 Test tank filled with geo-material

4.2 Dynamic Cone Penetration Test

The DCPT was executed to evaluate the impact resistance of the reinforced sand under dynamic loading. The sand bed preparation procedure was identical to that adopted in the SCPT, and the reinforcements were positioned at the optimum depth of 50 mm and 100 mm based on the SCPT results. A dynamic cone penetrometer is equipped with an hammer weighing 8 kg falling from 575 mm height. The number of blows of hammer noted for successive 10 mm increments in penetration was recorded up to cumulative 235 mm penetration depth. The change in dynamic penetration resistance was quantified by comparing the cumulative number of blows for reinforced and unreinforced conditions at equivalent penetration depths.

Dynamic Cone Penetrometer (DCP) Device: The DCP apparatus utilised in this work (Fig. 4.3). The specifications of the penetrometer are as per ASTM D6951-03.

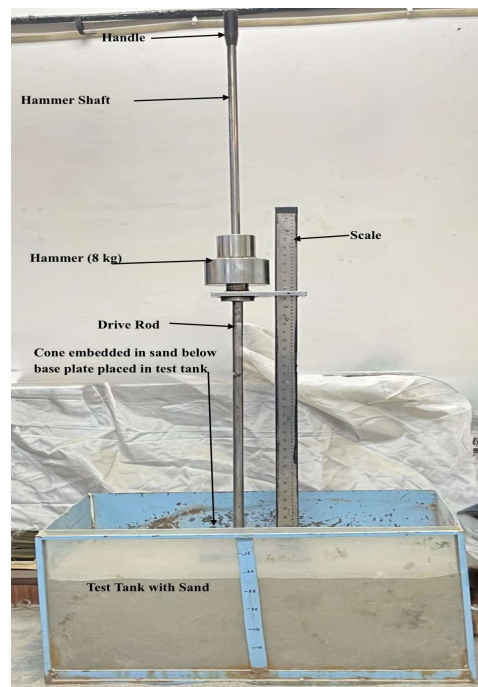


Figure 4.3 The Dynamic Cone Penetrometer (DCP) apparatus

The DCPT apparatus used in the study consists of a 60° steel cone of 20 mm base diameter. It is rigidly attached on a steel rod of 16 mm diameter. During testing, particular care was taken to maintain the penetration rod in a strictly vertical position to ensure uniform load transfer and reliable penetration measurements. The hammer of specifications as described in the previous section was raised to 575 mm height and dropped freely, driving the cone into the compacted subgrade.

While lifting the hammer, attention was given to ensure that it only came into contact with the underside of the handle without applying any upward force on the cone. Improper lifting techniques or uncontrolled hammer release can influence penetration resistance and lead to erroneous measurements; therefore, such deviations were carefully avoided during testing. The penetration corresponding to the first hammer blow was excluded from analysis, as the initial contact area of the cone differs from that developed during subsequent penetrations.

The cone diameter was intentionally selected to be slightly larger in comparison to the diameter of the drive rod so as to mobilise the penetration resistance of the soil entirely at the cone tip, as recommended in the literature [39]. Depth of penetration was noted after every blow of the hammer, and the Dynamic Cone Penetration Index (DCPI), expressed in mm/blow, was calculated using Eq. (4.1) [40]. In addition, a curve was plotted with cumulative penetration along y-axis(reversed direction) and the cumulative number of blows along the x-axis. The DCPI was obtained from the slope the best-fit curve following established practice [41].

$$DCPI = \frac{(P_{i+1} - P_i)}{(N_{i+1} - N_i)} \quad 4.1$$

where DCPI denotes dynamic cone penetration index (mm/blow). Here, P_i and P_{i+1} denote the penetration readings (mm) corresponding to blows i^{th} and $(i + 1)^{th}$ and N_i and N_{i+1} represent the associated blow counts. To obtain a representative value for each test layer, the individual DCPI values were averaged using Eq. (4.2) [40]

$$Avg. DCPI = \sum_{i=1}^N \frac{DCPI_i}{N} \quad 4.2$$

where N denotes the total number of DCPI readings within the selected penetration depth.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Particle Size Analysis

Particle size analysis was worked out to find the particle size distribution of the specimen soil. It helped in classifying the soil following the Indian Standard Soil Classification System (IS 1498:1985). The relevant analysis was done using a combination of sieve analysis for coarse particles. The test results formed the basis of a grain size distribution (GSD) curve, from which the characteristic particle sizes D_{10} , D_{30} , and D_{60} were determined. These parameters were subsequently used to evaluate the relevant parameters using the relationships as below:

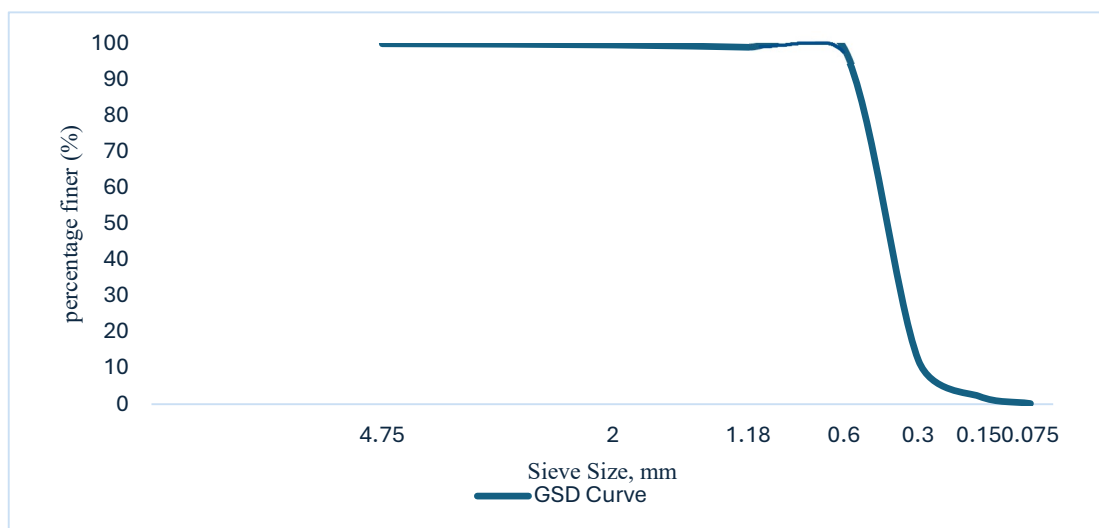


Figure 5.1 Grain Size Distribution Curve

Table 4. Grain Size Parameters

Parameter	Value (mm)
D_{10}	0.166 mm
D_{30}	0.189 mm
D_{60}	0.216 mm
$Cu = D_{60} / D_{10}$	1.3
$Cc = (D_{30})^2 / (D_{10} \times D_{60})$	0.99
Soil Classification (IS)	SP

On analysis of grain size distribution curve and the evaluated gradation parameters, the soil specimen was identified as poorly graded sand (SP). The low coefficient of curvature and the

narrow range of particle sizes indicate a lack of gradational diversity, which limits natural packing efficiency and reduces shear interlocking between particles. As a result, such soils generally exhibit relatively high permeability but inadequate compaction characteristics. Owing to these limitations, the strengthening of soil becomes necessary to **augment the load-bearing capacity of the soil** for pavement applications.

5.2 Standard Proctor Test Results

The Standard Proctor Compaction Test was performed as per illustrations of IS 2720 (Part 7). to determine the max. **dry density (MDD)** and corresponding **moisture content** referred to as **optimum moisture content (OMC)** of the sand. The variation of dry density with moisture content as recorded during the performance of test is shown in Figure 5.2.

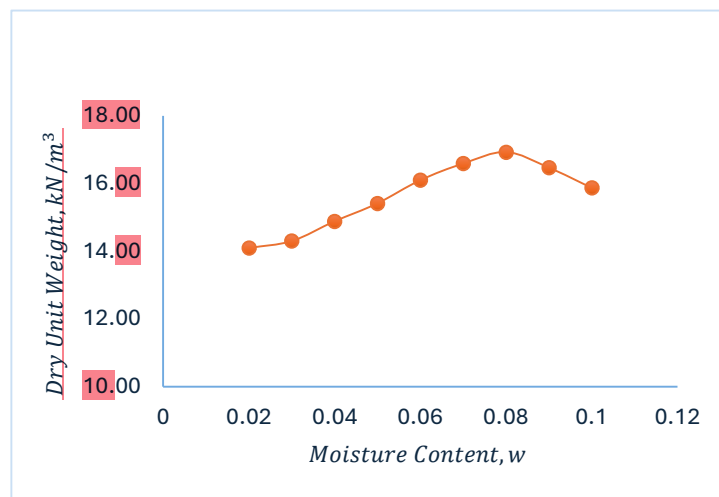


Figure 5.2 The graph corresponding to the Standard Proctor Compaction Test Results

On analysing the curve, it is observed that dry density improves gradually with incremental moisture content, reflecting improved particle rearrangement due to the lubrication effect of water. The dry density increases from approximately 14.8 kN/m³ at 2% water content and improves steadily to achieve a peak value. The maximum dry density of 17.5 kN/m³ (appx.) occurs at an moisture content of nearly 8%. This water content was recorded as optimum moisture content (OMC). Beyond this point, the dry density decreases, which can be due to the development of excess water occupying the void spaces and restricting further densification.

The bell-shaped nature of the compaction curve is typical of coarse-grained soils with limited fines content, further confirming the poorly graded nature of the sand. The moderate MDD value reflects the inherent limitation of uniform sands in achieving dense packing due to the absence of well-graded particle interlock. The determined OMC and MDD values were

subsequently adopted for preparing the sand beds for SCPT and DCPT testing to ensure consistency across all experiments.

Table 5. Soil Properties

Property	Test Standard	Result
Grain size distribution	IS 2720 (Part 4)	Poorly graded sand (SP)
Specific Gravity, G_s	IS 2720 (Part 3)	2.63
Maximum Dry Unit Weight	IS 2720 (Part 8)	17.5 kN/m ³
Optimum Moisture Content (OMC)	IS 2720 (Part 8)	8 %

5.3 Static Cone Penetration Test (SCPT) Result

The Static Cone Penetration Test (SCPT) was worked out to evaluate the influence of natural and synthetic reinforcements on the resistance to penetration and stiffness behaviour of a poorly graded sand subgrade. Reinforcement layers consisting of synthetic geotextile, jute geotextile (JGT), and coir mat were placed at depths of 50 mm, 100 mm, and 150 mm from top of the surface. Smoothened load–penetration curves were plotted to clearly visualise the trends, while raw measured peak loads were used for quantitative comparison and improvement assessment. The results presented in this section highlight the effect of reinforcement type and placement depth on the mobilised cone resistance and overall load–displacement response of the subgrade.

Response of Unreinforced Sand

The unreinforced load–penetration curve exhibits a gradual and nearly linear increase in load with increasing penetration, reflecting the low initial stiffness and weak confinement of the loose sand. The raw peak load of the unreinforced profile is 0.76 kN, representing the inherent bearing capacity of the untreated soil. The smoothened curve closely matches the raw behaviour, confirming minimal noise in the dataset. This baseline response provides the reference framework for quantifying the improvement due to reinforcement. The absence of reinforcement results in unrestricted lateral deformation beneath the cone, causing rapid loss of confinement and hence a relatively low and slowly mobilised resistance. Such behaviour corroborates previous studies reporting poor penetration resistance in uniformly graded sands with limited fines.

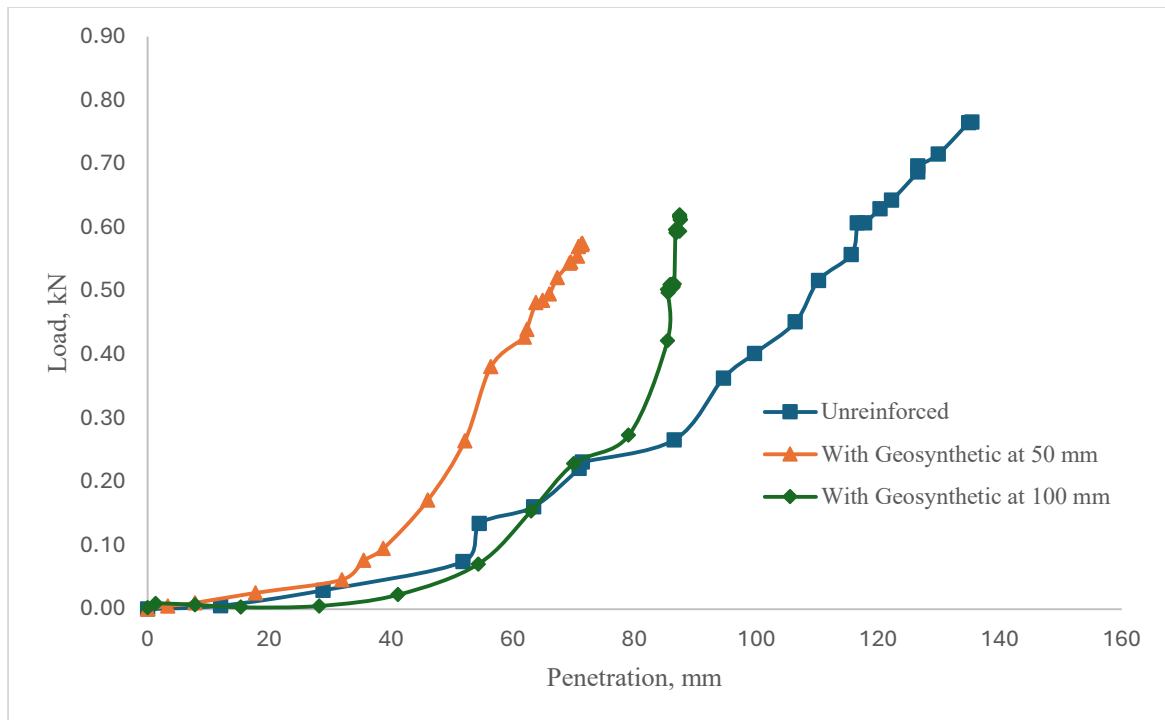


Figure 5.3 A comparison chart (Unreinforced vs Geosynthetic) using SCPT data at various depths

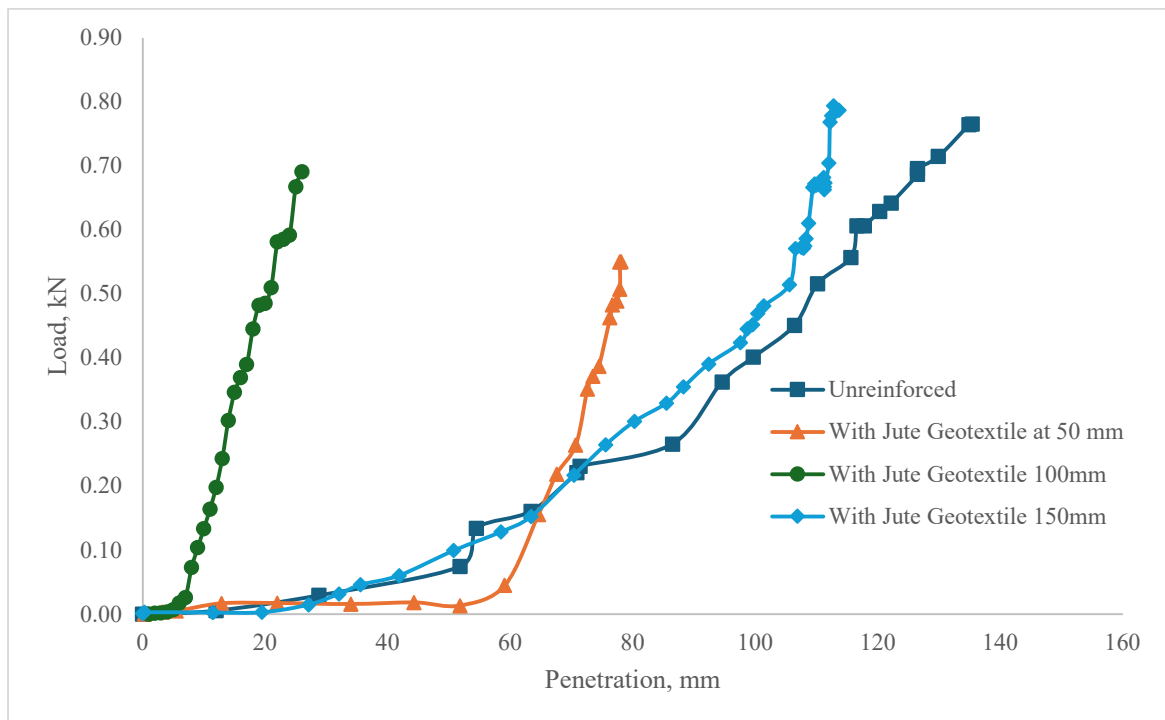


Figure 5.4 A comparison chart (Unreinforced vs Jute textile) using SCPT data at various depths

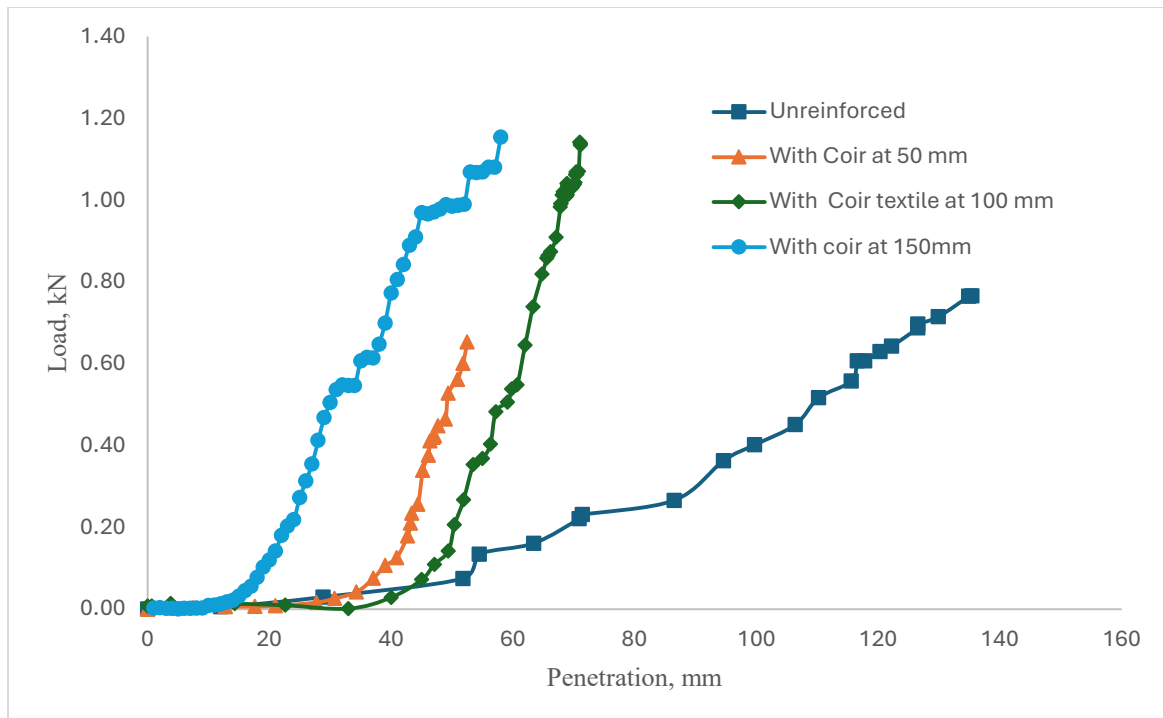


Figure 5.5 A comparison chart (Unreinforced vs Coir textile) using SCPT data at various depths

Effect of Reinforcement at 50 mm Depth

Reinforcement placed close to the surface (50 mm depth) shows the most pronounced enhancement in penetration resistance. The cone engages the reinforcement layer early in the penetration process, resulting in a noticeable upward shift in the load–penetration curve for all reinforcement types. Synthetic geotextile at 50 mm reaches a peak load of 0.57 kN, representing a notable improvement over the unreinforced condition. At the same reinforcement depth, the jute geotextile recorded a peak load of approximately 0.55 kN, reflecting a moderate level of improvement. Its performance was slightly lower than that of the synthetic geotextile, which can be attributed to the lower tensile stiffness and higher elongation behaviour of jute. In contrast, the coir mat positioned at 50 mm depth recorded the highest peak load among the materials tested at this depth, reaching about 0.65 kN. This enhanced response may be associated with the greater thickness, rough surface texture, and improved soil–fabric interlocking characteristics of the coir mat. The load–penetration curves obtained for the reinforced cases at 50 mm depth show steeper initial slopes and earlier mobilisation of stiffness when compared with the unreinforced condition. These observations indicate that reinforcement placed close to the surface is effective in confining the soil specimen in the vicinity of the tip of the cone, thereby increasing local bearing resistance. Since the 50 mm

depth lies within the zone of maximum stress influence during the initial stages of penetration, the relative improvement in performance is most pronounced at this depth.

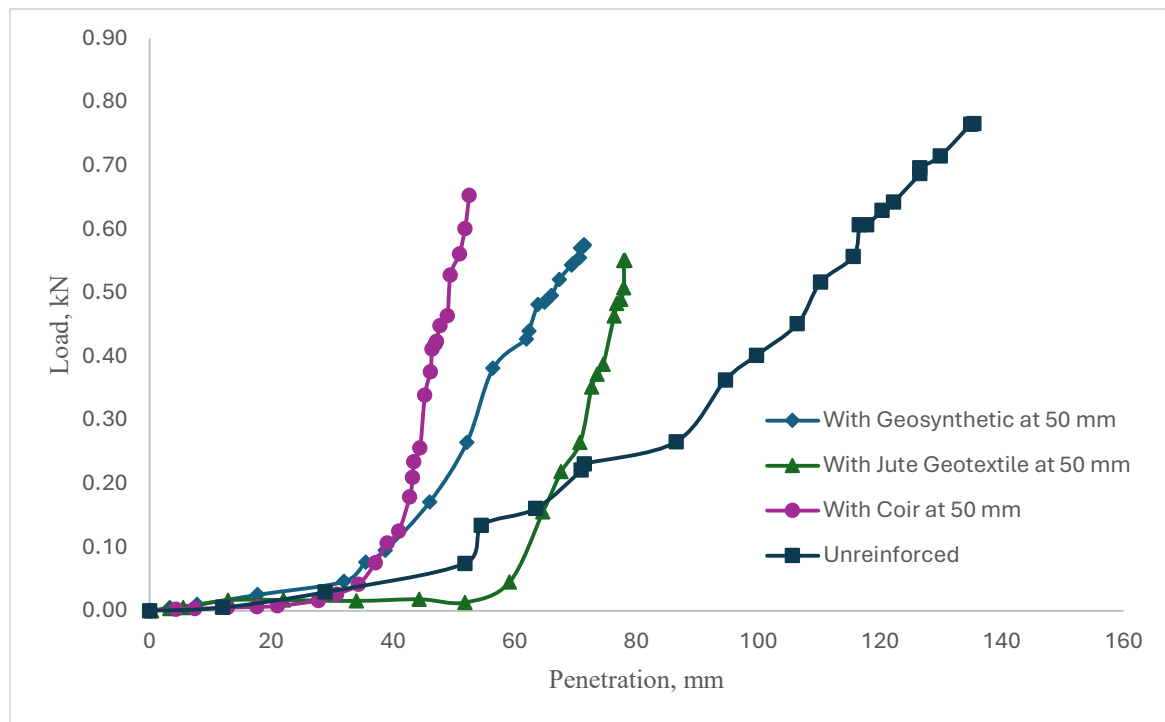


Figure 5.6 A comparison chart (Unreinforced vs Reinforcement at 50 mm) using SCPT data for different reinforcements

Effect of Reinforcement at 100 mm Depth

When reinforcement was placed at an intermediate depth of 100 mm, improvements in penetration resistance were still observed, although the response was mobilised at larger penetration depths compared to the 50 mm configuration. The delayed engagement is attributed to the need for sufficient penetration before the stress bulb reaches the reinforcement layer. Despite this delay, reinforced specimens—especially those with coir mats—exhibited high ultimate resistance due to enhanced confinement and tensile mobilisation at deeper penetrations. Synthetic geotextile at 100 mm shows a peak resistance of 0.62 kN, higher than the corresponding 50 mm placement, indicating that deeper placement allows better mobilisation of tensile forces, though initial stiffness remains lower. JGT at 100 mm shows a raw peak of 0.69 kN, suggesting better interaction with the soil at this depth compared to 50 mm due to improved confinement conditions. Coir at 100 mm exhibits the highest peak load of the entire dataset, reaching 1.14 kN, nearly 1.5 times the unreinforced substantial improvement highlights the superior reinforcing action of coir, which likely mobilises both

membrane tension and interlock at this depth. resistance. The smoothened curves for the 100 mm depth group are characterised by a noticeable “knee” or inflection point around the reinforcement depth, followed by a rapid increase in resistance. This behaviour reflects the transition from unconfined penetration to reinforced confinement once the cone engages the reinforcement.

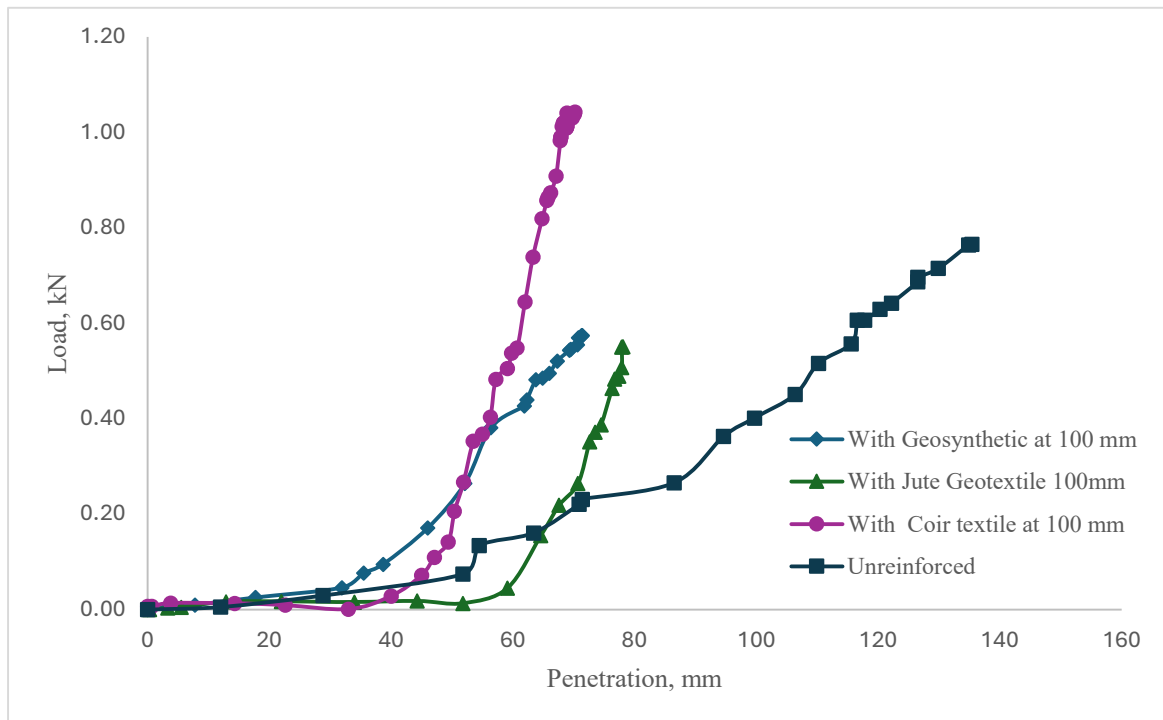


Figure 5.7 A comparison chart (Unreinforced vs Reinforcement at 100 mm) using SCPT data for different reinforcements

Effect of Reinforcement at 150 mm Depth

Reinforcement layers placed at 150 mm depth show the least improvement in early penetration stages but still offer significant gains once the cone reaches the reinforcement. JGT at 150 mm mobilises a peak load of 0.79 kN, slightly above the unreinforced value. Coir at 150 mm again performs exceptionally well, achieving 1.15 kN (raw peak) and a smoothed peak of 1.16 kN, demonstrating robust confinement effects even at deeper placement. The smoothened curves at this depth are flatter at low penetrations but steepen considerably after reaching the reinforcement. These results confirm that deeper reinforcement layers influence the resistance only after a certain penetration threshold, consistent with penetration mechanics and stress distribution theory. Although less effective for surface deformation control, deeper reinforcement still enhances ultimate bearing capacity.

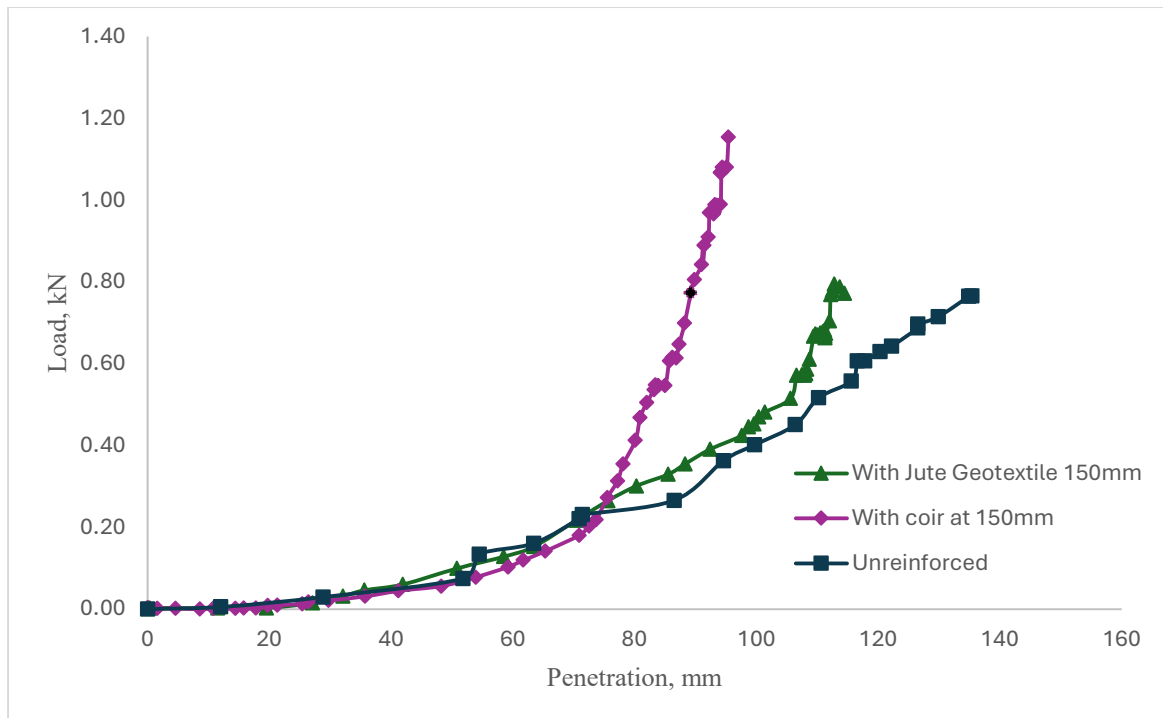


Figure 5.8 A comparison chart (Unreinforced vs Reinforcement at 150 mm) using SCPT data for different reinforcements

Comparative Behaviour Across All Reinforcement Depths

A comparison across depths reveals clear behavioural trends:

(a) Influence of reinforcement depth: The effectiveness of reinforcement decreases with increasing depth, particularly in the initial penetration stages. The load–penetration curves shows depth of 50 mm as the maximum effective and 150 mm as minimum effective in terms of early stiffness mobilisation.

(b) Influence of reinforcement material: Across all depths, Coir consistently demonstrates higher peak loads due to its greater thickness, rough surface texture, and superior interlocking behaviour, which enhance load transfer. Synthetic geotextile performs moderately well due to its high tensile modulus, whereas Jute Geotextile, being more compressible and extensible, provides less confinement but still improves performance relative to unreinforced soil.

(c) Improvement in peak load: Using peak load values relative to the unreinforced condition (0.76 kN), the highest improvements were observed for coir reinforcement at 100 mm and 150 mm depths, confirming that natural reinforcements can, under certain conditions, match or even exceed the performance of synthetic geotextiles.

5.4 Dynamic Cone Penetration Test (DCPT) Results

The DCPT was carried out to evaluate the dynamic penetration resistance of reinforced and unreinforced sand subgrades. Reinforcement layers included synthetic geotextile, jute geotextile, coir textile, and jute-gunny positioned at 50 mm and 100 mm depths. The curves with penetration in millimetre (mm) on y-axis (reversed) and number of blows on x-axis was plotted.

Behaviour of Unreinforced Sand : All reinforced configurations exhibited reduced penetration per blow relative to the unreinforced soil, indicating enhanced stiffness and improved energy absorption. Shallow reinforcement at 50 mm resulted in immediate resistance mobilisation, whereas deeper reinforcement at 100 mm showed delayed but significant improvement once the penetration depth reached the reinforcement layer. This baseline behaviour confirms that the unreinforced sand allows easy and continuous advancement of the cone with limited confinement, making it highly susceptible to deformation under repeated or impact loads typical in low-volume pavements.

Response of Reinforced Sand at the depth of 50 mm : Geotextiles positioned at the depth of 50 mm influences the DCPT response significantly, as the dynamic stress bulb engages the reinforcement early in the test.

(a) **Coir textile at 50 mm:** Coir reinforcement shows a pronounced improvement in resistance, with a clear reduction in penetration per blow compared to the unreinforced profile. The curve steepens as the number of blows increases, indicating progressive stiffness mobilisation. The thicker, rougher coir fibres likely mobilise strong soil–fabric interlock, enhancing confinement.



Fig.5.9 Coir textile in test tank for DCPT



Fig.5.10 Coir textile after DCPT

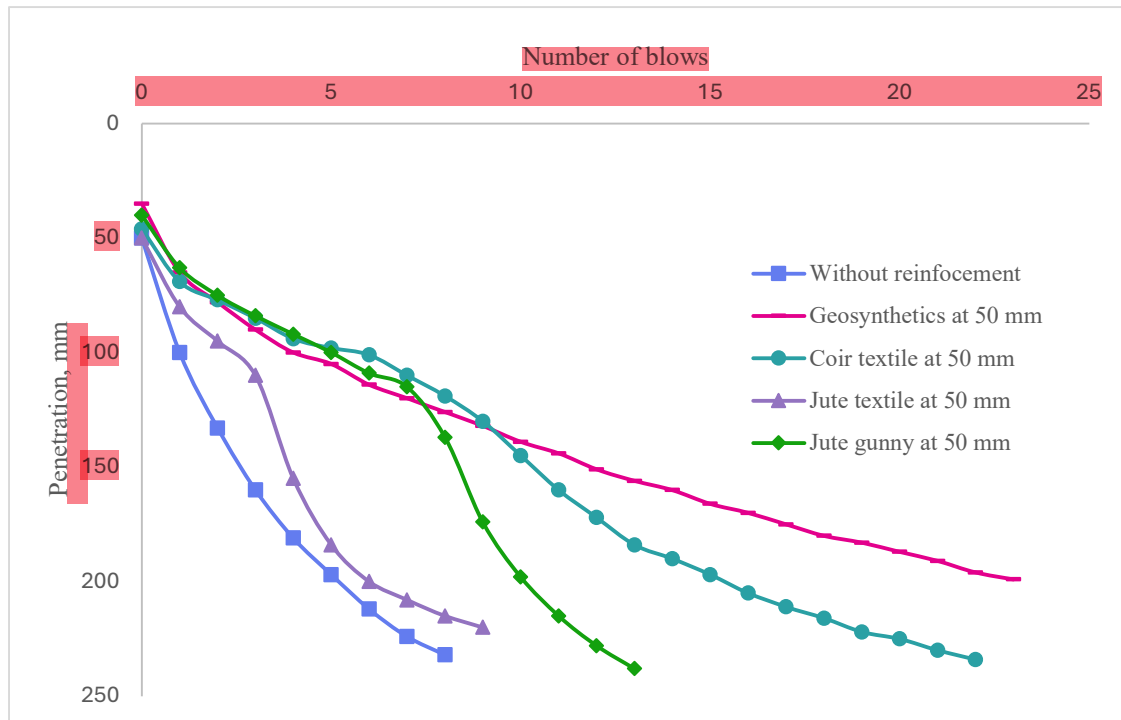


Fig. 5.11 DCPT data with reinforcement at 50 mm from top

(b) Geosynthetic at 50 mm: Synthetic geosynthetic placed at 50 mm provides a more moderate improvement. While resistance increases compared to the natural soil, the slope of the curve remains smoother and less abrupt than coir, reflecting the high tensile stiffness but lower surface interlock compared to natural fibres.



Fig. 5.12 shows geosynthetic in test tank



Fig. 5.13 shows geosynthetic after DCPT

(c) Jute textile and Jute-gunny at 50 mm: Both jute textile and jute-gunny layers improve resistance relative to unreinforced soil, though to a smaller degree than coir or synthetic geosynthetics. Jute-based reinforcements mobilise tensile capacity but exhibit larger deformation under impact loading, causing a gentler slope in the DCPT curve. Overall, reinforcement at 50 mm depth results in early engagement and maximum benefit from dynamic confinement.



Fig. 5.14 Jute Textile used for DCPT



Fig. 5.15 Jute Textile in test tank



(a)

Fig. 5.16 (a) Jute textile^a after DCPT



(b)

(b) Jute textile^b after DCPT

Response of Reinforced Sand at 100 mm Depth: At a deeper placement (100 mm), the reinforcement layer influences the resistance only after the cone has penetrated sufficiently to mobilise the layer.

(a) **Coir textile at 100 mm:** Coir again demonstrates the highest resistance in this group. After approximately 4–5 blows, the curve steepens significantly, indicating the onset of membrane action and enhanced confinement. The coir-reinforced soil exhibits the smallest penetration for a given number of blows among all materials at this depth.

(b) **Geosynthetic at 100 mm:** Synthetic geosynthetic reinforcement shows steady improvement, with the curve consistently above the unreinforced case. The effect becomes more pronounced after 8–10 blows, indicative of tensioned membrane behaviour once the geosynthetic engages.

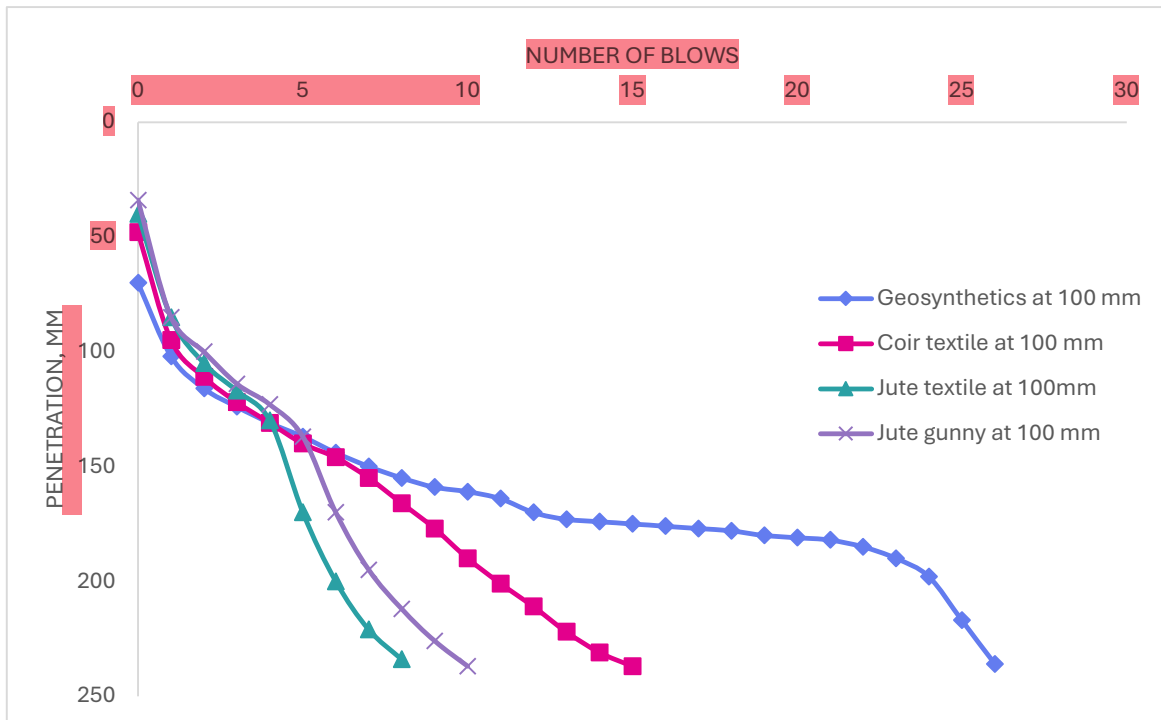


Figure 5.17 A comparison curve using DCPT data for reinforcement at 100 mm

(c) Jute textile and Jute-gunny at 100 mm: Jute textile and jute-gunny at 100 mm also improve performance but with delayed stiffness mobilisation. The curves display built up of gradual resistance, reflecting the lower modulus and higher deformability for jute materials. As seen from the results, both perform better than the unreinforced soil, especially in later stages of penetration. Overall, placement of geotextiles at higher depths produces delayed but still meaningful improvement.

Comparative Behaviour Across All Reinforcement Types and Depths: The comparative DCPT chart displays distinct behavioural patterns that puts light on the role of reinforcement type and placement depth:

(a) Influence of reinforcement depth: Reinforcement at 50 mm provides the maximum improvement in the early stages of penetration. Reinforcement at 100 mm produces noticeable improvement only after the cone reaches the reinforcement layer. The difference in performance becomes appreciable with continued loading, showing greater ultimate resistance at deeper reinforcement placements, especially for coir and geosynthetic layers.

(b) Influence of reinforcement material: Across both depths, Coir reinforcement provides superior confinement through greater thickness, roughness, and interlock, making it highly effective under dynamic loading. Synthetic geosynthetics provide moderate but reliable

improvement due to high tensile stiffness. Jute-based reinforcements are effective but limited by their higher compressibility and lower tensile modulus.

(c) Overall performance trend: Coir consistently reduces penetration per blow the most. Geosynthetic provides a smooth, controlled increase in resistance. Jute materials offer improvement but are more compliant, providing less confinement. Unreinforced soil exhibits the weakest performance and highest penetration rate.

Implications for Reinforced Pavement Design: It can be observed from the DCPT results that the inclusion of reinforcement layers leads to a marked improvement in stiffness and resistance to dynamic penetration in sandy subgrades. From the observed behaviour, the below mentioned inferences can be drawn;

(i) Shallow reinforcement (50 mm): Placement of reinforcement close to the surface is particularly effective in improving resistance to surface deformation and rutting. This configuration is therefore well suited for unpaved roads or thin pavement sections subjected to repeated traffic loading.

(ii) Deeper reinforcement (100 mm): Reinforcement placed at greater depths contributes more significantly to ultimate load-bearing capacity and long-term settlement control. Although its effect is mobilised after a certain level of penetration, deeper reinforcement provides enhanced structural support at larger deformation levels.

(iii) Material selection: Among the materials evaluated, coir reinforcement demonstrated strong performance under dynamic loading conditions. Owing to its effective confinement and interlocking characteristics, coir can be considered a practical and sustainable substitute to synthetic reinforcement for rural and low-volume road applications.

5.5 Combined SCPT and DCPT Results Analysis

The combined interpretation of SCPT and DCPT results provides a comprehensive understanding of reinforcement behaviour under static and dynamic loading conditions. The unreinforced sandy soil specimen exhibited low cone resistance in SCPT and high DCPI values in DCPT, confirming its susceptibility to deformation and rutting.

Baseline Behaviour of Unreinforced Sand: It can be seen from the penetration test results, that the unreinforced sand offers low resistance to both static and dynamic penetration. The SCPT curve exhibits a gradual and almost linear increase in penetration with load, reflecting the low stiffness of the material. Correspondingly, the DCPT profile shows high penetration per blow, with an average DCPI of approximately 22.75 mm/blow. This behaviour indicates poor

confinement of the sand particles, making the material susceptible to deformation and rutting under repeated loading.

Influence of Reinforcement on Static (SCPT) and Dynamic (DCPT) Response

From the test results, it is observed that reinforcement alters the penetration behaviour of sand under both static and dynamic loading conditions. Reinforced cases consistently exhibit higher SCPT cone resistance and reduced DCPI values compared to the unreinforced condition, resulting in higher stiffness index values and lower deformation. This behaviour can be attributed to the mobilisation of tensile resistance in the reinforcement, which provides additional confinement and improves interaction between the soil and the reinforcement layer.

Material wise behaviour: From the comparative analysis, it is observed that geosynthetic reinforcement performs more consistently than the other materials under both static and dynamic penetration. The load–penetration curves obtained from SCPT are relatively smoother and steeper, while DCPT results indicate lower penetration per blow. When positioned at 100 mm depth, the improvement in stiffness index reaches nearly 243%, suggesting effective mobilisation of tensile resistance and confinement at deeper penetration levels. Coir reinforcement also performed strongly, outperforming all natural materials and in some cases approaching geosynthetic behaviour; SCPT results showed higher initial stiffness and a clear increase in cone resistance after mobilisation, while DCPT results indicated DCPI improvements of 62% at 50 mm and 45% at 100 mm, with stiffness index gains up to 147%, reflecting excellent soil interlock from its thick, rough fibres. Jute textile and jute textile^b provided moderate improvements, with SCPT showing smaller stiffness gains and earlier yielding, while DCPT showed DCPI reductions of ~33% for jute textile^b and ~17% for jute textile at 50 mm, but negative improvement for jute textile at 100 mm, indicating poor dynamic engagement; overall, jute materials were more compliant, leading to delayed stiffness mobilisation and depth-sensitive performance.

Reinforcement placement depth: Reinforcement placement depth had a clear influence on both SCPT and DCPT responses. Shallow reinforcement at 50 mm engaged early under static and dynamic loading, producing immediate stiffening in SCPT and rapid DCPI reduction in DCPT, making it most effective for controlling surface rutting and shallow stress conditions. In contrast, reinforcement placed at 100 mm mobilised only after a threshold penetration, resulting in delayed DCPI reduction but greater enhancement of ultimate resistance and deeper structural stiffness. Overall, both SCPT and DCPT consistently show that 50 mm placement

improves near-surface confinement, while 100 mm placement contributes to improved stiffness at greater depths.

Table 6. Average DCPI(mm/blow) corresponding to Reinforcement

Reinforcement	Placement Depth (mm)	Average DCPI
Unreinforced	-	22.75
Geosynthetic	50	7.13
Geosynthetic	100	6.38
Coir Textile	100	12.60
Coir Textile	50	8.55
Jute Textile ^a	50	18.89
Jute Textile ^a	100	24.25
Jute Textile ^b	100	20.30
Jute Textile ^b	50	15.23

a and b corresponds to Jute Textile of lower GSM of lower and higher GSM respectively

SCPT–DCPT Curves and Correlation Analysis

The combined interpretation of the SCPT and DCPT datasets provides an integrated understanding of the static and dynamic penetration behaviour of reinforced and unreinforced sand. It allows direct comparison of stiffness mobilisation, reinforcement efficiency, and depth effects. The DCPI–penetration curves when plotted for different reinforcement types show clear differentiation in dynamic resistance, with geosynthetic and coir reinforcements producing lower DCPI values relative to unreinforced soil, while jute-based reinforcements provide moderate but depth-dependent improvements. The combined DCPI curves reflect consistent performance across all depths, with the geosynthetic-reinforced specimens showing lowest penetrations per blow. When the curves are grouped according to reinforcement depth (50 mm and 100 mm), we observe a consistent trend with shallow reinforcement resulting in earlier and greater reduction in DCPI, indicating more rapid stiffness mobilisation under dynamic loading. At 100 mm depth, the reinforcement response is delayed until sufficient penetration occurs, after which the DCPI curves steepen as the reinforcement layer begins contributing to lateral confinement. From these grouped plots, it can be inferred that reinforcement placement has a strong influence on dynamic response, with the 50 mm configuration being more effective in mitigating near-surface deformation.

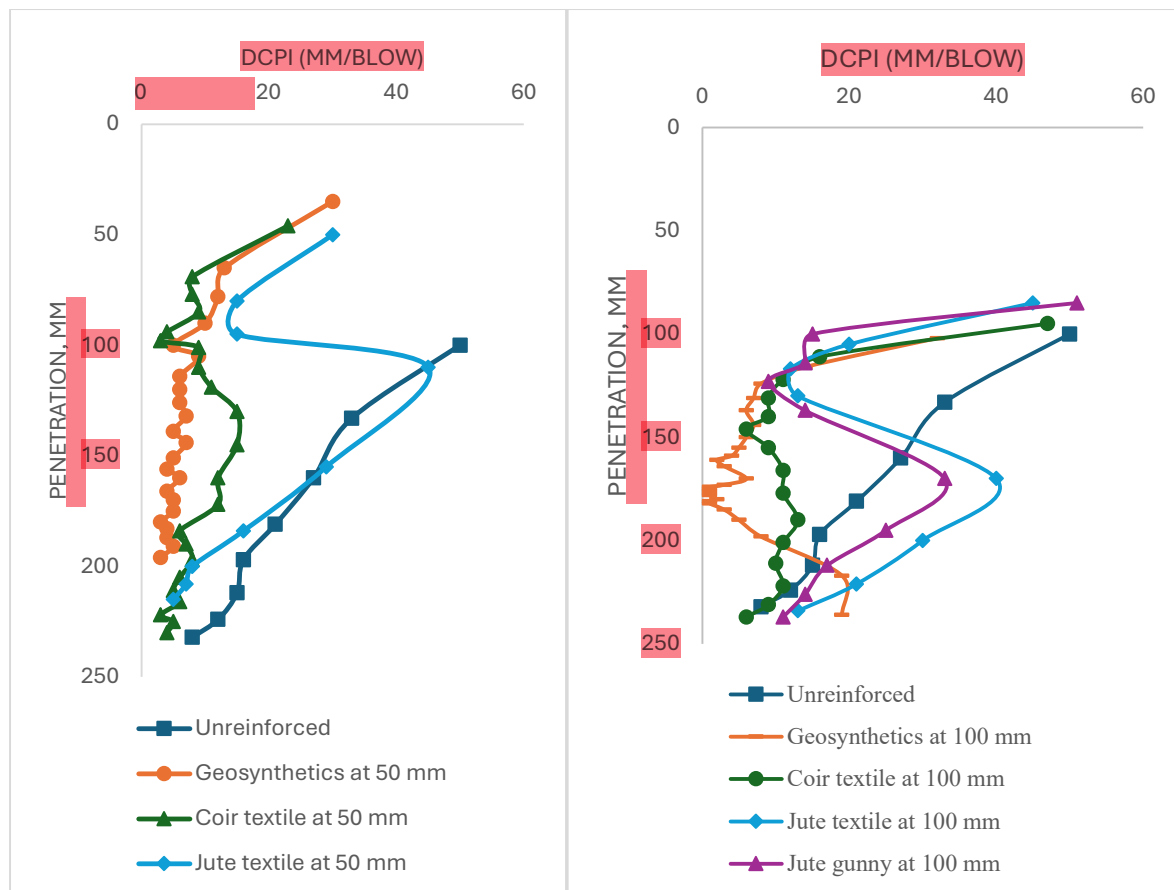


Fig. 5.18 A comparison curve using DCPT data for (a) reinforcement at 50 mm, (b) for reinforcement at 100 mm

The SCPT curves shows corresponding trends in static load transfer behaviour. Reinforcement significantly alters the load–penetration response. It increases both peak load and initial stiffness for most reinforced cases. The highest peak loads are observed in coir and geosynthetic reinforcement at 100 mm depth, whereas jute-based reinforcements provide relatively modest gains. When SCPT peak resistance and initial stiffness are plotted against average DCPI values and average SI values, the expected inverse relationship appears qualitatively consistent: specimens with lower DCPI (higher dynamic resistance) generally exhibit higher static peak resistance. However, quantitative correlation analysis shows that while the trend direction is consistent, the statistical strength of the simple empirical models is low. Empirical correlations of the form of Eqn. 5.1 have been widely used to relate dynamic penetration index to soil strength and bearing capacity parameters based on regression fits to field and laboratory DCPT data.

$$q_{peak} = a. (DCPI)^{-b} \quad 5.1$$

The parameters a and b in the empirical correlation represent regression constants obtained from experimental data. The coefficient a reflects the overall strength and stiffness of the soil–reinforcement system, while the exponent b indicates the sensitivity of peak static cone resistance to changes in dynamic penetration index. Higher values of a and b correspond to improved confinement and more efficient load transfer, typically observed in reinforced soil systems.

The above power law model co-relation yielded weak correlation (Coefficient of co-relation $R^2 \approx 0.03$), indicating that DCPI alone cannot reliably predict SCPT peak resistance in reinforced configurations. Despite the low R^2 values, the correlations remain valuable from an interpretative point of view. Reinforced cases with lower DCPI consistently correspond to higher stiffness and higher peak resistance in SCPT tests, confirming an expected qualitative link between static and dynamic penetration resistance. However, the scatter observed across reinforcement types highlights the fact that the interaction mechanisms such as membrane tension, soil–fabric interlocking, and anisotropic confinement affect static and dynamic loading modes differently. These mechanisms modify penetration resistance in ways that cannot be described solely by DCPI or SI. Thus, the combined SCPT–DCPT evaluation verifies that reinforcement improves both static and dynamic resistance. It also demonstrates that reinforced soils require multi-parameter or reinforcement-specific models for accurate predictive correlations. The correlation analysis provides insight into the limitations of single-parameter empirical models in reinforced soils and highlights the need for more advanced mechanistic or multi-variable regression approaches for predictive modelling.

Chapter 6

Conclusion

1. The inclusion of geosynthetic reinforcement resulted in an increase in static cone resistance (q_c) of approximately 40–50 percent compared to the unreinforced condition, indicating a substantial enhancement in load-carrying capacity.
2. Dynamic Cone Penetration Test results showed a reduction in Dynamic Cone Penetration Index (DCPI) of approximately 30–40 percent, confirming improved resistance to impact-induced penetration and higher dynamic stiffness of the reinforced sections.
3. Near-surface stiffness, inferred from the initial slope of SCPT load–penetration curves and early DCPT penetration response, improved by approximately 45–55 percent, highlighting effective confinement in the rutting-critical upper layer.
4. Reinforcement placed at shallow depth (around 50 mm) exhibited approximately 20–25 percent higher initial stiffness mobilisation compared to deeper placement, demonstrating the importance of reinforcement location for early deformation control.
5. Natural geotextiles (jute and coir) achieved near-surface stiffness and penetration resistance within approximately 10–15 percent of synthetic geotextiles, particularly under static loading conditions.
6. The combined SCPT–DCPT interpretation confirmed a consistent inverse relationship between static cone resistance and dynamic penetration rate, validating the complementary use of both tests for performance-based evaluation.
7. Reinforcement primarily improved near-surface stiffness, with the most pronounced effects observed within the upper 100–150 mm, corresponding to the critical zone governing rutting and surface deformation in unpaved pavements.
8. Synthetic geotextiles exhibited the highest static and dynamic resistance due to superior tensile stiffness; however, natural geotextiles (jute and coir) demonstrated comparable performance in near-surface zones through effective frictional interlock and confinement.
9. The study confirms to a large extent, through small sample size the technical feasibility of using natural geosynthetics as sustainable and cost-effective alternatives to synthetic geotextiles for low-volume and rural unpaved road applications.



Chapter 7

Limitations and Future Scope

7.1 Limitations of the Work

1. The experimental programme was carried out under controlled laboratory conditions. As a result, certain field-level variables such as fluctuations in moisture content, traffic loading patterns, and environmental degradation effects could not be fully represented.
2. The investigation was conducted using a single poorly graded sand. Consequently, the findings of the study may not be directly applicable to cohesive soils or well-graded granular subgrades without additional experimental verification.
3. The study focused only on single-layer reinforcement configurations. Multi-layer reinforcement systems, which may exhibit different load transfer and stiffness mobilisation mechanisms, were not considered.
4. The penetration tests adopted in the study primarily reflect short-term mechanical response. Long-term performance aspects, including creep behaviour, durability, and progressive degradation of natural geotextiles, were beyond the scope of the present investigation.
5. DCPT interpretations were based on penetration resistance characteristics alone. Direct correlations with rut depth measurements or repeated load deformation behaviour were not established in this study.

7.2 Future Scope of the Study

1. Field-scale validation of the proposed SCPT–DCPT correlations under actual traffic loading conditions may be undertaken to enhance their practical applicability for unpaved pavement evaluation.
2. Further studies may investigate the performance of natural geotextiles under varying moisture regimes and cyclic wetting–drying conditions to assess their durability in realistic environmental conditions.
3. Multi-layer and hybrid reinforcement configurations involving combinations of natural and synthetic geotextiles may be explored to optimise mechanical performance while maintaining sustainability benefits.
4. Long-term investigations focusing on creep behaviour, biodegradation, and strength retention of natural geosynthetics are required to support lifecycle-based pavement design approaches.

5. The integration of SCPT and DCPT parameters into mechanistic–empirical pavement design frameworks can be developed for reinforced unpaved road systems.