

Quality Control of Pavement Subgrade and Base Materials Using Advanced Field-testing Techniques

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ABSTRACT

Quality control during pavement construction is essential for achieving the stiffness, load-bearing capacity, durability and serviceability required throughout the design life of a road. Conventional density-based control methods are useful for verifying compaction but are generally destructive or semi-destructive, labour-intensive, time-consuming and restricted to a limited number of locations. The present paper synthesizes an experimental investigation into advanced semi-destructive and non-destructive field-testing techniques for pavement subgrade and base materials. The programme considered the Plate Load Test (PLT), Light Weight Deflectometer (LWD), Dynamic Cone Penetrometer (DCP/DCPT), Digital Static Cone Penetrometer (DSCP/DSCPT), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). Unreinforced soils and aggregates were evaluated first, followed by triaxial-geogrid reinforcement, geocell confinement and chemical stabilization with hydrated lime and Portland cement. A large-scale testing chamber of 0.9 m × 0.9 m × 0.9 m was used for controlled specimen preparation. The LWD employed a 300 mm loading plate; deformation modulus was calculated from measured surface deformation using a Boussinesq-based relationship. The results showed that deformation modulus increased with relative compaction and aggregate thickness, whereas increasing moisture content reduced dynamic resistance, cone index and stiffness. For triaxial geogrid-reinforced Soil-1, the optimum reinforcement position was 50 mm below the loading surface ($u/a = 0.17$). At 97% relative compaction and 0.15 MPa contact pressure, E_{LWD} reached 29.45 MPa, compared with 18.50 MPa for unreinforced Soil-1. The corresponding LWD- and PLT-based MIF values were 1.42 and 1.37, respectively. A strong linear relationship was reported between the two MIF measures ($R^2 = 0.962$). Geocell reinforcement increased the deformation modulus of Soil-1 by approximately 45.7% at the optimum embedment configuration, while its influence on aggregate layers was comparatively limited. Chemical stabilization produced substantial improvements in subgrade strength; the reported optimum contents were 6% lime and 8% cement, with strength continuing to increase with curing period. Regression relationships between E_{LWD} , dynamic resistance, cone index

and CBR produced R^2 values of 0.78–0.99. The findings support modulus-based quality control, with LWD providing a rapid, portable and economical complement to conventional PLT and laboratory strength tests.

Keywords: pavement quality control; Light Weight Deflectometer; Plate Load Test; Dynamic Cone Penetrometer; Digital Static Cone Penetrometer; deformation modulus; geogrid reinforcement; geocell; chemical stabilization; CBR; UCS; modulus improvement factor.

1. INTRODUCTION

Road transportation is a fundamental component of economic development because highways provide connectivity between production centres, markets, communities and strategic locations. As traffic volumes and axle loads increase, pavement construction must achieve not only the specified density but also adequate stiffness and resistance to repeated deformation. The quality of the subgrade and base layers is particularly important because these layers control stress distribution and the magnitude of deformation transferred to the pavement surface. The uploaded project report notes that Indian highway development has expanded rapidly through major programmes and corridor projects, increasing the need for reliable and efficient construction quality-control procedures.

Compaction reduces air voids and increases particle interlocking, thereby improving shear strength, stiffness and bearing capacity while reducing settlement and deformation. Traditional field acceptance is commonly based on relative compaction, which compares field dry density with laboratory maximum dry density. However, density is only an indirect descriptor of mechanical behaviour. Two locations having similar density can exhibit different stiffness because of differences in moisture, gradation, particle arrangement, stress history and layer confinement. The project therefore emphasizes deformation modulus as a performance-oriented quality-control parameter.

Conventional methods such as the Sand Cone Test, Core Cutter Test, Rubber Balloon Test and Nuclear Density Gauge can provide acceptable density measurements, but their testing frequency is normally limited. Excavation, sampling, laboratory handling, radiation-safety requirements for nuclear gauges, and skilled labour can further constrain their use. Modern devices such as the DCP, DSCP and LWD can provide

rapid measurements over a greater number of locations with little disturbance to the compacted layer. This makes them attractive for construction-stage quality assurance, particularly when pavement design is based on mechanistic–empirical principles.

1.1 Problem Statement

The principal quality-control problem addressed in this investigation is the mismatch between density-based acceptance and the actual stiffness behaviour required under traffic loading. Limited test coverage may allow weakly compacted zones to remain undetected. In addition, pavement layers may be mechanically improved using geosynthetics or chemically stabilized with lime and cement, creating a need for testing systems capable of quantifying the resulting stiffness and strength gains.

1.2 Aim and Objectives

- To determine deformation modulus and strength characteristics of selected pavement soils and granular materials.
- To evaluate LWD, PLT, DCP/DCPT and DSCP/DSCPT as rapid quality-control techniques and establish correlations among measured parameters.
- To investigate the influence of triaxial geogrid reinforcement depth on deformation modulus and calculate the Modulus Improvement Factor (MIF).
- To assess geocell reinforcement for subgrade soil and aggregate layers and identify the influence of embedment depth and infill material.
- To investigate lime and cement stabilization of weak subgrade soil using CBR, UCS, DCPT, DSCPT and LWD.
- To examine the effect of LWD contact pressure and relative compaction on measured deformation modulus.
- To develop relationships among deformation modulus, dynamic resistance, cone index and CBR that can support practical pavement quality control.
- To recommend an integrated modulus-based quality-control framework that reduces testing time and improves construction coverage.

1.3 Significance of the Study

The significance of the work lies in combining conventional reference tests with rapid field-oriented measurements and then examining the effect of reinforcement and stabilization within the same quality-control framework. The investigation does not treat LWD as an isolated device; rather, it evaluates LWD response against PLT and strength-related measurements. This approach is useful because a practical field-quality system must be both rapid and sufficiently representative of pavement behaviour. The results further show that reinforcement position, moisture, compaction and layer configuration can materially affect the

measured response and therefore should be incorporated into quality-control decisions.

2. LITERATURE REVIEW

The literature reviewed in the project shows that density-based control has been widely used because relative compaction is easy to understand and can be related to laboratory compaction characteristics. Sand Cone, Core Cutter, Rubber Balloon and density-gauge methods remain common. Their principal limitation is that density alone does not directly describe stiffness under traffic loading, and the small number of tests normally performed over a large construction area can fail to identify local weak zones.

Dynamic penetration methods

The Dynamic Cone Penetrometer is widely used because it is simple, portable and economical. Its output includes blow count, Dynamic Penetration Index and Dynamic Resistance. Previous work has established empirical relationships between penetration resistance and CBR, resilient modulus, bearing capacity and other strength descriptors. The project emphasizes that such correlations are soil- and condition-dependent; site-specific calibration is therefore preferable before direct design application.

Static cone methods

The Digital Static Cone Penetrometer provides a continuous penetration resistance measure and is particularly useful for fine-grained and softer soils. Cone Index can be related to strength and compaction. The combination of DCPT and DSCPT gives complementary information because one represents dynamic resistance and the other static cone resistance.

Plate Load Test

The Plate Load Test is treated as a reference method for deformation response because the test directly measures load and settlement under a circular plate. Its disadvantages are the need for substantial equipment, reaction arrangements and skilled labour, which make it less suitable for high-frequency construction control.

Falling Weight and Light Weight Deflectometers

The Falling Weight Deflectometer can simulate wheel loading through controlled impact and is widely used for structural pavement evaluation. The Light Weight Deflectometer is much more portable and can be operated by a small field team. The literature reviewed in the project reports useful relationships between LWD modulus and PLT modulus, CBR, UCS, density and resilient modulus.

Geosynthetic reinforcement

Geogrids improve pavement performance by interlocking with granular particles, mobilizing tensile membrane action

and redistributing surface loads. Triaxial geogrids provide radial stiffness in multiple directions, while geocells provide three-dimensional confinement. Previous research has shown that reinforcement effectiveness depends on embedment depth, material type, layer thickness and stress distribution.

Chemical stabilization

Lime and cement are established methods for improving weak subgrades. Lime can reduce plasticity and swelling through cation exchange and flocculation and can subsequently contribute to pozzolanic reactions. Cement forms cementitious products through hydration and can increase stiffness and UCS. The project evaluates both treatments using strength and rapid field-oriented parameters.

2.1 Research Gap

Although the literature contains extensive evidence for density control, DCP correlations, geosynthetic reinforcement and chemical stabilization considered separately, fewer investigations integrate these components into a single modulus-based quality-control programme. The present work addresses this gap by using a common testing framework for unreinforced, geogrid-reinforced, geocell-reinforced and chemically stabilized pavement materials. Particular attention is given to reinforcement depth, relative compaction, contact pressure, layer thickness and correlations between rapid field measurements and conventional strength or stiffness parameters.

Table 1. Comparison of conventional and advanced pavement quality-control methods.

Test/technology	Main output	Primary advantage	Main limitation
Sand Cone / Core Cutter	Field dry density	Established density acceptance	Destructive ; limited coverage
Nuclear Density Gauge	Density and moisture	Rapid in-situ reading	Radiation safety and licensing
DCP/DCPT	N, DPI, DR	Portable; continuous strength profile	Empirical calibration required
DSCP/DSCPT	Cone Index / qc	Rapid static resistance	Sensitive to soil and surface conditions
PLT	Elastic/deformation modulus	Reference-type stiffness measurement	Time, labour and reaction system

FWD	Deflection / back-calculated modulus	Simulates wheel loading	Higher cost and specialized operation
LWD	E_LWD	Portable, rapid, economical	Sensitive to plate, moisture, density and layer effects

3. MATERIALS AND METHODOLOGY

3.1 Research Design

The experimental programme was organized into four linked stages. Stage I characterized the pavement materials and established compaction parameters. Stage II evaluated unreinforced soils and aggregate layers using LWD, PLT, DCPT and DSCPT. Stage III introduced triaxial geogrid and geocell reinforcement and examined the influence of reinforcement position, layer thickness, relative compaction and contact pressure. Stage IV treated weak subgrade soil with lime and cement and evaluated the resulting CBR, UCS, penetration resistance and LWD modulus. Regression analysis and statistical descriptors were then used to compare the measurements and identify practical relationships.

Proposed integrated modulus-based pavement quality-control workflow



The workflow synthesizes the testing sequence and decision logic reported in the project.

Figure 1. Integrated research and quality-control workflow synthesized from the experimental programme.

3.2 Materials and Physical Properties

Eight representative soils were collected from nearby borrow pits in the project programme. Soil-1 was used as the principal foundation material for mechanical reinforcement experiments, Soil-2 and Soil-3 were used to study moisture effects on strength and stiffness, and Soil-4 was used for chemical stabilization. Natural aggregates and Wet Mix Macadam were used to represent granular pavement layers. Hydrated lime and OPC 53-grade cement were used as stabilizing agents. The project also characterized biaxial and triaxial geogrids and a three-dimensional geocell system.

Table 2. Selected physical and engineering properties of pavement materials used in the investigation.

Material	Selected reported properties	Classification / role
Soil-1	Gravel 0.72%; sand 98.45%; fines 0.83%; Gs 2.63; γ_{max} 17.80 kN/m ³ ; e_{max} 0.80	SP (USCS), A-3 (AASHTO); mechanical reinforcement
Soil-2	Gravel 4.25%; sand 89.50%; fines 6.25%; OMC 8.0%; MDD 20.4 kN/m ³ ; soaked CBR 5.9%	SP-CL; A-2-6; moisture-response study
Soil-3	Gravel 21.00%; sand 67.05%; fines 11.95%; OMC 12.0%; MDD 18.8 kN/m ³ ; soaked CBR 3.0%	SC-CI; A-2-7; moisture-response study
Soil-4	Gravel 28.50%; sand 60.83%; fines 10.67%; OMC 9.3%; MDD 20.6 kN/m ³ ; soaked CBR 5.1%	SC-CL; A-2-6; chemical stabilization
WMM	MDD 21.4 kN/m ³ ; OMC 9.40%; LA abrasion 35.28%; impact value 22.66%	Granular base material
Triaxial geogrid	Radial secant stiffness 390 kN/m at 0.5% strain; 290 kN/m at 2% strain; pitch 80 mm	Tensar TX; mechanical reinforcement
Geocell	Weld spacing 356 mm; cell depth 100 mm; expanded cell 259/224 mm; max weld force 1566 N	TechFAB Techcell TC1356; confinement
Hydrated lime	Ca(OH) ₂ ; pH 12.4; specific gravity 2.2–2.3	Chemical stabilizer
OPC 53 grade	Specific gravity 3.10–3.15; initial setting 30 min; final setting 600 min	Chemical stabilizer

3.3 Specimen Preparation

Mechanical reinforcement specimens were prepared in a Large-Scale Testing Chamber measuring 0.9 m × 0.9 m × 0.9 m. The chamber dimensions were selected to reduce boundary effects; the project relates the arrangement to ASTM E2835 guidance for LWD testing. Materials were compacted in successive 100 mm layers using pneumatic plate vibration to achieve the target relative compaction. Reinforcement was placed at predetermined depths below the loading surface. For chemically stabilized materials, soil-4 was dry-mixed with the selected stabilizer before water was added. CBR specimens were compacted in five equal layers and soaked for 96 h, while UCS specimens were

cured for 7, 14 and 28 days. Large-scale stabilized specimens were constructed in 100 mm layers to a total depth of 600 mm for DCPT, DSCPT and LWD testing.

3.4 Testing Equipment and Procedures

Table 3. Testing equipment, configurations and measured quality-control parameters.

Method	Configuration reported in project	Measured parameter
LWD	300 mm diameter plate; $q = 0.15$ MPa for principal analysis; three measurement drops	Mean surface deformation; E_{LWD}
LWD contact-pressure study	10 kg and 15 kg drop weights; $q = 0.10$ and 0.15 MPa	Effect of contact pressure on E_{LWD}
PLT	Circular plate under static loading	Settlement, bearing pressure, E_{PLT}
DCPT	Dynamic cone penetration under repeated hammer blows	N, DPI, DR
DSCPT	Static cone penetration	Cone Index / CI
CBR	Standard soaked test; 96 h soaking	CBR (%)
UCS	Split-mould specimens; 7, 14, 28 d curing	UCS

3.5 Governing Parameters and Equations

The principal quality-control descriptors were calculated as follows:

- $DPI = (D_{n+1} - D_n) / \text{blow}$, where DPI is the dynamic penetration index in mm/blow.
- $DR = (mgh) / (A^e \Delta d)$, where m is hammer mass, g is gravitational acceleration, h is drop height, A^e is cone area and Δd is penetration per blow.
- $E_{PLT} = [q a \pi / 4 (1 - \mu^2)] / w$, where q is contact pressure, a is plate diameter, μ is Poisson's ratio and w is settlement.
- $E_{FWD} = [2 q r (1 - \mu^2)] / w$, using the reported Boussinesq-based relationship for the 40 kN impulse configuration.
- $E_{LWD} = [q r (1 - \mu^2) f_r] / \bar{w}$, with $q = 0.15$ MPa, $r = 150$ mm, $\mu = 0.3$, $f_r = 1.65$ and $\bar{w}$ as the mean deformation.
- $MIF = E_{LWD}(s) / E_{LWD}(us)$, representing the normalized stiffness improvement from geosynthetic reinforcement.
- $SIF = \text{strength parameter of stabilized material} / \text{corresponding parameter of untreated material}$.

3.6 Statistical Analysis

The project uses mean (μ), standard deviation (σ), coefficient of variation (COV), regression analysis and semi-variogram descriptors to quantify variability and relationships. The semi-variance was expressed as $SV = (1/2m) \sum (sp_i - sp_{i+1})^2$. Regression equations were used to relate LWD deformation modulus to DR, CBR and cone index. The statistical framework is particularly important for quality control because field measurements are spatially variable and affected by material heterogeneity, compaction variability, moisture and instrumentation.

4. RESULTS AND DISCUSSION

4.1 Unreinforced Materials and Moisture Effects

The unreinforced testing programme established the baseline behaviour against which reinforcement and stabilization could be evaluated. The project reports that both LWD and PLT deformation response increased with increasing relative compaction. Similarly, increasing aggregate layer thickness increased the deformation modulus and bearing capacity, although the change in modulus with thickness was more moderate than the change in load-bearing capacity. This indicates that a granular layer can redistribute applied stresses even when the increase in measured surface stiffness is not proportionally large.

Moisture had a strong influence on Soil-2 and Soil-3. As water content increased, dynamic resistance, cone index and LWD deformation modulus decreased, while dynamic penetration index increased. Soil-2 consistently showed higher resistance and stiffness than Soil-3 under comparable conditions. The behaviour is mechanically consistent with reduced effective inter-particle contact and increased pore-water effects as the soils become wetter. The project tested moisture contents from 6% to 14% at 2% increments and used both 300 mm and 600 mm layer configurations.

Table 4. Physical properties of Soil-2, Soil-3 and Soil-4 used in the moisture and strength investigation.

Soil	Gravel (%)	Sand (%)	Fines (%)	USCS	AASHTO	OMC (%)	MDD (kN/m ³)	Soaked CBR (%)
Soil-2	4.25	89.50	6.25	SP-CL	A-2-6	8.0	20.4	5.9
Soil-3	21.00	67.05	11.95	SC-CI	A-2-7	12.0	18.8	3.0
Soil-4	28.50	60.83	10.67	SC-CL	A-2-6	9.3	20.6	5.1

4.2 Regression Relationships for Rapid Quality Control

Regression analysis produced several useful relationships. For Soil-2, the relationship between dynamic resistance and LWD modulus achieved $R^2 = 0.99$, while CBR–E_{LWD} and CBR–CI relationships achieved $R^2 = 0.94$ and 0.93 . For Soil-3, DR–E_{LWD} achieved $R^2 = 0.95$, CBR–E_{LWD} achieved $R^2 = 0.78$, and CBR–CI achieved $R^2 = 0.87$. These results show that the rapid stiffness and penetration measurements can provide a useful estimate of conventional strength parameters, but the quality of the relationship varies with soil type. Site-specific calibration is therefore recommended.

Table 5. Reported regression relationships among dynamic resistance, LWD modulus, cone index and CBR.

Soil	Relationship	Reported regression equation	R^2
Soil-2	DR–ELWD	$DR = 0.0354 ELWD^2 - 1.6772 ELWD + 26.121$	0.99
Soil-2	CBR–ELWD	$CBR = 0.154 ELWD^2 - 7.9279 ELWD + 94.041$	0.94
Soil-2	CBR–CI	$CBR = 64.072 CI^2 - 346.3 CI + 445.44$	0.93
Soil-3	DR–ELWD	$DR = 0.0337 ELWD^2 - 1.622 ELWD + 26.863$	0.95
Soil-3	CBR–ELWD	$CBR = 0.2947 ELWD^2 - 14.043 ELWD + 120.48$	0.78
Soil-3	CBR–CI	$CBR = 67.389 CI^2 - 278.61 CI + 277.96$	0.87

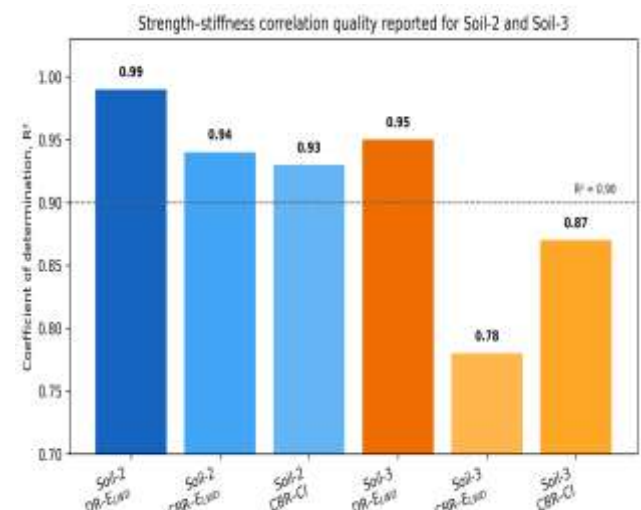


Figure 2. Coefficients of determination for reported strength-stiffness correlations.

4.3 Interpretation for Construction Quality Control

The unreinforced results indicate that density should not be treated as the only acceptance descriptor. Relative compaction remains important because higher compaction generally increased stiffness, but LWD provides direct information about the mechanical response of the compacted layer. DCP and DSCP add a strength-oriented perspective, particularly in fine-grained materials. The combination can therefore provide a layered decision system: density verifies compaction effort, penetration resistance indicates local strength, and LWD indicates surface stiffness relevant to pavement structural response.

4.4 Triaxial Geogrid-Reinforced Soil-1

The triaxial geogrid experiments evaluated embedment ratios u/a of 0.17, 0.25, 0.33 and 0.50, corresponding to depths of 50, 75, 100 and 150 mm below the loading plate. Tests were conducted at relative compaction levels of 89%, 93% and 97%. The results consistently identified the shallowest reinforcement position, $u/a = 0.17$, as the optimum. This position places the reinforcement within the most active stress-influence zone and allows the geogrid to mobilize lateral confinement, particle interlock and tensile membrane action.

Table 6. Deformation modulus response of triaxial geogrid-reinforced Soil-1 at different embedment depths.

u/a	u (mm)	E_{LWD} at RC=97%, $q=0.15$ MPa (MPa)	Mean deformation (mm)	Interpretation
0.17	50	29.45	0.76	Optimum
0.25	75	27.37	0.90	High improvement
0.33	100	24.32	1.01	Reduced influence
0.50	150	23.23	0.99	Lowest among reinforced cases
—	—	18.50	1.24	Unreinforced reference

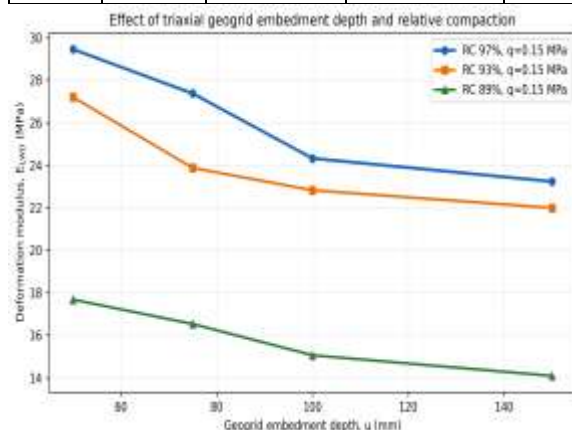


Figure 3. Variation of E_{LWD} with triaxial-geogrid embedment depth at different relative compaction levels.

At 97% relative compaction, the optimum reinforced section reached $E_{LWD} = 29.45$ MPa, compared with 18.50 MPa for the unreinforced reference. This represents a substantial increase in surface stiffness. The mean deformation decreased from 1.24 mm in the unreinforced section to 0.76 mm at the optimum reinforcement position. As the geogrid was moved deeper, its ability to intercept and redistribute the stress bulb decreased and the measured modulus gradually declined.

4.5 Modulus Improvement Factor and LWD-PLT Agreement

The Modulus Improvement Factor provides a normalized measure of reinforcement effectiveness. The project reports LWD-based MIF values of 1.42, 1.33, 1.18 and 1.13 for u/a ratios of 0.17, 0.25, 0.33 and 0.50. The corresponding PLT-based MIF values were 1.37, 1.21, 1.17 and 1.12. The close agreement in trend demonstrates that LWD can reproduce the reinforcement ranking obtained from the more laborious PLT.

Table 7. Comparison of LWD- and PLT-based deformation modulus and Modulus Improvement Factor.

u/a	E_{LWD} (MPa)	E_{PLT} (MPa)	MIF – LWD	MIF – PLT
0.17	29.09	15.30	1.42	1.37
0.25	27.37	13.50	1.33	1.21
0.33	24.32	13.35	1.18	1.17
0.50	23.23	13.10	1.13	1.12
Unreinforced	20.64	11.13	—	—

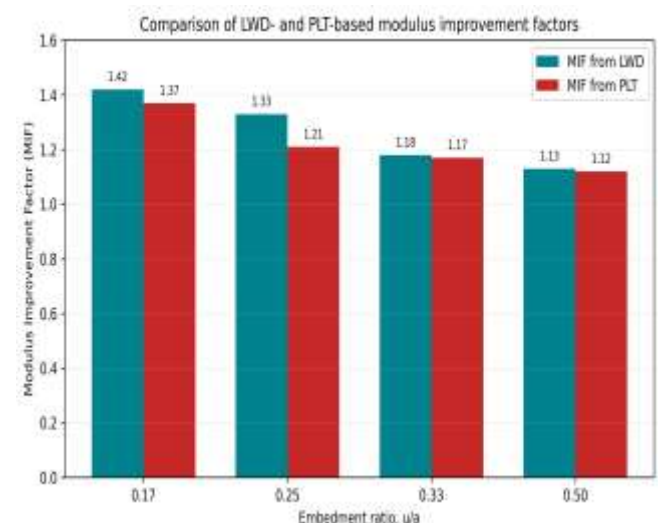


Figure 4. Comparison of LWD- and PLT-based Modulus Improvement Factors.

A linear regression between the LWD- and PLT-derived MIF values produced $R^2 = 0.962$ with the reported relationship $MIF_{PLT} = 0.6974(MIF_{LWD}) + 0.307480$.

This is one of the most practically significant findings because it supports the use of a rapid LWD measurement to infer a PLT-based improvement indicator, provided the relationship is calibrated for the material and reinforcement system being evaluated.

4.6 Influence of LWD Contact Pressure

The LWD response was examined at two contact pressures, 0.10 MPa and 0.15 MPa, using 10 kg and 15 kg drop weights, respectively. The results show that increasing contact pressure caused a small increase in measured deformation modulus. Importantly, the optimum reinforcement position did not change: $u/a = 0.17$ remained the best configuration at all investigated relative compaction levels. The project therefore selected 0.15 MPa for subsequent analysis because it produced slightly higher modulus values and better mobilized the elastic-plastic response without changing the overall trend.

Table 8. E_{LWD} of triaxial geogrid-reinforced Soil-1 at different contact pressures and relative compaction levels.

u/a	u (m m)	RC=89 %, $q=0.10$	RC=89 %, $q=0.15$	RC=93 %, $q=0.10$	RC=93 %, $q=0.15$	RC=97 %, $q=0.10$	RC=97 %, $q=0.15$
0.1 7	50	16.55	17.68	26.63	27.20	28.09	29.45
0.2 5	75	15.43	16.53	22.60	23.87	24.83	27.37
0.3 3	100	13.70	15.06	21.30	22.82	23.54	24.32
0.5 0	150	12.44	14.09	20.52	21.99	22.08	23.23

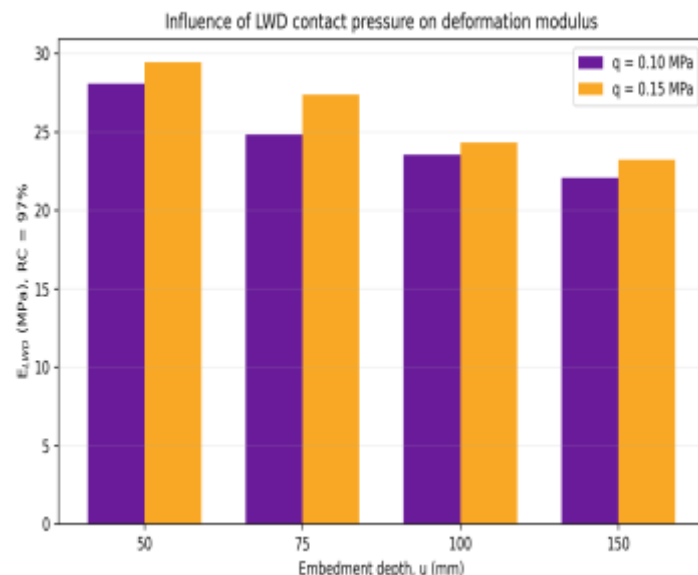


Figure 5. Effect of LWD contact pressure on E_{LWD} at 97% relative compaction.

4.7 Reinforced Aggregate Layers

A 200 mm thick aggregate layer overlying Soil-1 was also tested with triaxial geogrid reinforcement at the same u/a ratios. The project reports that the highest E_{LWD} occurred at 50 mm embedment ($u/a = 0.17$). The reinforcement improved confinement and aggregate interlocking and distributed the applied load over a wider area. However, the increase in deformation modulus was more moderate than that observed for the weak subgrade because the aggregate layer already possessed relatively high stiffness. Thus, in aggregate layers, the reinforcement contribution is better interpreted as improved load distribution and confinement rather than a large intrinsic increase in material modulus.

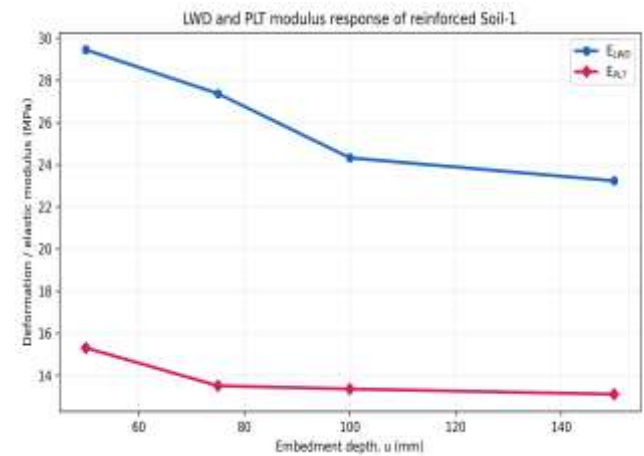


Figure 6. LWD and PLT modulus response for triaxial-geogrid-reinforced Soil-1.

4.8 Geocell-Reinforced Soil and Aggregate Layers

Geocell reinforcement provides three-dimensional confinement by restricting lateral movement of the infill and mobilizing hoop stresses in the cell walls. For Soil-1, the project reports that the maximum improvement was obtained at a 50 mm embedment depth corresponding to $u/a = 0.50$, with an approximately 45.7% increase in deformation modulus. The improvement is attributed to confinement and improved stress distribution. The result also demonstrates that the optimum embedment ratio for geocell need not be identical to the optimum ratio for triaxial geogrid; reinforcement geometry and confinement mechanism matter.

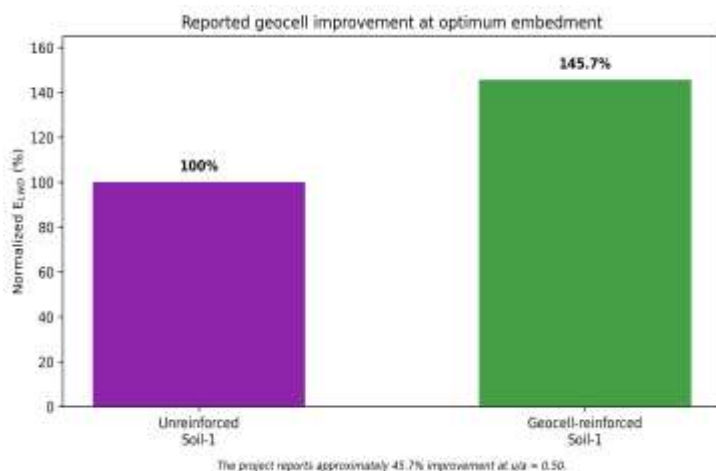


Figure 7. Normalized representation of the reported 45.7% geocell improvement in Soil-1 at the optimum configuration.

In contrast, geocell reinforcement did not provide a significant improvement in the deformation modulus of aggregate layers overlying Soil-1. Aggregate layers of 100, 200 and 300 mm thickness were investigated. Unreinforced aggregate sections showed increasing modulus with increasing thickness, while geocell-reinforced aggregate sections showed a reduction in modulus as embedment depth increased. The project attributes this behaviour to reduced aggregate interlocking, localized stress concentration and the influence of particle size within the geocell pockets. Consequently, MIF was not evaluated for the reinforced aggregate case because a significant stiffness gain was not observed.

4.9 Chemical Stabilization of Weak Subgrade Soil

Chemical stabilization was conducted on Soil-4 using hydrated lime and OPC 53-grade cement. The dry soil and stabilizer were thoroughly blended before the required water was added. CBR specimens were compacted in five equal layers and soaked for 96 h. UCS specimens were cured for 7, 14 and 28 days. Large-scale specimens were compacted in 100 mm layers to a total thickness of 600 mm and subsequently tested with DCPT, DSCPT and LWD.

The reported results show a clear beneficial effect of both stabilizers. Increasing stabilizer content reduced maximum dry density, while CBR, UCS and deformation-related strength characteristics increased. The optimum contents reported in the project were 6% lime and 8% cement, corresponding to the highest CBR and UCS values within the investigated ranges. Strength also continued to increase with curing period, which is consistent with the development of cementitious and pozzolanic products.

Table 9. Reported optimum contents and observed trends for chemical stabilization of Soil-4.

Treatment	Reported optimum content	Main measured responses	Observed trend
Hydrated lime	6%	CBR, UCS, DR, CI, E_LWD	Strength increased; MDD decreased with dosage; curing enhanced response
OPC 53 cement	8%	CBR, UCS, DR, CI, E_LWD	Strength increased; MDD decreased with dosage; curing enhanced response

The project defines the Strength Improvement Factor (SIF) as the ratio of a stabilized strength parameter to the corresponding untreated value. Depending on the analysis, the parameter may be CBR, UCS, dynamic resistance, cone index or LWD deformation modulus. The SIF concept is useful for comparing treatments because it normalizes the response against the untreated baseline.

4.10 Mechanisms of Improvement

- Triaxial geogrid: mechanical interlock, radial tensile stiffness, lateral confinement, membrane action and wider load distribution.
- Geocell: three-dimensional confinement, reduced lateral deformation, improved stress redistribution and mobilization of cell-wall hoop stresses.
- Lime stabilization: cation exchange and flocculation reduce plasticity and moisture sensitivity, followed by pozzolanic reactions that develop cementitious products.
- Cement stabilization: hydration and formation of cementitious compounds bind soil particles, increase compressive strength and reduce compressibility.
- LWD quality control: rapid surface stiffness measurements provide direct information on deformation response rather than relying only on density.

4.11 Comparative Assessment of Reinforcement and Stabilization

Table 10. Comparative engineering assessment of the investigated reinforcement and stabilization interventions.

Intervention	Primary target	Best reported configuration	Principal benefit	Limitation noted
Triaxial geogrid	Soil-1 / aggregate layers	$u/a = 0.17$; $u = 50$ mm	Highest stiffness and MIF	Benefit decreases with depth
Geocell	Soil-1	$u/a = 0.50$; $u = 50$ mm	~45.7% E _{LWD} improvement	Limited benefit in aggregate layers
Geocell	Aggregate over Soil-1	100–300 mm aggregate layers	No significant MIF reported	Reduced interlocking / particle-size effect
Hydrated lime	Soil-4	6% lime	Highest reported CBR and UCS	MDD decreases as dosage rises
OPC 53 cement	Soil-4	8% cement	Highest reported CBR and UCS	MDD decreases as dosage rises

5. INTEGRATED DISCUSSION AND ENGINEERING IMPLICATIONS

5.1 Why Modulus-Based Quality Control is More Representative

Density remains an important construction-control parameter, but the experimental evidence indicates that deformation modulus provides a closer representation of the structural behaviour required from pavement layers. The LWD measures the response of the compacted surface to a dynamic load and therefore captures the combined effects of density, moisture, particle arrangement, layer thickness and underlying support. This is particularly valuable for mechanistic–empirical design, in which stiffness parameters are required as inputs or acceptance descriptors.

5.2 Practical Role of the LWD

The LWD is particularly attractive because it is portable, requires relatively few operators and produces results rapidly. The reported agreement with PLT, including the MIF relationship with $R^2 = 0.962$, demonstrates that the device can reproduce important trends observed by a reference test. The project nevertheless shows that LWD results are sensitive to plate diameter, contact pressure, loading rate, sensor calibration, moisture, density, gradation, layer thickness and the stiffness of underlying layers.

Therefore, LWD acceptance limits should be developed with controlled test conditions and material-specific calibration.

5.3 Moisture as a Critical Quality-Control Variable

Moisture is a major source of variability in pavement construction. The DCPT, DSCPT and LWD results for Soil-2 and Soil-3 demonstrated that increased water content reduced resistance and stiffness. A density value measured at an unsuitable moisture condition may therefore be misleading if interpreted without considering mechanical response. A practical quality-control system should record moisture together with density and stiffness so that weak locations can be distinguished from locations that are simply at a different moisture state.

5.4 Influence of Reinforcement Position

The reinforcement results provide a clear engineering lesson: the position of a geosynthetic relative to the applied load can be as important as the presence of the reinforcement itself. For triaxial geogrid, the 50 mm position generated the highest modulus and MIF. Moving the grid deeper reduced its ability to interact with the stress influence zone. For geocell-reinforced Soil-1, the reported optimum was also associated with a shallow 50 mm embedment, although the normalized u/a ratio differed because of the configuration adopted in the project. These results support reinforcement placement based on stress distribution rather than arbitrary depth selection.

5.5 Quality-Control Framework for Pavement Construction

Proposed integrated modulus-based pavement quality-control workflow



The workflow synthesizes the testing sequence and decision logic reported in the project.

Figure 8. Recommended integrated workflow for modulus-based pavement quality control.

1. Verify material classification, gradation, moisture condition and laboratory compaction characteristics before field acceptance.

2. Use density-based testing to verify compaction effort and maintain compliance with the project specification.
3. Use LWD at a higher frequency to map surface stiffness and identify weak or non-uniform zones.
4. Use DCP/DCPT or DSCP/DSCPT where a penetration-based strength profile is required, especially for subgrade soils.
5. Use PLT or another reference method periodically for calibration and verification of LWD-based acceptance relationships.
6. For reinforced sections, record reinforcement type, depth, layer thickness and relative compaction because these variables strongly affect modulus.
7. For stabilized soils, monitor stabilizer content, curing period and moisture and evaluate CBR/UCS together with rapid stiffness measurements.
8. Use regression and spatial statistics to identify systematic trends, outliers and weak zones rather than relying on a single isolated measurement.
9. Base final acceptance on a combination of density, stiffness, strength and construction records so that the quality-control decision reflects actual pavement behaviour.

5.6 Sustainability and Construction Efficiency

Although the uploaded project does not provide a complete life-cycle cost or carbon assessment, the engineering implications are clear. Portable rapid testing can reduce interruptions to construction and allow more frequent measurements. Early identification of weak areas can reduce the risk of premature pavement distress and associated maintenance. Geosynthetic reinforcement can reduce deformation and improve load distribution, while stabilization can make marginal soils usable as pavement foundation materials. The project therefore supports the broader objective of durable, economical and sustainable highway construction, while also identifying life-cycle cost, environmental assessment and field validation as areas for future work.

6. CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

- Modulus-based quality control provides a more realistic representation of pavement structural behaviour than density alone because it directly reflects stiffness and deformation response.
- The LWD proved to be a rapid, portable and economical method for evaluating deformation modulus of subgrade and base materials and showed good agreement with PLT trends.
- Relative compaction increased deformation modulus, while increased moisture content reduced dynamic

resistance, cone index and LWD modulus in the investigated soils.

- For triaxial geogrid-reinforced Soil-1, the optimum embedment was 50 mm ($u/a = 0.17$). At 97% relative compaction and 0.15 MPa contact pressure, E_{LWD} was 29.45 MPa compared with 18.50 MPa for unreinforced Soil-1.
- The LWD-based MIF at the optimum geogrid position was 1.42, while the corresponding PLT-based MIF was 1.37. The LWD and PLT MIF relationship achieved $R^2 = 0.962$.
- In reinforced aggregate layers, triaxial geogrid also performed best at 50 mm embedment, but the stiffness gain was more moderate because the aggregate layer already had relatively high stiffness.
- Geocell reinforcement increased the deformation modulus of Soil-1 by approximately 45.7% at the reported optimum configuration, demonstrating the benefit of three-dimensional confinement.
- Geocell reinforcement did not provide a significant stiffness improvement in the investigated aggregate layers, showing that geocell effectiveness depends strongly on infill material and particle interaction.
- Chemical stabilization with lime and cement substantially improved weak-soil strength. The reported optimum stabilizer contents were 6% lime and 8% cement, with strength increasing with curing period.
- The reported regression relationships between rapid field parameters and conventional strength measures produced R^2 values from 0.78 to 0.99, supporting the use of calibrated correlations for rapid quality control.
- An integrated QC approach combining density, LWD, DCP/DSCP, PLT and laboratory strength tests can improve test coverage, identify weak zones and support mechanistic-empirical pavement evaluation.

6.2 Limitations

- The reported experimental programme is primarily laboratory and controlled large-scale testing; long-term in-service field validation is still required.
- Some chemical-stabilization results are reported in the project primarily through trends and optimum contents rather than a complete numerical matrix; this paper therefore does not invent missing numerical values.
- Empirical correlations should be calibrated for local soil, moisture, compaction and equipment conditions before being adopted as universal acceptance equations.
- The uploaded project identifies, but does not fully quantify, life-cycle cost and sustainability benefits.

6.3 Future Scope

10. Conduct long-term field performance studies under actual traffic and environmental conditions.
11. Evaluate additional soil types, aggregate materials and pavement layer configurations using modulus-based quality control.
12. Study biaxial geogrids, woven geotextiles, hybrid reinforcement systems and other geosynthetics.
13. Investigate fly ash, GGBS, rice husk ash, geopolymers and other industrial by-products as stabilization agents.
14. Develop machine-learning and artificial-intelligence models for predicting deformation modulus and strength from rapid field data.
15. Integrate LWD, DCP, GPS and wireless sensors for continuous real-time construction monitoring.
16. Develop standardized modulus-based acceptance criteria and national specifications for routine field use.
17. Carry out life-cycle cost, carbon and sustainability assessments comparing modulus-based and conventional quality-control systems.

REFERENCES

1. Agarwal, S.R. and Saran, N.K. (1983). Widening and Strengthening of Existing Pavements in Black Cotton Soil Areas and Investigation of Failures. *Journal of IRC*, 44(2), 391–439.
2. Al-Qadi, I.L., Brandon, T.L. and Bhutta, A. (1997). Geosynthetic Stabilized Flexible Pavements. *Proceedings of Geosynthetics '97*, IFAI, Long Beach, California.
3. Barksdale, R.D., Brown, S.F. and Chan, F. (1989). Potential Benefits of Geosynthetics in Flexible Pavement Systems. NCHRP Report 315, Transportation Research Board.
4. Baker, J.C., Thomas, P.J. and Zelazny, L.W. (2000). An Expansive Soil Index for Predicting Shrink–Swell Potential. *Soil Science Society of America Journal*, 64.
5. Bender, D.A. and Barenberg, E.J. (1978). Design and Behaviour of Soil Fabric Aggregate System. *Transportation Research Record No. 671*, 64–75.
6. Binquet, J. and Lee, K.L. (1975). Bearing Capacity Tests on Reinforced Earth Slabs. *Journal of Geotechnical Engineering Division, ASCE*, 101(GT12), 1241–1255.
7. Brorsson, I. and Irikson, L. (1986). Long Term Properties of Geotextiles and Their Function as a Separator in Road Construction. *Proceedings of the 3rd International Conference on Geotextiles, Vienna*, 93–98.
8. Button, J.W. (1989). Overlay Construction and Performance Using Geotextiles. *Transportation Research Record No. 1248*.
9. Cancelli, A., Rimoldi, P. and Togni, A. (1992). Frictional Characteristics of Geogrids by Means of Direct Shear and Pull-Out Tests. *IS Kyushu '92 International Symposium on Earth Reinforcement Practice*, 51–56.
10. Chang, D.J.J., Ho, N.H., Chang, H.Y. and Yeh, H.S. (1999). Laboratory and Case Study for Geogrid Reinforced Flexible Pavement Overlay. *Transportation Research Record No. 1687*, 125–130.
11. Chen, F.H. (1988). *Foundations on Expansive Soils*. Elsevier Publishing Co., Amsterdam.
12. Collin, J.G., Kinney, T.C. and Fu, X. (1996). Full Scale Highway Load Test of Flexible Pavement Systems with Geogrid Reinforced Base Courses. *Geosynthetics International*, 3(4), 537–549.
13. Das, B.M. (2004). *Principles of Foundation Engineering*, 5th ed. Thomson Brooks/Cole.
14. Das, B.M. (2006). *Principles of Geotechnical Engineering*, 6th ed. Thomson.
15. Deshpande, M.D., Pandya, P.C., Shah, J.D. and Vanjara, S.V. (1990). Performance Study of Road Section Constructed with Local Expansive Clay Stabilised with Lime as Sub-Base Material. *Indian Highways*, 18(6).
16. Evans, R.P. and McManus, K.J. (1999). Construction of Vertical Moisture Barriers to Reduce Expansive Soil Subgrade Movement. *Transportation Research Record No. 1652*.
17. Fannin, R.J. and Sigurdson, O. (1996). Field Observations on Stabilisation of Unpaved Roads with Geosynthetics. *Journal of Geotechnical Engineering, ASCE*, 122(7), 541–552.
18. Ghosh, R.K., Chadda, L.R., Pant, C.S. and Sharma, R.K. (1973). Stabilisation of Alluvial Soils with Lime and Fly Ash. *Journal of Indian Roads Congress*, 35.
19. Giroud, J.P., Ah-Line, C. and Bonaparte, R. (1985). Design of Unpaved Roads and Trafficked Areas with Geogrids.
20. Giroud, J.P. and Noiray, L. (1981). Geotextile-Reinforced Unpaved Road Design. *Journal of Geotechnical Engineering*.
21. Giroud, J.P. and Han, J. (2004). Design Method for Geogrid-Reinforced Unpaved Roads – II: Calibration and Applications. *Journal of Geotechnical and Geoenvironmental Engineering*.
22. Holtz, R.D., Christopher, B.R. and Berg, R.R. (1998). *Geosynthetic Design and Construction Guidelines*. FHWA.
23. IRC:37-2000. *Guidelines for Design of Flexible Pavements*. Indian Roads Congress.

24. IS 2720 (Part 5):1995. Determination of Liquid and Plastic Limit for Soils.
25. IS 2720 (Part 16):1997. Laboratory Determination of California Bearing Ratio (CBR) for Soil.
26. M.O.R.T.H. (2001). Specifications for Roads and Bridge Works.
27. Koerner, R.M. (1986). Designing with Geosynthetics. Prentice Hall.
28. Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T. and Yasuhara, K. (1990). Polymer Grid Reinforced Pavement on Soft Clay Grounds. Geotextiles and Geomembranes, 9(1), 99–123.
29. Natarajan, T.K. and Shanmukha Rao, E. (1979). Practical Lessons on Road Construction in Black Cotton Soil Areas. Journal of Indian Roads Congress, 40(1), 153–185.
30. Uploaded Project Report: Quality Control of Pavement Subgrade and Base Materials Using Advanced Field-Testing Techniques, M.V.R. College of Engineering and Technology, Paritala, Andhra Pradesh, 2024–2026.