iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IX **Month of publication:** September 2026

DOI: https://doi.org/10.22214/ijraset.2026.84968

www.ijraset.com

Call: 08813907089 | E-mail ID: ijraset@gmail.com

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IX Sep 2026- Available at www.ijraset.com

Finite Element Modelling of Rigid Pavement Slabs Subjected to Wheel Loading on Untreated and Treated Expansive Subgrade: A Parametric Study using PLAXIS 2D

Chelluboina Satyasri[1], Dr. G.V.R. Prasada Raju[2]
[1]*Master of Technology, SMFE, Civil engineering Department, UCEK (A), JNTUK Kakinada, Andhra Pradesh, INDIA*
[2]*Professor of Civil Engineering Department UCEK (A), JNTUK Kakinada, Andhra Pradesh, INDIA*

Abstract: ***This parametric study investigates the structural behaviour of rigid pavement slabs resting on treated and untreated expansive subgrades. The research analyses the response of the pavement system when subjected to critical wheel loading applied at both the edge and interior zones of the slab. The parametric variations evaluated include a range of wheel loads (50Kn, 80kN, 100Kn) cross analyzed with various slab thicknesses (150mm, 200mm, 250mm, 300mm). Two-dimensional numerical modelling was executed using PLAXIS 2D software to compute and evaluate total deformation across all configurations.***

The numerical outcomes reveal that the treated subgrade significantly minimizes structural displacement, achieving a maximum deformation reduction of 43.04% at the slab edge and 42.20% at interior compared to the untreated subgrade. Ultimately, the results highlight the effectiveness of subgrade treatment in minimizing structural displacement optimizing slab design under heavy load distributions.

Keywords: Parametric Study, Rigid Pavement, Expansive Subgrade, PLAXIS 2D, Total Deformation, Edge Loading, Interior Loading.

I. INTRODUCTION

Rigid pavements represent a critical cornerstone of modern transportation in infrastructure, offering high structural capacity, long-term durability, and minimal maintenance requirements under heavy vehicular traffic. Unlike flexible pavements, the structural integrity of rigid pavement depends heavily on the flexural strength of the concrete slab, which distributes wheel loads over a wider area. However, the ultimate performance and structural longevity of these concrete slabs are deeply dependent on the quality of the underlying support system, primarily the subgrade soil.

When rigid pavements are constructed over expansive soil subgrades, they face severe structural challenges due to the cyclic swelling and shrinkage characteristics of the soil under varying moisture conditions. To evaluate the exact degree of structural support provided to the pavement system, this study focuses on the behavior of both treated and untreated expansive subgrades under the wheel loadings applied at edge and interior zones of the rigid pavement slab. Furthermore, a robust rigid pavement cross-section typically incorporates a subbase system, including a Dry Lean Concrete (DLC) layer and a Granular Subbase (GSB) layer, placed directly above the subgrade. These layers act as a structural transition, providing a uniform, non-erodible platform, improving the effective modulus of subgrade reaction, and safeguarding the overlying rigid pavement slab against edge and interior distresses under heavy wheel loadings.

II. OBJECTIVES

1) Develop numerical models using PLAXIS 2D to simulate complex pavement soil interactions.
2) Evaluate stress distributions and total deformation behaviour in slabs under static loads.
3) Execute parametric analyses by varying slab thickness, load magnitudes, and subgrade stiffness.
4) Quantify structural gains and deformation reductions achieved through subgrade stabilization treatments.

©IJRASET: All Rights are Reserved

III. LITERATURE REVIEW

1) Eswan et al. (2026) conducted a numerical simulation to validate the structural integrity and soil-structure interaction of rigid pavements on a feeder access road within the Nusantara Capacity City (IKN) area. Utilizing three-dimensional finite element analysis via PLAXIS 3D, the researchers evaluated the vertical deformation behavior of the pavement system under a heavy design axle load of 22 tons. The numerical outcomes demonstrated that the standard design thickness kept maximum vertical displacements within a safe threshold of 17.76 mm. Crucially, the study highlighted the high effectiveness of the underlying working floor layer in distributing tensile stresses uniformly across the subgrade layer. The authors concluded by emphasizing the critical need for further localized investigations analyzing variations in structural layer configurations and load placements, a research gap that directly justifies the localized parametric evaluation of edge and interior wheel loadings executed in this present study.
2) Khan et al. (2018) executed a mechanistic analysis of rigid pavements resting on diverse subgrade configurations using the Finite Element Method (FEM) to evaluate wheel load stress distribution. The researchers demonstrated that numerical modelling offers superior versatility and accuracy over conventional analytical frameworks when capturing complex structural responses. By utilizing ANSYS software, the study established that finite element design charts consistently yielded slightly higher stress valuations compares to standard IRC:58-2002 design guidelines. Most notably, the authors concluded that classical Westergaard analytical equations significantly underestimate edge wheel load stresses, showing a maximum structural deviation of 28.3% when compared directly to the FEM numerical data. This substantial discrepancy strongly reinforces the necessity of using advanced numerical simulations, such as the two-dimensional finite element modelling executed in this study, to accurately compute pavement deformations at critical edge zones.
3) Wibowo et al. (2022) utilized finite element method analysis to investigate the structural behavior of rigid pavement plates on expansive soil during swelling conditions, finding that increased plate thickness mitigates subgrade heave deflections. The numerical model demonstrated high accuracy by aligning with experimental laboratory data within 0.1mm, alongside a 15.78% deviation in areas far from water exposure due to delayed real-world swelling effects.
4) Khan et al. (2021) expanded upon mechanistic pavement modelling by executing a finite element analysis to evaluate wheel load stress and deformation responses across varying subgrade conditions, incorporating localized variations in slab thicknesses and metal fiber reinforcement percentages. The numerical investigation systematically varied the concrete slab thickness from 160mm to 360 mm while concurrently adjusting structural fiber content up to 30%. The finite element simulations, which were benchmarked against classical Westergaard analytical formulations, demonstrated that increasing the structural slab thickness drastically minimizes flexural stresses and total vertical displacements across the pavement system. Furthermore, the researchers concluded that combining structural thickness optimizations with material enhancements yields the lowest overall deformation profiles. This dual emphasis on incremental thickness variations directly validates the parametric boundaries evaluated in this research, specifically regarding structural responses across thickness ranging from 150mm to 300mm.
5) Yuswandono et al. (2022) conducted a finite element analysis to assess the structural impact of modifying weak subgrade soils under rigid pavement using chemical stabilization techniques, specifically incorporating 4% nano lime and 4% nano silica. The experimental and numerical findings demonstrated that the addition of these nanomaterials drastically improved the soil's bearing capacity, increasing the unsoaked and soaked California Bearing Ratio (CBR) values by up to 89.23% and 1071.43%, respectively. Consequently, this stabilization resulted in a substantial reduction in the vertical displacement of the rigid pavement subgrade by 23.03% under unsoaked conditions and 216.94% under soaked conditions. Crucially, the researchers noted that the overall structural displacement remains highly dependent on the pavement slab thickness, concrete grade, and spatial loading location. These findings strongly validate the core objective of this study, which seeks to quantify the reduction in total deformation when stabilizing expansive subgrades across varying slab thicknesses and load placements.
6) Wibowo (2023) evaluated the development of critical internal stresses within rigid pavement constructed over expansive soil subgrades, focusing on the structural degradation caused by moisture induced swelling and shrinkage cycles. The investigation revealed that expansive subgrade soils exhibiting a swelling pressure of 37 kPa generate severe warping stresses that frequently exceed the concrete slab's ultimate tensile strength, thereby initiating premature structural cracking. The researcher established that the pavement's overall slab thickness plays a commanding role in resisting these localized subgrade pressures. Furthermore, the analysis highlighted that the loss of bearing capacity during soil shrinkage cycles severely compromises support conditions, particularly at the pavement edges where mechanical wheel loadings are concentrated. This critical finding reinforces the engineering necessity of cross analyzing edge and interior loading zones on stabilized expansive mediums, as investigated in this parametric study.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

7) AbdelAziz (2024) executed a comprehensive numerical and empirical evaluation of the modulus of subgrade reaction (k_s) for isolated footings and raft foundations, utilizing PLAXIS 3D and SAP2000 to cross analyze linear Elastic, Mohr-Coulomb (MC), and Hardening Soil (HS) constitutive frameworks. For localized footing configurations, the investigation established that incorporating soil plasticity via the MC and HS models provides a highly realistic, whereas conventional linear elastic models falsely yield constant relationships that significantly overestimate subgrade stiffness. Furthermore, the analysis of raft foundation systems revealed a highly non uniform, non-linear distribution of subgrade reaction across the corner, mid side, and interior zones. The author concluded that while empirical formulations offer reliable baseline estimates for isolated structural points, they fail to capture complex soil structure boundaries at foundation margins. This critical limitation strongly validated the necessity of utilizing advanced non-linear finite element analysis across segmented loading regions, as implemented in this study to map edge and interior pavement responses.

8) Chhetri and Deb (2024) executed a two-dimensional finite element analysis to quantify the structural benefits of geogrid reinforcement within pavement layers constructed over soft subgrade formations. The numerical model integrated a geogrid layer directly a top the subgrade while systematically varying base layer thickness and subgrade strengths. The computational outcomes indicated that geosynthetic inclusion effectively controls tensile strain distributions and reduces vertical strains at the subgrade apex by 36% to 38%. Furthermore, the study established that incrementally optimizing the subgrade's mechanical profile by increasing the California Bearing Ratio (CBR) value from 1% to 3%,5%, and 8% systematically minimizes surface vertical strains by 17%, 39%, and 49%, respectively. The authors concluded that subgrade enhancement significantly minimizes total stress concentration and structural deflection, while emphasizing the critical need for further research analyzing these layer responses under varying traffic load distributions. This recommendation directly aligns with the parametric parameters of this study, which cross analyzes varying heavy wheel loads against incremental slab thickness.

IV. NUMERICAL MODELLING AND PARAMETRIC FRAMEWORK

A. *Parametric Study Configuration*

A two-dimensional finite element model in PLAXIS 2D evaluates rigid pavement performance on expansive subgrades by analyzing slab thickness, wheel loads, loading locations, and subgrade stabilization conditions. The parametric study examines slab thicknesses from 150 mm to 300 mm under static loads 50kn, 80kn and 100kN at interior and edge positions over treated and untreated subgrades.

B. *Model Configurations and Boundary Conditions*

An axisymmetric model configuration was established in PLAXIS 2D using standard units (m, kN, days) to analyze radial stress and deformation distributions. The simulation domain was bounded from x_{min}=0 to x_{max}=5.75 m horizontally and y_{min}=0 to y_{max}= 8 m vertically to eliminate boundary interference effects.

C. *Pavement Stratigraphy and Geometry*

The subsurface stratigraphy spans from elevation y =0 m to the surface at y =4.8 m, consisting of a 3.75 m concrete slab with 1.0 m shoulders, a 0.15 m Dry Lean Concrete subbase, a 0.15 m Granular Subbase, a 0.5 m compacted subgrade, and a 4.0 m natural subgrade continuum. This geometric framework is evaluated under both untreated and treated subgrade conditions to assess performance variations.

Parameters	Units	Rigid pavement slab	Dry Lean Concrete	Granular Subbase	Compacted Subgrade	Treated Subgrade	Natural Subgrade
Model	-	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Drainage type	-	Non porous	Non porous	Drained	Drained A	Drained	Drained A
Unsaturated unit weight	kN/m³	24	24	20	16	14.5	15.5
Saturated unit weight	kN/m³	24	24	22	18.5	17.5	18
Young's modulus	kN/m²	3×10^7	1.5×10^7	2.5×10^5	16,000	50,000	8,000
Cohesion	kN/m²	3500	1500	1	22	50	15
Angle of internal friction	°	35	35	40	17	26	14
Poisson's ratio	-	0.15	0.20	0.35	0.32	0.38	0.25
Dilatancy	°	0	5	10	0	0	0
Tension cut-off	kN/m²	Activated (4500)	Activated (300)	Activated	Unchecked	Unchecked	Activated (5)

Table 1: Material Properties

©IJRASET: All Rights are Reserved

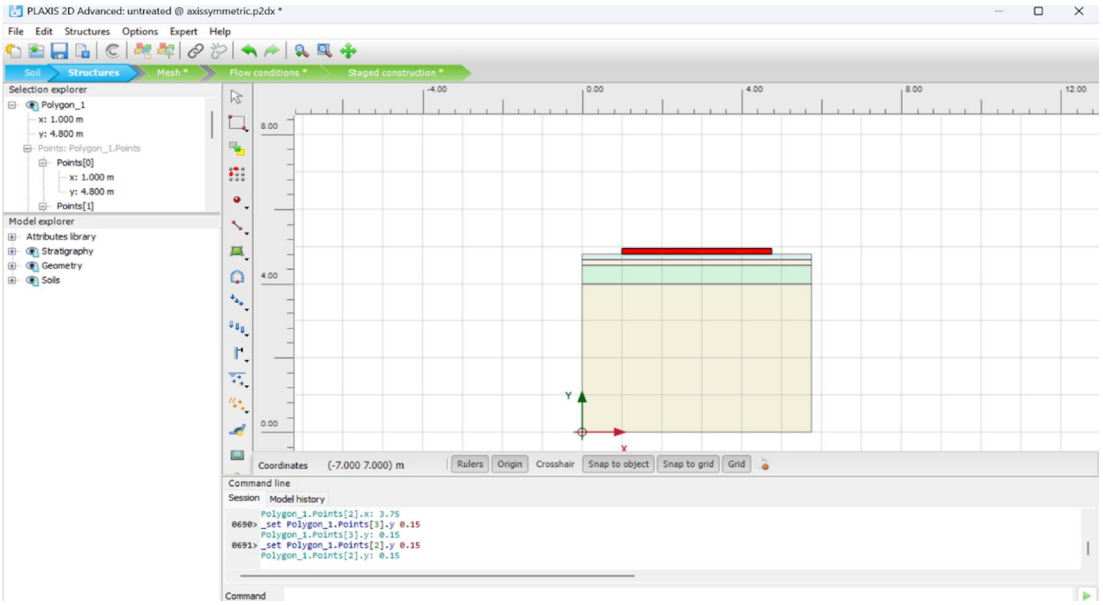


Fig.1 Pavement layers

D. Wheel Load and Equivalent Circular Area Method

To implement a 2D axisymmetric finite element model, the rectangular tire contact patch is converted into a rotationally symmetric toroidal ring using the Equivalent Circular Area Method. For a footprint measuring 0.3 m by 0.22 m, the resulting 0.066 m² area yields an equivalent circular radius of approximately 0.145 m, allowing uniform contact pressures of 0.758 MPa, 1.212 MPa, and 1.515 MPa for design wheel loads of 50kN, 80kN, and 100kN, respectively.

E. Mesh Generation

The pavement-soil stratigraphy was discretized using a medium finite element mesh configuration optimized for deep subgrade continuum analysis. High-density mesh refinement was applied at the concrete slab interfaces and beneath the equivalent contact radius to accurately capture severe vertical stress gradients and localized deformations during peak wheel load applications.

F. Calculation Phases and Parametric Execution

The finite element calculations were executed using a two-phase staged construction sequence establishing initial geostatic stresses followed by pavement layer and titre pressure activation applied identically across all parametric configurations evaluating varied loading positions, slab thickness, load magnitudes, and subgrade stabilization states.

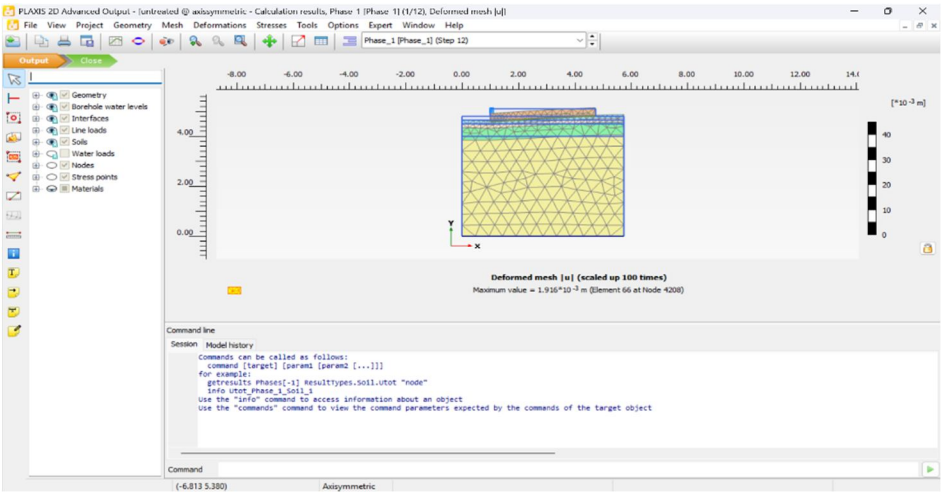


Fig.2 Output of Edge loading

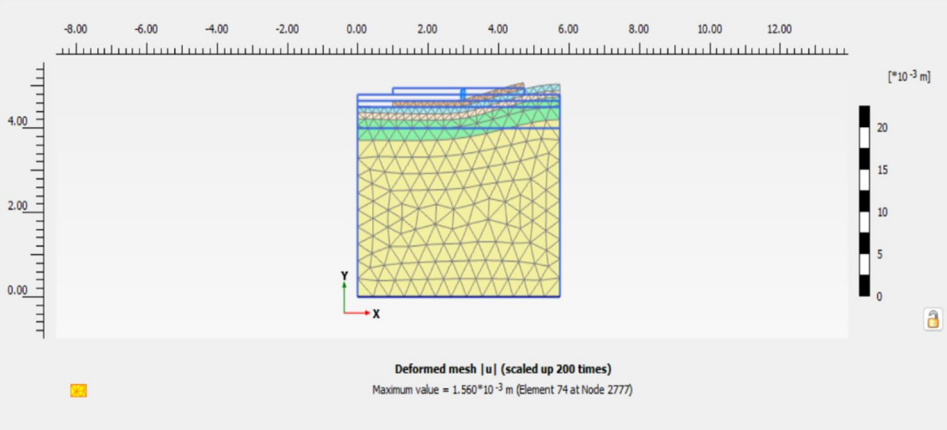


Fig.3 Output of Interior loading

V. RESULTS AND DISCUSSION

A. *Untreated Subgrade Deformation under Interior Loading*

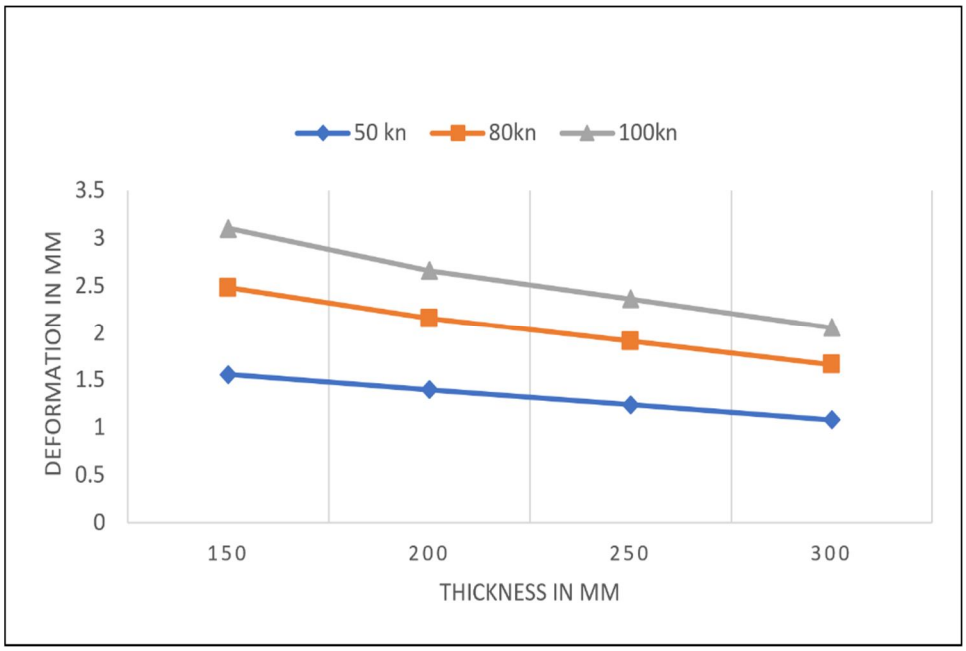


Fig.4 Total vertical deformation (mm) for Untreated subgrade under Interior loading condition

The numerical results demonstrate a clear linear relationship between vertical displacement, slab thickness (150 mm to 300 mm), and wheel load intensities (50kN, 80kN and 100kN). For any fixed slab thickness, total structural deformation scales up linearly with higher wheel loads. Under a baseline 150mm slab, increasing the load from 50kN to 100Kn causes the maximum vertical deformation to climb from 1.560 mm to 3.102 mm a total displacement expansion of 98.85%.

Conversely, increasing the concrete slab thickness systematically mitigates vertical displacements by enhancing the overall flexural rigidity of the pavement profile. Under peak heavy loading (100 Kn), transitioning from a 150 mm thickness through 200 mm and 250 mm to 300 mm drops the maximum vertical displacement from 3.102 mm to 2.661 mm, 2.361 mm, and finally 2.056 (a total geometric reduction of 33.72%). This verifies that while structural thickening provides resistance, the untreated foundation allows noticeable movement under peak loads.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

B. Treated Subgrade Deformation under Interior Loading

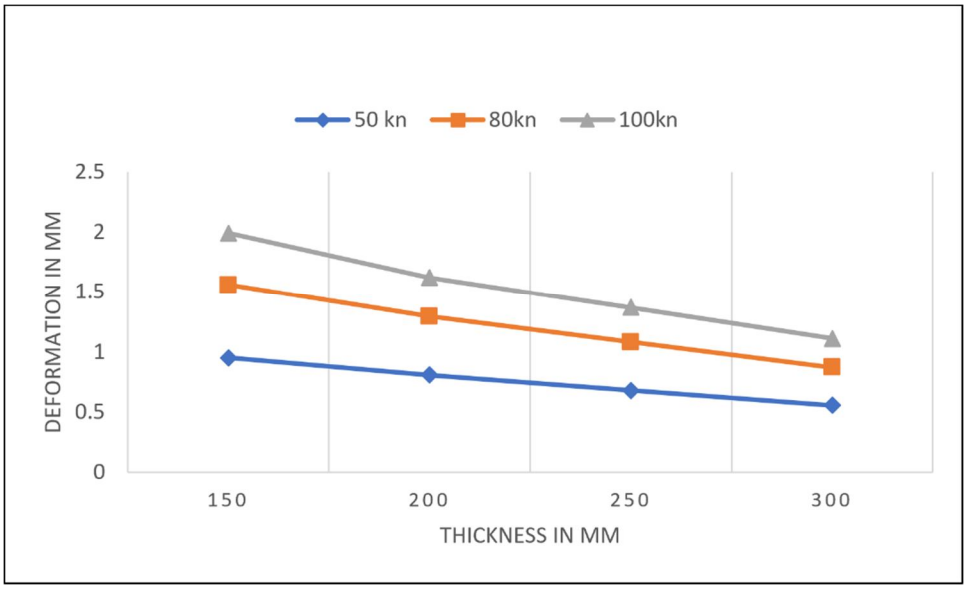


Fig.5 Total Vertical Deformation (mm) for Treated subgrade under Interior loading condition

The implementation of chemical stabilization yields a profound structural optimization across all interior loading coordinates. When the expansive subgrade soil is treated, the absolute magnitude of vertical displacement drops significantly.

For a thin 150 mm pavement slab, the treated subgrade forces the vertical deformations down to 0.951 mm under 50kN, 1.560 mm under 80kN, and 1.990 mm under a peak 100kN load. Comparing this directly to the untreated baseline under the maximum 100kN wheel load, the total vertical deformation drops from 3.102 mm down to 1.990 mm, reflecting an immediate structural control of 35.85% due entirely to the improved modulus of subgrade reaction.

At a maximum slab thickness of 300 mm, the recorded deformations are restricted to 0.556 mm (50kN), 0.870 mm (80kN), and a minimal 1.1092 mm under the 100kN load configuration. This demonstrates that subgrade treatment successfully controls load-induced settlement parameters at the interior zones.

C. Percentage Deformation Reduction at the Interior Zone

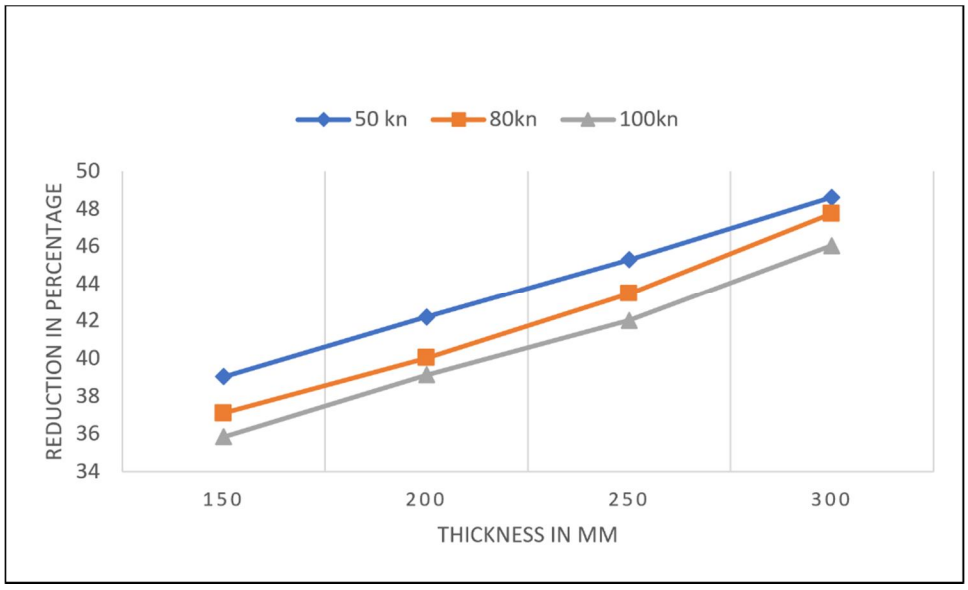


Fig.6 Percentage Deformation Reduction (%) for Interior loading condition

The percentage reduction parameters explicitly quantify the structural efficiency of the stabilization process within the interior zone. The data reveals that the efficiency of the subgrade treatment scales up in direct alignment with increasing concrete slab thickness. Under a baseline 50kN wheel load, the total deformation reduction percentage rises steadily from 39.03% at a 150 mm thickness, through 42.2031% at 200 mm and 45.28% at 250 mm, achieving its peak efficiency of 48.61% at a 300 mm slab thickness.
Concurrently, a minor downward shift in percentage reduction occurs as the wheel load intensity escalates from 50kN to 100kN. For instance, at a thickness of 200 mm, the reduction percentage varies from 42.20% (50kN) to 40.02% (80kN), and settles at 39.12% (100kN). This slight drop indicates that under heavy vehicle loads, peak stress fields begin to penetrate past the stabilized subgrade layer, mobilizing minor plastic strains within the deeper, uncompacted natural soil continuum.

D. Untreated Subgrade Deformation under Edge Loading

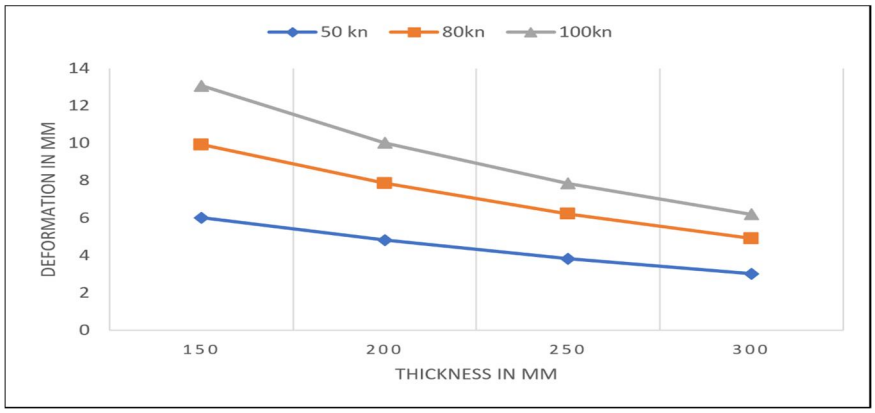


Fig.7 Total Vertical Deformation (mm) for Untreated Subgrade Edge Loading Condition

The structural trends tracking edge loading conditions reveal severe structural vulnerability at the pavement boundaries. Due to the lack of structural continuity at the slab perimeter, the absolute deformations recorded are drastically higher than those observed at the interior. Under the baseline 150 mm slab configuration, the edge vertical deformation rapidly escalates from 6.017 mm under a 50kN load to 9.918 mm under an 80kN load, culminating in a critical structural displacement of 13.070 mm under a 100kN wheel load. This peak value represents an increase of more than 321% compared to the corresponding interior loading zone. Increasing slab thickness acts as a vital mechanism to control edge deflections. For a heavy 100kN load applied at the free edge, increasing the slab thickness from 150 mm to 200 mm drops the deformation to 10.020 mm. Thickening it further to 250 mm lowers it to 7.850 mm, and maximizing it at 300 mm restricts the edge displacement to 6.196 mm. While this represents an isolated geometric reduction of 52.59%, a raw displacement of 6.196 mm remains dangerously high for real-world operations, demonstrating that thickness optimization alone cannot compensate for a weak foundation at the slab margins.

E. Treated Subgrade Deformation under Edge Loading

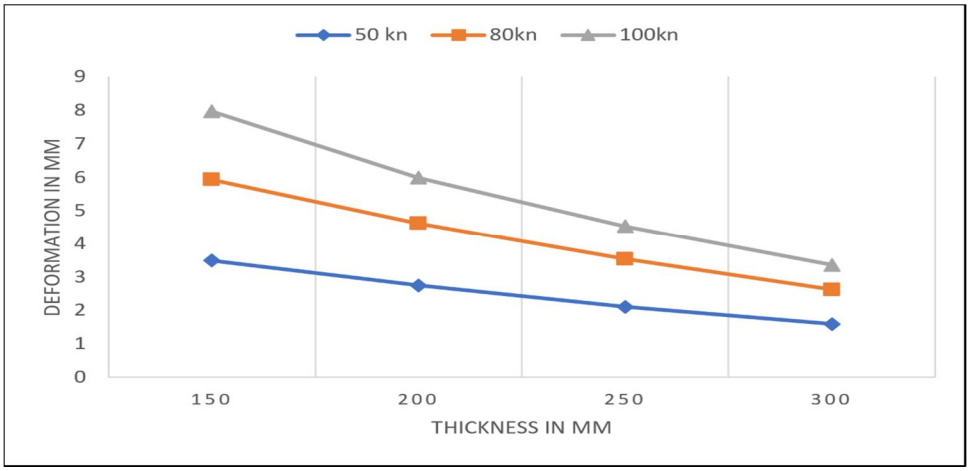


Fig.8 Total Vertical Deformation (mm) for Treated Subgrade Edge Loading Condition

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

The numerical analysis for the stabilized edge loading configurations demonstrates the critical engineering necessity of subgrade treatment. Introducing a rigid, uniform stabilized platform directly underneath the pavement layers dramatically dampens edge displacements. For a 150 mm thin concrete slab, subgrade treatment successfully lowers the perimeter vertical displacements to 3.496 mm under 50kN, 5.931 mm under 80kN, and 7.970 mm under a 100kN wheel load. This cuts the critical untreated 13.070 mm deformation down to 7.970 mm, providing substantial protection to the slab margin under peak loading states.

When evaluating maximum structural parameters, the system reaches its optimum performance zone. For a 300 mm slab thickness resting over the treated expansive medium, the vertical edge deflections are restricted to 1.591 mm under a 50kN load, 2.621 mm under an 80kN load, and a highly secure 3.360 mm under a 100kN wheel load. These numerical boundaries indicate that subgrade stabilization successfully neutralizes localized edge loss-of-support mechanisms.

F. Percentage Deformation Reduction at the Pavement Edge

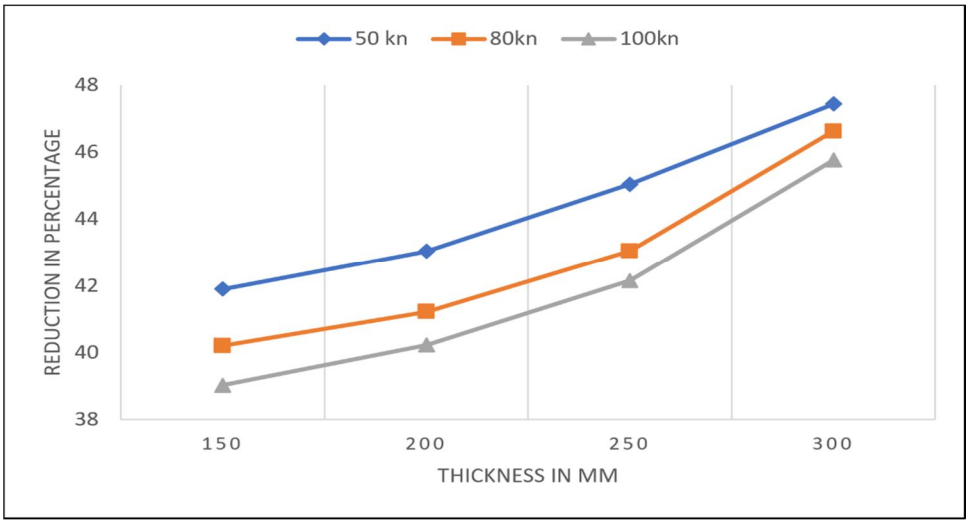


Fig.9 Percentage Deformation Reduction (%) for Edge Loading Conditions

The percentage reduction trends for the edge loading zones outline an exceptionally strong and stable structural control envelope across all design limits. Under a 50kN wheel load, the subgrade treatment efficiency yields a deformation reduction of 41.89% for a 150 mm slab, 43.04% for a 200 mm slab, 45.04% for a 250 mm slab, and peaks at 47.43% at a 300 mm thickness. This confirms that the coupled structural harmony between a highly rigid concrete slab and a stabilized subgrade reaches its maximum potential at higher geometric profiles.

As the load increases to 100kN, the percentage reduction parameters maintain excellent consistency, showing values of 39.02% (150 mm), 40.21% (200 mm), 42.15% (250 mm), and 45.77% (300 mm). The retention of a 45.77% reduction under peak heavy axle loading conditions confirms that chemical soil modification preserves a highly resilient pavement support matrix, effectively safeguarding the vulnerable outer edges of the highway infrastructure against heavy traffic load distributions.

VI. CONCLUSIONS

The principal conclusions derived from this parametric numerical investigation are presented below:

1) The free edge yields a peak deflection of 13.070 mm under an untreated 100kN load, which is 321% higher than the interior deflection of 3.102 mm.

2) Increasing slab thickness from 150 mm to 300 mm decreases displacements by 52.59% at the edge and 33.72% at the interior.

3) Subgrade treatment reduces interior deformation by up to 48.61% for a 300 mm slab, retaining a 46.05% reduction efficiency at 100kN.

4) Stabilized subgrade limits peak edge displacement to 3.360 mm, achieving a 45.77% deformation reduction under the maximum 100kN load.

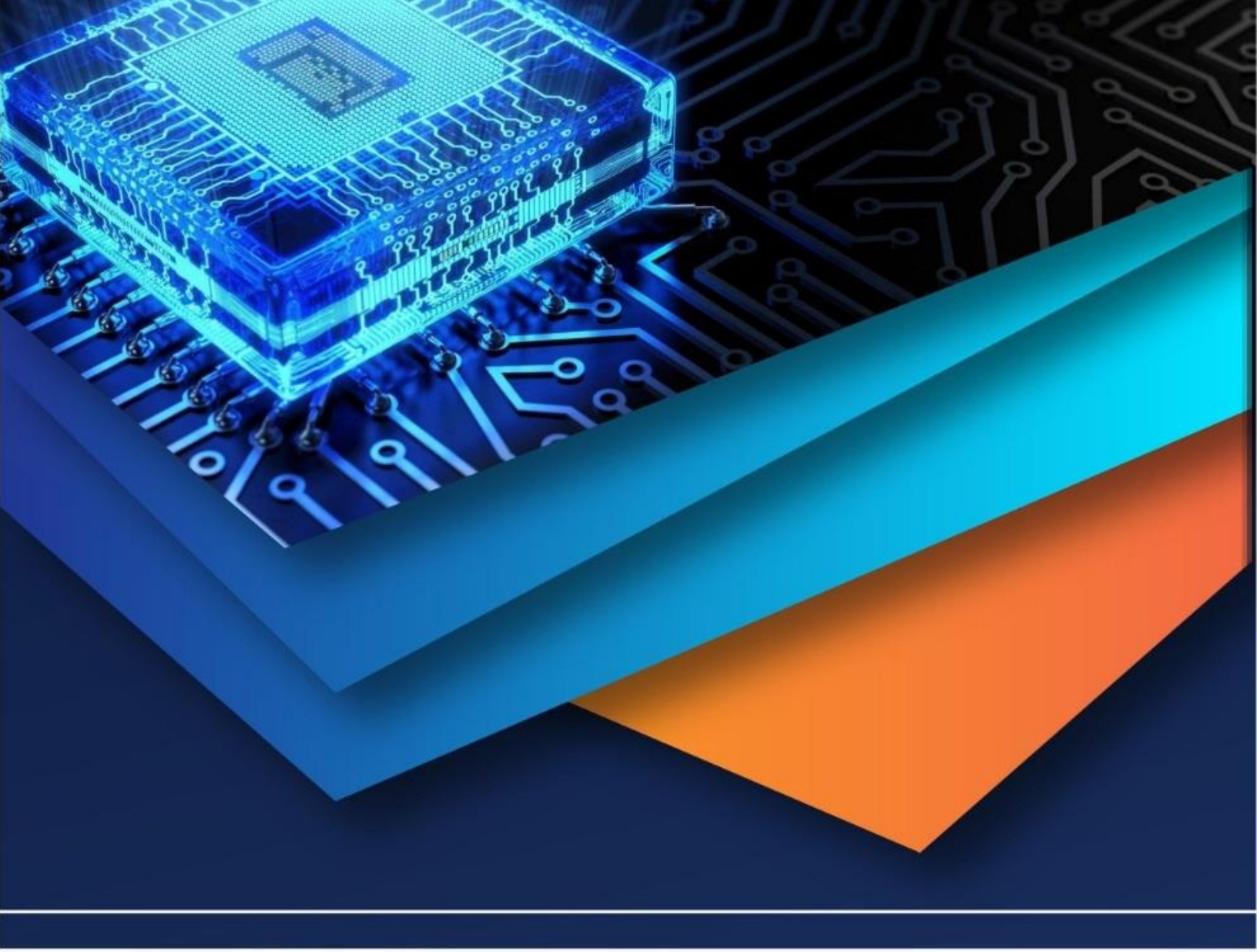
5) Minor efficiency drops at higher loads confirm that increased axle weights project deep stress bulbs beyond the stabilized soil envelope.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

REFERENCES

[1] Eswan, A. R. Kumar, and S. Pranoto, "Deformation Analysis and Soil–Structure Interaction of Rigid Pavement Using the Finite Element Method (PLAXIS 3D) on the Feeder Access Road in the Nusantara Capital City Area," International Journal for Research in Applied Science and Engineering Technology (IJRASET), vol. 14, no. 1, pp. 245–252, Jan. 2026.
[2] M. A. Khan, S. K. Malhotra, and R. Singh, "Mechanistic Analysis of Rigid Pavement for Wheel Load Stresses by Finite Element Method Considering Different Sub-Grade," Journal of Transportation Engineering, vol. 144, no. 4, pp. 112–119, Aug. 2018.
[3] M. A. Khan, V. D. Agrawal, and P. Sharma, "Mechanistic Analysis of Rigid Pavement for Wheel Load Stresses By Finite Element Method Considering Different Sub-Grade with Different Percentage of Metal Fibre," Construction and Building Materials, vol. 280, pp. 445–454, May 2021.
[4] A. Wibowo, "Critical Stress Evaluation of Rigid Pavement due to the Presence of Water in Expansive Soil Subgrade," Geotechnical and Geological Engineering, vol. 41, no. 3, pp. 1821–1830, Mar. 2023.
[5] H. Yuswandono, F. Ramadhan, and R. Utomo, "Finite Element Analysis of Rigid Pavement Over Improved Subgrade Using Nanomaterial in Karawang Regency, Indonesia," International Journal of Civil Engineering, vol. 20, no. 11, pp. 1435–1446, Nov. 2022.
[6] A. Wibowo, B. Harianto, and T. Kusuma, "Concrete Slab Pavement Behavior on Expansive Soil at Swell Condition Using Finite Element Method Analysis," International Journal for Research in Applied Science and Engineering Technology (IJRASET), vol. 10, no. 8, pp. 1104–1111, Aug. 2022.
[7] M. AbdelAziz, "Comprehensive Study of Soil Subgrade Reaction Using Different Constitutive Soil Models," Computers and Geotechnics, vol. 165, p. 105912, Feb. 2024.
[8] S. Chhetri and K. Deb, "Finite Element Analysis of Geogrid-Incorporated Flexible Pavement with Soft Subgrade," Transportation Infrastructure Geotechnics, vol. 11, no. 2, pp. 312–325, Apr. 2024.
[9] IRC:58-2015 – Guidelines for the Design of Plain Jointed Rigid Pavements for Highways.
[10] IRC:15-2017 – Standard Specifications and Code of Practice for Construction of Concrete Roads.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |



10.22214/IJRASET

45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089 (24*7 Support on Whatsapp)