International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 4, July-Aug-2026, ISSN (Online): 2395-566X

Geosynthetic Reinforcement of Clay Subgrades in Flexible Pavements: A Review

Ramanuj Singh[1], Hariram Sahu[2]
M.Tech scholar, Transportation and Highway Engineering, Department of Civil Engineering, School of Engineering, Eklavya University, Damoh (M.P.), India[1]
Assistant Professor, Department of Civil Engineering, School of Engineering, Eklavya University, Damoh (M.P.), India[2]

Abstract — Flexible pavements founded on clay subgrades are prone to premature distress because clay soils frequently combine low bearing capacity with pronounced moisture sensitivity. Expansive clays undergo cyclic swelling and shrinkage that produce heave and cracking, while non-expansive clays exhibit low shear strength and high compressibility that lead to rutting and shear failure. Conventional remedies, such as soil replacement, chemical stabilization, and cohesive non-swelling cushions, are often costly, site-sensitive, or only partially effective, and the empirical California Bearing Ratio (CBR) design framework used across India does not explicitly capture swelling behaviour or the beneficial contribution of reinforcement. This paper presents a detailed literature review of the growing body of laboratory, test-track, and field research on the use of geotextiles and geogrids to reinforce clay subgrades beneath flexible pavements. The mechanisms of tensioned-membrane action in geotextiles and lateral-restraint/reinforced-mattress action in geogrids are examined, together with reported improvements in bearing capacity, rutting resistance, and pavement service life. Findings from Indian and international studies that employ the CBR test as the principal evaluation framework are synthesized, and Indian standards and codes relevant to reinforced-pavement design are discussed. The review identifies a persistent gap between the extensive experimental evidence for the benefits of geosynthetic reinforcement and the absence of a unified, quantitative, bearing-capacity-based design procedure that differentiates between expansive and non-expansive clay subgrade conditions, and concludes with directions for future research in this area.

Keywords— Flexible pavement, Clay subgrade, Geosynthetics, Geotextile, Geogrid, California Bearing Ratio, Subgrade reinforcement, Expansive soi.

I. INTRODUCTION

A well-connected, durable road network underpins economic growth, agricultural marketing, industrial logistics, and social development, and in India this network is increasingly extended over regions where clay forms the natural subgrade. A large proportion of the Indian landmass is underlain by clayey soils, a substantial share of which are expansive black-cotton soils concentrated in the Deccan trap region, while non-expansive clays and silts dominate large parts of the Indo-Gangetic plain and coastal alluvial tracts. Clay subgrades pose two mechanistically distinct engineering problems: expansive clays undergo pronounced seasonal swelling and shrinkage that produces heave, cracking, and loss of riding quality, while non-expansive clays suffer from low undrained shear strength and high compressibility that manifest as rutting and shear failure under repeated traffic loading. Both categories of distress are costly for rural and low-volume roads in particular, where limited engineering supervision and modest budgets amplify the consequences of premature failure.

Conventional ground-improvement measures, including full or partial replacement, chemical stabilization with lime, cement, or fly ash, and the provision of a cohesive non-swelling (CNS) cushion, can mitigate these problems but are frequently uneconomical, sensitive to field construction control, or only partially effective over the long service life expected of a modern pavement. Geosynthetic reinforcement, in the form of geotextiles and geogrids placed within or beneath the granular pavement layers, has emerged over the past four decades as a complementary and increasingly preferred approach to improving the performance of pavements founded on weak or problematic clay subgrades.

This paper reviews the literature on the mechanisms, reported performance benefits, and design implications of geosynthetic reinforcement of clay subgrades in flexible pavements, drawing together studies that use the CBR test as the principal laboratory evaluation framework. The remainder of the paper is organized as follows: Section II presents a comprehensive literature review covering the engineering behaviour of clay subgrades, the limitations of conventional treatment and design methods, the classification and mechanisms of geosynthetic reinforcement, and a synthesis of reported experimental studies, concluding with the identified research gap. Section III presents the conclusions drawn from the review, and Section IV outlines directions for future research in this area.

II. LITERATURE REVIEW

This section reviews the literature relevant to flexible pavements constructed over clay subgrades, with particular emphasis on expansive and non-expansive clay soils and the application of geosynthetic reinforcement. The review examines the engineering behaviour of clay subgrades, conventional pavement design approaches, and the mechanisms through which geotextiles and geogrids improve pavement performance, before critically reviewing previous experimental, analytical, and field investigations and identifying the research gap that motivates continued work in this area.

1. Clay Subgrades in Flexible Pavement Construction

Role of the Subgrade and Occurrence of Clay Soils in India

A conventional flexible pavement comprises a bituminous surface course, a granular base course, and, where required, a granular sub-base, all resting on the prepared subgrade. Because the granular layers derive part of their confinement and load-spreading capacity from the reaction of the underlying soil, a weak, compressible, or volumetrically unstable subgrade compromises the performance of the pavement irrespective of the quality of the layers above it. Wheel loads applied at the surface disperse through the successive layers as a widening stress bulb, so that only a fraction of the applied contact pressure is ultimately transmitted to the subgrade; thicker or stiffer granular layers therefore reduce the vertical stress increment reaching the subgrade, while thinner or weaker layers concentrate load over a smaller area and increase the risk of localized shear failure or excessive deformation. Geosynthetic reinforcement, introduced either at the base of the granular layer or within it, directly augments this load-dispersion function without requiring a proportionate increase in granular layer thickness.

Clay and clayey soils are estimated to underlie a very large part of the Indian landmass. Expansive clays, popularly termed black-cotton soils, occur extensively across Madhya Pradesh, Maharashtra, Gujarat, and parts of Rajasthan and the southern Deccan plateau, while non-expansive clays and silts dominate the Indo-Gangetic plain and low-lying coastal alluvial tracts of Odisha, West Bengal, and Kerala. Although the boundaries between these regions are gradational, clay-related subgrade problems recur across a large part of the country and affect the national highway network as well as, more acutely, the rural and district road network constructed with limited engineering supervision and budget.

Distress Mechanisms: Expansive versus Non-Expansive Clays

Expansive soils owe their behaviour to montmorillonite-group clay minerals with high specific surface area and a strong affinity for water. Moisture gain causes the clay structure to expand and generate swelling pressures that can range from tens to several hundred kilopascals depending on dry density, plasticity index, and initial moisture content; subsequent drying produces shrinkage and deep desiccation cracking. Because this cycle repeats seasonally, expansive clay subgrades are subjected to a continuing pattern of swelling and shrinkage rather than a single volume change, producing longitudinal and transverse cracking, riding-surface undulation, loss of camber, edge cracking, and shoulder drop-off, particularly during and immediately after the monsoon season.

Non-expansive clays, generally classified CI or CL, do not exhibit this volumetric instability; their principal deficiency is low undrained shear strength and appreciable compressibility, which under repeated traffic loading and elevated moisture produces progressive rutting along the wheel path and, in severe cases, localized shear or punching failure, typically appearing first at the pavement edge where confinement is weakest. Expansive soils are conventionally graded by degree of expansion using free swell index and plasticity index, providing a practical basis for triaging subgrade sections according to the reinforcement effort likely to be warranted, with the primary reinforcement mechanism differing between the two soil categories: tensioned-membrane action of a geotextile for expansive clays versus geogrid lateral restraint and reinforced-mattress action for non-expansive clays.

Climatic Influence and Economic Consequences

Both categories of distress are strongly modulated by climate, particularly the intensity and duration of the monsoon. Infiltration through pavement cracks, poorly sealed shoulders, and inadequate side drains raises subgrade moisture well above its as-compacted value, triggering swelling in expansive soils and strength loss in non-expansive soils alike; reported pavement distress is consequently concentrated during and shortly after the peak monsoon months. This has two implications for design: methodology should account for the worst-case, monsoon-saturated condition rather than the as-compacted condition typically used in routine CBR testing, and drainage detailing together with the moisture-retarding function of any geosynthetic layer assumes importance beyond its purely structural role.

Economically, frequent maintenance after distress disrupts traffic, raises vehicle operating costs, and, on rural roads, can seasonally isolate communities from markets and services.

Because pavement-thickness reductions achieved reliably through reinforcement translate into savings across a very large network of rural roads built with limited budgets, the literature reviewed here consistently reports a favourable trend in life-cycle cost once thickness savings and reduced maintenance frequency are taken into account, notwithstanding the modest additional cost of the reinforcement material itself.

2. Limitations of Conventional Subgrade Treatment and CBR-Based Design

Conventional Ground-Improvement Techniques

Historically, deficiencies in clay subgrades have been addressed through full or partial soil replacement, chemical stabilization with lime, cement, or fly ash, cohesive non-swelling cushioning, and pre-wetting or surcharging ahead of construction. Soil replacement is often uneconomical where suitable borrow material is distant; stabilization performance is sensitive to field mixing and compaction control and can degrade under repeated wetting–drying cycles; CNS cushioning typically requires a large layer thickness, of the order of 600–1000 mm, entailing substantial earthwork; and pre-wetting is time-consuming and difficult to control uniformly. None of these techniques offers a universally reliable, economical, and easily constructible solution across the full range of clay conditions encountered in India, and in practice several are used in combination with geosynthetic reinforcement rather than as a substitute for it.

Shortcomings of the CBR-Based Empirical Design Method

The CBR method remains the most widely used procedure for determining flexible pavement thickness in India, correlating pavement thickness with the soaked CBR of the subgrade and the design traffic. While computationally simple and well calibrated for granular and moderately plastic subgrades, it was not developed with the volumetric and shear-strength complexities of expansive clays in mind. The soaked CBR test captures subgrade strength only at a single, arbitrarily defined moisture condition and does not account for the swelling pressure that develops when a confined expansive soil is subsequently wetted; it provides no direct mechanism for evaluating differential heave, desiccation cracking, or long-term cyclic degradation of subgrade support; and, because design thickness is derived purely from an empirical CBR–traffic correlation, resulting sections over highly plastic clays are frequently either uneconomically conservative or inadequate against observed rutting and shear failure. The framework also offers no explicit provision for the beneficial contribution of reinforcement, since tensioned-membrane and confinement mechanisms were not contemplated in the original empirical correlations.

Relevant Indian Standards and Codes of Practice

Design and construction of flexible pavements over clay subgrades in India is governed by a combination of Bureau of Indian Standards soil-testing procedures, including IS 1498 for soil classification [3] and IS 2720 (Part 16) for CBR determination [4], and Indian Roads Congress design guidelines, principally IRC:37 for the empirical design of unreinforced flexible pavements [15] and IRC:SP:59 for qualitative guidance on geotextile selection and placement [16]. While these codes provide the regulatory and procedural basis for conventional design and materials testing, none currently offers a fully quantitative, safe-bearing-capacity-based design procedure that explicitly incorporates the reinforcing contribution of geotextiles or geogrids over expansive or non-expansive clay subgrades.

3. Geosynthetics in Pavement Engineering

Classification and Functions

Geosynthetics are planar polymeric products manufactured specifically for geotechnical and pavement applications. Since their introduction into civil engineering practice in the 1970s [5], they have evolved from simple separation layers into engineered reinforcement elements. Woven geotextiles, formed from interlaced polypropylene or polyester yarns, provide separation, filtration, and tensioned-membrane reinforcement; non-woven geotextiles, bonded or needle-punched polymer filaments, are used mainly for separation, filtration, and drainage; uniaxial geogrids, extruded and stretched in one direction, provide high tensile reinforcement for embankments and walls; biaxial and triaxial geogrids, with apertures in two or three directions, provide lateral restraint and interlock with base aggregate; geocells form three-dimensional honeycomb cellular confinement; and geocomposites combine a geotextile with a geogrid or drainage core to deliver separation, filtration, drainage, and reinforcement in a single product.

Tensioned Membrane Action of Geotextiles

When placed at the interface between a soft clay subgrade and the overlying granular layer, a geotextile performs separation, filtration/drainage, and reinforcement functions simultaneously [6]. As the subgrade beneath a wheel load deforms into a shallow depression, the geotextile, anchored on either side of the loaded zone, stretches into a curved shape and develops tensile stress in its plane; the vertical component of this tensile stress acts upward against the applied load, reducing the net stress transmitted to the subgrade and permitting a reduction in pavement thickness for a given rutting or deformation criterion. This mechanism, generally termed tensioned membrane action, is the dominant reinforcement mechanism attributed to woven geotextiles in the literature.

Reinforced Mattress Action of Geogrids

Geogrids are not primarily filtration elements; their reinforcing action depends on mechanical interlock with surrounding aggregate. When placed within or beneath a granular base, aggregate particles penetrate and interlock within the geogrid apertures, restraining lateral aggregate movement under traffic loading [7], [8]. This lateral-restraint mechanism increases the effective shear strength and stiffness of the reinforced granular layer, enabling it to spread applied wheel loads over a wider area of the underlying subgrade, commonly termed the reinforced-mattress or soil-mattress effect, and also raises bearing capacity by forcing the potential shear-failure surface deeper into stronger soil, with a secondary tensioned-membrane contribution developing once appreciable deformation has occurred.

Geocells, Geocomposites, and Durability

Geocells extend the interlock principle of geogrids into three dimensions, confining infill aggregate on all sides; accelerated pavement testing has shown geocell confinement to be particularly effective in controlling surface deformation over weak or saturated subgrades [11]. Geocomposites combine separation, filtration, drainage, and mechanical reinforcement in a single product where more than one geosynthetic function is required but installing separate layers is impractical. The long-term effectiveness of any geosynthetic layer depends on durability under installation and in-service conditions: buried geosynthetics are susceptible to mechanical damage during compaction of the overlying layer, to creep under sustained load, and, to a lesser extent, to chemical or biological attack depending on soil chemistry; manufacturers therefore specify reduction factors for installation damage, creep, and durability when converting index tensile strength to an allowable long-term design strength, and these reduction factors should be applied consistently in any reinforced-pavement design procedure.

4. Review of Experimental Studies on Geosynthetic-Reinforced Clay Subgrades

A substantial body of laboratory, test-track, and limited field research has quantified the performance benefits of geosynthetic reinforcement over weak or problematic subgrades, with the CBR test the most consistently adopted evaluation framework in Indian and comparable international practice. Table I summarizes representative studies of direct relevance, spanning early foundational work on geogrid-reinforced sections through to recent Indian investigations using the woven geotextile and biaxial geogrid products most commonly specified in practice.

Table 1: Summary of Representative Studies on Geosynthetic-Reinforced Subgrades

Study	Reinforcement / Subgrade	Reported Finding
Al-Qadi & Brandon (1988) [8]	Geogrid over soft clay subgrade	Increased bearing capacity; reduced settlement and improved load distribution
Zornberg et al. (2003) [9]	Geotextile and geogrid over weak clayey subgrades	Enhanced subgrade confinement; reduced rutting; increased service life
Giroud & Han (2004) [10],[11]	Geogrid-reinforced unpaved/lightly paved sections	Mechanistic–empirical prediction of reduced rutting with reinforcement
Pokharel et al. (2011) [12]	Geocell and geogrid, accelerated pavement testing	50–70% lower surface deformation than unreinforced sections
Indraratna et al. (2018) [13]	Geosynthetic-reinforced granular base, cyclic triaxial testing	Improved stress distribution; reduced subgrade shear failure under cyclic loading
Pupalwad et al. (2019) [24]	Woven/nonwoven geotextiles (TS-50, PEC, HP-370) on silty expansive clay	Shallower placement gave greater CBR gain; woven geotextiles outperformed nonwoven
Rajesh et al. (2016) [25]	Geogrids of varying aperture size on soft subgrade	Plasticity and fines content strongly influenced improvement; poorest soils gained most
Ramjiram Thakur et al. (2021) [26]	Nonwoven geotextile on high-plasticity clay (CH)	CBR improved consistently; degree dependent on thickness and number of layers
Aga (2021) [20]	PP and HDPE geogrids on expansive black soil	Both geogrids raised soaked CBR; PP geogrid outperformed HDPE
Tiwari & Satyam (2022) [27]	Polypropylene fibre + geogrid on expansive subgrade	Combined fibre and geogrid raised interface shear strength and UCS substantially
Balamaheswari et al. (2022) [21]	Anchored vs. conventional geogrid on weak subgrade	Anchored geogrid gave greater CBR

Study	Reinforcement / Subgrade	Reported Finding
		improvement at its optimum depth
Banyhussan et al. (2025) [22]	Waste foundry sand + biaxial geogrid on clay subgrade	CBR and interface shear strength rose with waste-sand content; interaction coefficient > 1
Harshitha et al. (2025) [23]	Biaxial geogrid on fine-grained and expansive soils	CBR rose significantly for fine-grained soil; expansive soil needed extra stabilization

Taken together, the studies summarized above indicate three consistent themes. First, both woven and non-woven geotextiles have been repeatedly shown to improve the CBR of clay subgrades, with the degree of improvement depending on geotextile type, placement depth, and soil plasticity; shallower placement within the compacted specimen and a woven rather than non-woven construction generally produce a greater gain [20], [24]. Second, biaxial geogrids consistently improve CBR through an aggregate-interlock and confinement mechanism, with the degree of improvement sensitive to placement depth, geogrid stiffness, and supplementary features such as anchorage [21], [25]. Third, expansive clay subgrades generally respond differently to reinforcement than non-expansive or fine-grained subgrades, often requiring either a favourable placement depth or a supplementary stabilization measure, such as fibre inclusion or waste-material blending, to realize the full benefit of geosynthetic reinforcement [22], [23], [27].

5. Research Gap

The literature reviewed in the preceding sections establishes three consistent conclusions. First, both expansive and non-expansive clay subgrades impose distinct, mechanistically different forms of distress on flexible pavements, neither of which is adequately captured by the soaked-CBR strength parameter alone [1], [2]. Second, conventional ground-improvement techniques, while sometimes effective, are frequently uneconomical or unreliable over the long service life expected of a modern road pavement. Third, geosynthetic reinforcement using geotextiles and geogrids has been repeatedly and independently demonstrated, across laboratory, test-track, and limited field studies, to reduce pavement thickness requirements and to improve resistance to rutting, heave, and shear failure [8]–[13].

Notwithstanding this convergence of evidence, the translation of these findings into a routine, code-embedded design procedure for flexible pavements over Indian clay subgrades remains incomplete. Existing Indian guidance, whether the CBR-based empirical procedure of IRC:37 [15] or the qualitative recommendations of IRC:SP:59 [16], stops short of a fully quantitative, safe-bearing-capacity-based methodology that explicitly incorporates reinforcement effects for both expansive and non-expansive clay conditions. It is also apparent from the literature that expansive and non-expansive clay subgrades, despite both falling under the general heading of problematic clay soils, warrant distinct reinforcement strategies rather than a single, undifferentiated design procedure: the swelling-dominated behaviour of expansive clay is most directly addressed through the tensioned-membrane action of a geotextile layer placed to control differential heave, whereas the strength- and compressibility-dominated behaviour of non-expansive clay is more directly addressed through the lateral-restraint and load-spreading action of a geogrid-reinforced granular mattress. No published study has yet developed and validated separate reinforced-pavement design procedures for expansive (CH) and non-expansive (CI/CL) clay subgrades within a unified framework compatible with current Indian pavement design practice.

III. CONCLUSION

Clay subgrades, whether expansive or non-expansive, remain one of the principal sources of premature distress in flexible pavements, and conventional ground-improvement techniques and the CBR-based empirical design method in current Indian use address this problem only partially. The reviewed literature demonstrates consistently, across laboratory, test-track, and limited field investigations, that woven geotextiles and biaxial geogrids improve the bearing capacity of clay subgrades through tensioned-membrane action and reinforced-mattress action respectively, and that the resulting improvement can be translated into reduced pavement thickness, better rutting resistance, and a longer service life.

The magnitude of improvement is sensitive to reinforcement type, placement depth, and subgrade plasticity, and expansive clays appear to require different reinforcement strategies from non-expansive clays. The principal gap identified in this review is the absence of a unified, quantitative, safe-bearing-capacity-based design procedure that explicitly incorporates these reinforcement effects for both categories of clay subgrade within current Indian pavement design practice, an objective that motivates continued experimental and design-oriented research in this area.

Future Scope

Although the reviewed literature establishes the general effectiveness of geosynthetic reinforcement for clay subgrades, several directions merit further research attention. Full-scale or accelerated pavement testing is needed to validate laboratory CBR-based findings under actual traffic loading conditions, since laboratory specimens cannot fully replicate field compaction, drainage, and loading variability. The behaviour of geosynthetic-reinforced subgrades under repeated cyclic loading warrants further investigation to better simulate long-term traffic effects and to predict rutting progression over the design life of a pavement.

The influence of multiple reinforcement layers and varying reinforcement spacing on pavement performance remains comparatively under-studied relative to single-layer configurations, and further evaluation of other geosynthetic products, including nonwoven geotextiles, triaxial geogrids, geocells, and geocomposites, alongside the woven geotextiles and biaxial geogrids most commonly reported, would broaden the evidence base available to designers. Numerical modelling using finite element software such as Abaqus or PLAXIS could usefully simulate stress distribution and reinforcement mechanisms in combination with physical testing, while the long-term durability and environmental performance of geosynthetic reinforcement under varying climatic conditions, particularly repeated monsoon wetting and drying, also requires further field-oriented study.

Cost-benefit and life-cycle cost analyses are needed to place the indicative economic trends discussed in this review on a firmer quantitative footing. Finally, extending the evidence base to a wider range of soil types, including additional expansive, silty, and sandy subgrades, would help generalize design recommendations beyond the specific soil conditions examined in individual studies, and would support the development of the unified, bearing-capacity-based design procedure identified as the principal research gap in this review.

REFERENCES

1. Holtz, W. G., & Gibbs, H. J. (1956). Engineering properties of expansive clays. Transactions of the American Society of Civil Engineers, 121, 641–663.
2. Chen, F. H. (1975). Foundations on expansive soils. Elsevier.
3. Bureau of Indian Standards. (1970). IS 1498: Classification and identification of soils for general engineering purposes. BIS.
4. Bureau of Indian Standards. (1987). IS 2720 (Part 16): Methods of test for soils — Laboratory determination of California Bearing Ratio (CBR). BIS.
5. Barenberg, E. J., Anderson, K. A., & Lamb, D. (1975). Evaluation of fabrics in asphalt pavements. University of Illinois.
6. Giroud, J. P., & Noiray, L. (1981). Geotextile-reinforced unpaved roads. Journal of the Geotechnical Engineering Division, ASCE, 107(9), 1233–1254.
7. Al-Qadi, I. L., & Brandon, T. L. (1988). Laboratory evaluation of geogrid-reinforced pavement sections. Transportation Research Record.
8. Zornberg, J. G., Christopher, B. R., & Canéla, A. (2003). Geosynthetics in pavements: North American contributions. Geosynthetics International, 10(4), 97–122.
9. Giroud, J. P., & Han, J. (2004). Design method for geogrid-reinforced unpaved roads. Part I: Development of design method. Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 775–786.
10. Giroud, J. P., & Han, J. (2004). Design method for geogrid-reinforced unpaved roads. Part II: Calibration and applications. Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 787–797.
11. Pokharel, S. K., Han, J., Leshchinsky, D., & Parsons, R. L. (2011). Performance of geocell-reinforced bases under dynamic loading. Geotextiles and Geomembranes, 29(5), 377–388.
12. Indraratna, B., Ngo, T., Rujikiatkamjorn, C., & Vinod, J. S. (2018). Behaviour of geosynthetic-reinforced granular layers under cyclic loading. Engineering Geology, 235, 34–48.
13. Zornberg, J. G. (2017). Functions and applications of geosynthetics in roadways. Procedia Engineering, 189, 298–306.
14. Katti, R. K. (1978). Search for solutions to problems in black cotton soils. Indian Geotechnical Society.
15. Indian Roads Congress. (2018). IRC:37-2018: Guidelines for the design of flexible pavements. IRC.
16. Indian Roads Congress. (2002). IRC:SP:59-2002: Guidelines for the use of geotextiles in road pavements and associated works. IRC.
17. American Association of State Highway and Transportation Officials. (1961). The AASHTO Road Test: Report on pavement research. National Academy of Sciences.
18. The Asphalt Institute. (1962). Thickness design of flexible pavements. The Asphalt Institute.
19. Ministry of Road Transport and Highways. (2023). Basic Road Statistics of India. Government of India.

20. Aga, S. Y. (2021). Physical stabilization of expansive subgrade soil using locally produced geogrid material. SN Applied Sciences, 3(5), 568.
21. Balamaheswari, M., Anitha, B., Kanimozhi, B., & Prabhu, N. (2022). Improvement of California bearing ratio value in weak subgrade soil with the developed anchored geogrid. Materials Today: Proceedings, 49, 1537–1542.
22. Banyhussan, Q. S., Abdulrazzaq, J., Hussein, A. A., Dulaimi, A., Andrade, J. M. A., & Bernardo, L. F. A. (2025). Stabilization of clay subgrade soil by using waste foundry sand with a geogrid. CivilEng, 6(2), 26.
23. Harshitha, M., Kumar, R., Vidyashree, J. C., Agrawal, U., & Sathvik, S. (2025). Investigating the impact of biaxial geogrid reinforcement on subgrade soil strength enhancement: A machine learning analysis using the MARS model. Indian Geotechnical Journal.
24. Pupalwad, A. S., Padmavathi, M., Ravikumar, K., & Nagaraju, M. (2019). An experimental study on CBR of expansive soil subgrades using geotextiles. International Journal of Civil and Structural Engineering Research, 7(1).
25. Rajesh, U., Sajja, S., & Chakravarthi, V. K. (2016). Studies on engineering performance of geogrid reinforced soft subgrade. Transportation Research Procedia, 17, 164–173.
26. Ramjiram Thakur, S., Naveen, B. P., & Tegar, J. P. (2021). Improvement in CBR value of soil reinforced with nonwoven geotextile sheets. International Journal of GeoEngineering, 12, 8.
27. Tiwari, N., & Satyam, N. (2022). An experimental study on strength improvement of expansive subgrades by polypropylene fibers and geogrid reinforcement. Scientific Reports, 12(1), 6685.