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# STRUCTURAL PERFORMANCE ASSESSMENT OF ECOLOGICALLY STABILIZED ROAD LAYERS

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***Abstract***

*The long-term durability and structural integrity of stabilised layers are essential for sustainable infrastructure. Eco-friendly materials that utilise environmentally friendly binders and additives have the potential to improve mechanical performance while minimising environmental impact. Assessing the effectiveness of these materials requires a thorough framework that considers various parameters impacting mechanical stability, thermal resistance, and load-bearing capacity. A performance index (PI) approach is used to assess the structural performance of stabilised layers, incorporating a catalyst to enhance the bitumen-aggregate interface within the bitumen matrix and modifying physicochemical reactions during operation. Key mechanical and physical parameters - including compressive strength, degree of compaction, load-bearing capacity, dynamic modulus, and resistance to mechanical and thermal stresses - were measured or estimated for the stabilised layers. Compared to baseline or minimally compliant layers, the calculated PI showed a significant improvement in overall structural integrity. This reflects enhanced load transfer, stiffness, and durability. These findings support the adoption of environmentally sustainable stabilisation techniques as reliable alternatives for infrastructure applications, providing long-term performance.*

***Key words****: eco-friendly materials, performance, stabilisation, sustainable.*

## INTRODUCTION

In recent years, growing concerns about environmental impact have prompted the development of alternative solutions for stabilizing road infrastructure. Ecologically stabilized road layers aim to reduce the carbon footprint by utilizing biological binders, recycled materials, low-carbon additives, and innovative physicochemical modification processes. These solutions seek to achieve mechanical performance that is comparable to that of conventional cement or lime-treated materials, all while simultaneously lowering energy consumption and greenhouse gas emissions (Consoli et al., 2009; Puppala, 2016; Behnood, 2018). Organosilane additives can enhance the performance of unbound layers by increasing moisture resistance (Barbieri et al., 2019; 2021). They also emphasize the benefits of lignin in stabilizing clayey soils, which can improve stiffness (Vaiana et al., 2021). The use of biopolymers for stabilization has been shown to increase strength and enhance compaction (Cabalar et al., 2023). Additionally, polymer additives have been found to reduce the deformation potential of expansive soils (Liu et al., 2025). Ecological additives used as cement substitutes designed in the process of stabilizing cohesive, non-cohesive materials and aggregates are not directly comparable in terms of their composition or mechanisms of action. Other studies (Radu et al., 2015; Saca et al., 2024; Ionescu & Dobre, 2025) indicate that the mechanical properties of materials are closely related to the composition of the mixture and the ratios between the components, which in turn influence the material's mechanical strength and structural behaviour.

While various methodologies for incorporating alternative materials into stabilization projects have been suggested over the years, there remains a critical need for a systematic evaluation of structural performance (Dobrescu,

2017). Additionally, the analysis of parametric correlations between California Bearing Ratio (CBR) and other geotechnical parameters underscores the significance of a multi-parameter evaluation (Dobrescu, 2017). Therefore, a meaningful comparison can only be made using functional and structural performance indicators, such as stiffness, load-bearing capacity, resistance to deformation, and long-term durability under various traffic and environmental conditions. These indicators can be integrated into a Performance Index (PI), which reflects the overall efficiency of the pavement system, rather than the individual properties of the materials. In this context, the comparison between a hydraulic binder and a organic binder should be interpreted as a comparison between two technological solutions that enhance the performance of the road structure, rather than as a comparison between two materials with identical functions. However, without an integrated evaluation framework, it becomes challenging to make an objective comparison between conventional and eco-friendly solutions. Thus, the study proposes a weighted aggregation method that integrates the mechanical characteristics of stabilized road layers into a synthetic parameter, called performance index. The calculated performance index allows a comparative evaluation of conventional (hydraulic binder)/ecological (organic binder) solutions used for stabilizing road layers.

## MATERIALS AND METHODS

In this study, for the stabilization of the road layer, a hydraulic road binder based on Portland cement (HB) and an organic binder (OB) with a lignosulfonate structure (calcium – CLS, respectively sodium – SLS) were used. CLS is an anionic polymer, extracted from sulfite liquors resulting from cellulose production, water-soluble, with a molecular weight ranging between 2000-100000 and a three-dimensional structure. SLS is an anionic polymer obtained from the semicellulose production stream from wood through the NSSC process (neutral sulfite semichemical process).
The functional group in lignosulfonates are represented in Figure 1.

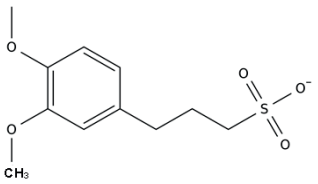



Figure 1. Representative structure of a lignosulfonate molecule showing polar functional groups (–$SO_3^-$, –OH) and the nonpolar hydrocarbon chain (Moldovan, 1978)

Their molecule is composed of polar groups such as –$SO_3^-$ and –OH, and a group of atoms linked by covalent bonds forming the hydrocarbon chain with a nonpolar character, such as $C_6H_4$– and $CH_3$–.
The following figure (Figure 2), illustrates the primary application principles of two approaches: the stabilization of soil and granular materials using lignosulfonates.

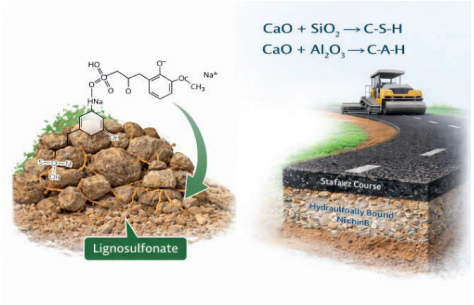



Figure 2. Ecologically stabilised road layers (adapted from Mostafa et al., 2024; Jiang et al., 2021; Yang et al., 2025)

The stabilization of road layers with organic binders consists in their fixation by adsorption onto the surface of solid particles (clay, sand, ballast), forming a layer between particles that reduces the repulsive forces between them and results in their agglomeration.
On the other hand, the polar groups act as molecular bridges, leading to the formation of a three-dimensional structure that enhances cohesion, while the hydrophobic hydrocarbon chain creates a barrier against water penetration. In addition, $Ca^{2+}$ ions contribute to compressing the diffuse double layer and reduce the repulsion between particles through ion-exchange reactions with $Na^+$ ions on the surface of clay particles (Shiyuan et al., 2025).

The stabilization with hydraulic road binders involves mineral reactions between calcium oxide (CaO), silicon dioxide ($SiO_2$), and aluminum oxide ($Al_2O_3$), resulting in the formation of cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H).

The differences between the stabilisation mechanisms and their associated structural effects are summarised (Table 1).

A performance index (PI) is established based on four key parameters that reflect the behaviour of the treated or stabilized layer: the degree of compaction (D), the California Bearing Ratio (CBR), the static linear deformation modulus, determined in situ using the static plate (Lucas) test and calculated from the second loading (Ev2), respectively, the 28-day compressive strength ($Rc_{(28)}$) (equation1).

These indicators describe complementary aspects of structural performance, namely the degree of compaction, load-bearing capacity, stiffness, and mechanical strength of the stabilized material. The methodological framework used to evaluate these parameters and to determine the performance index is presented (Figure 3).

Table 1. Comparative analysis of the mechanisms and structural effects of hydraulic road binders and ecological additives used in the pavement system

| Stage | Hydraulic binder | Organic binder |
|---|---|---|
| Product incorporation | Hydraulic road binder incorporated into soil/aggregate mixtures with water | Additive incorporated into soil structure |
| Primary mechanism | Hydration reactions of hydraulic compounds | Modification of the aggregate interface |
| Microstructural process | Formation of cementitious hydration products (C–S–H, C–A–H) | Reduction of interfacial tension and enhancement of binder–aggregate adhesion |
| Structural modification | Particle cementation and development of a rigid structural matrix | Improved and more uniform distribution of aggregate surfaces |
| Mechanical effects | Increase in stiffness of the stabilized layer | Increase in stability of the soil mixture |
| Affected technical parameters | Ev2 ↑, CBR ↑, Rc ↑ | Mechanical properties ↑ |
| Level of action within the pavement structure | Subgrade or stabilised base layer | Soil layers |
| Structural impact | Increase in structural bearing capacity | Improvement in soil durability and stability |
| Overall outcome | Contributes to an increase in the PI | |

$$PI = w_D \cdot S_D + w_{CBR} \cdot S_{CBR} + w_{Ev2} \cdot S_{Ev2} + w_{Rc} \cdot S_{Rc}$$

where:

- $PI$ – global performance index;
- $w_D$, $w_{CBR}$, $w_{Ev2}$, $w_{Rc28}$ – weights associated with each indicator;
- $w_i D_j + w_i CBR_j + w_i Ev2_j + w_i Rc_j = 1$
- $S_D$, $S_{CBR}$, $S_{Ev2}$, $S_{Rc28}$ – normalized values of the indicators.

The weights are assigned based on the significance of each indicator in assessing pavement layer performance. While the PI provides a comprehensive assessment, its interpretation must be linked with the specific values of the parameters being analysed.

This correlation helps identify the technical advantages of each solution. The data were normalised by using the maximum value, resulting in a range between 0 and 1.

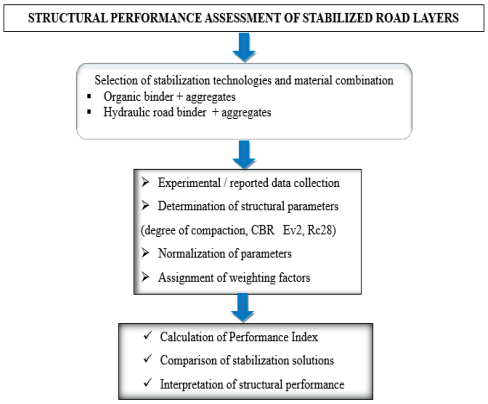



Figure 3. Road Layer Performance Framework (developed by the authors)

## RESULTS AND DISCUSSIONS

To evaluate the mechanical behavior of stabilized materials used in pavement structures, geotechnical parameters were analyzed to assess the performance of the stabilized material. The results are presented in Table 2. Overall, they indicate a general correlation between CBR, $Ev_2$, and $Rc_{28}$, demonstrating a simultaneous increase in bearing capacity, stiffness, and mechanical strength. This relationship suggests that improvements in the stabilization process contribute not only to enhanced load distribution and reduced deformation under traffic loading but also to a more durable pavement foundation. Furthermore, the observed correlation indicates that CBR and $Ev_2$ may serve as practical

indicators of the long-term strength development of the stabilized material, facilitating quality control during construction.

Table 2. Mechanical parameters

| Mixture | D (%) | CBR (%) | Ev2 (MPa) | Rc28 (MPa) |
|---|---|---|---|---|
| Aggregate layer+ SLS | 98.0 | 166.21 | 93.22 | 0.79 |
| Aggregate layer +CLS | 98 | 178.79 | 104.27 | 0.85 |
| Clayey soil + 5% HB | 99.0 | 80 | 160 | 1.24 |
| Sandy soil + HB | 99.0 | 150 | 195 | 2.25 |
| Ballast + 3 % HB | 99.0 | 180 | 300 | 2.49 |
| *Reference values* | *100* | *170* | *350* | *4.0* |

A sensitivity analysis of the performance index was performed by varying the weights associated with the mechanical parameters (Table 3), and the corresponding results are presented in Tables 4a and 4b.

Table 3. Weighting scenarios for the parameters used in the Performance Index calculation

| Scenario | w(D) | w(CBR) | w(Ev2) | w(Rc28) |
|---|---|---|---|---|
| S0 – Current weighting | 0.20 | 0.10 | 0.40 | 0.30 |
| S1 – Balanced weighting | 0.25 | 0.25 | 0.25 | 0.25 |
| S2 – CBR emphasis | 0.15 | 0.40 | 0.25 | 0.20 |
| S3 – $Ev_2$ emphasis | 0.15 | 0.10 | 0.55 | 0.20 |
| S4 – $\sigma_{28}$ emphasis | 0.15 | 0.10 | 0.20 | 0.55 |
| S5 – Compaction emphasis | 0.50 | 0.10 | 0.20 | 0.20 |
| S6 – Mechanical performance emphasis | 0.10 | 0.20 | 0.35 | 0.35 |
| S7 – Subgrade-oriented scenario | 0.30 | 0.30 | 0.20 | 0.20 |
| S8 – Stiffness and strength emphasis | 0.10 | 0.10 | 0.40 | 0.40 |
| S9 – CBR and compaction emphasis | 0.35 | 0.35 | 0.15 | 0.15 |
| S10 – $Ev_2$ dominant | 0.10 | 0.05 | 0.65 | 0.20 |

Table 4a. Multicriteria evaluation scenarios based on the mechanical parameters of the analysed materials

| Solution | S0 | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|---|
| Aggregate layer+ SLS | 0.460 | 0.605 | 0.628 | 0.479 | 0.375 | 0.670 |
| Aggregate layer +CLS | 0.484 | 0.636 | 0.665 | 0.507 | 0.396 | 0.683 |
| Clayey soil + 5% HB | 0.521 | 0.557 | 0.567 | 0.527 | 0.460 | 0.653 |
| Sandy soil + HB | 0.678 | 0.748 | 0.761 | 0.717 | 0.674 | 0.827 |
| Ballast + 3% HB | 0.834 | 0.882 | 0.917 | 0.857 | 0.838 | 0.905 |

The scenarios presented in Table 4b highlight the relative influence of the mechanical parameters on the overall performance ranking of the analyzed materials.

Table 4b. Multicriteria evaluation scenarios based on the mechanical parameters of the analyzed materials

| Solution | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|
| Aggregate layer+ SLS | 0.439 | 0.680 | 0.384 | 0.755 | 0.360 |
| Aggregate layer +CLS | 0.466 | 0.718 | 0.404 | 0.788 | 0.387 |
| Clayey soil + 5% HB | 0.414 | 0.678 | 0.436 | 0.626 | 0.482 |
| Sandy soil + HB | 0.655 | 0.861 | 0.704 | 0.823 | 0.618 |
| Ballast + 3% HB | 0.802 | 0.972 | 0.831 | 0.939 | 0.834 |

The Performance Index values indicate that all the stabilization solutions examined enhance the structural performance of the subgrade layer compared to the reference level (Figure 4). The graphical representation of the Performance Index highlights a consistent ranking of the stabilization solutions across different weighting scenarios.

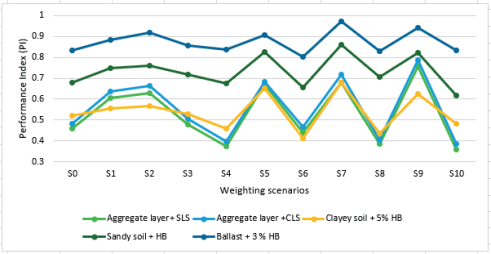



Figure 4. Sensitivity analysis of the PI for the investigated stabilization solutions under different weighting scenarios

The ballast stabilized with hydraulic binder exhibits the highest performance in all cases, followed by sandy soil stabilization. In contrast, clayey soil shows the lowest performance values, reflecting its weaker mechanical behaviour even after stabilization (realistic for cohesive soils). It is important to note that the values presented in the table are not absolute; they stem from a specific normalisation and weighting methodology. If the reference values, normalisation method, representative interval values, or criteria weights are adjusted, the scores and the PI may change. Nevertheless, the general trend in the performance of the analysed solutions is likely to remain consistent.

## CONCLUSIONS

The current study aimed to identify the key mechanical and physical parameters that influence the structural behaviour of stabilised formation layers and to evaluate the impact of various stabilisation methods. Additionally, a

normalized performance index was developed to facilitate consistent comparisons between different stabilization solutions.

The sensitivity analysis conducted with varying weighting scenarios revealed that the combination of ballast + HB consistently achieved the highest performance index (PI) values. This indicates a robust structural performance, irrespective of the relative importance assigned to individual parameters. In contrast, the sandy soil combined with HB exhibited intermediate performance with relatively stable results. Meanwhile, the clayey soil stabilized with 5% HB and lignosulfonate compounds + aggregates showed greater variability depending on the weighting configuration.

This approach serves as a valuable tool for the comparative assessment of stabilization strategies, supporting decision-making in the design and optimization of pavement foundation layers. Future work may refine the weighting methodology and extend the proposed framework to include additional materials, different environmental conditions, and long-term performance indicators.

Also, integrating experimental results and monitoring data into a digital environment based on Building Information Modeling (BIM) and Structural Health Monitoring (SHM) enables the upgrading of traditional infrastructure databases into more advanced and dynamic information systems (Dobre et al., 2025). Through this approach, data related to mechanical behavior, degradation processes, and long-term performance of road layers can be continuously collected, managed, and analyzed. The BIM model acts as a central platform for integrating SHM data and supports the development of a digital twin of the road structure. This synergy improves long-term performance evaluation, facilitates predictive maintenance strategies, and supports the implementation of more sustainable road engineering solutions.

Integrating multicriteria performance assessment with digital monitoring and modelling technologies offers a promising approach to creating more efficient, resilient, and sustainable road infrastructure systems.

The implementation of these products addresses several critical challenges, including the inadequate technical condition of existing road infrastructure, the environmental impact associated with infrastructure development, and the high costs of operation and maintenance of transport systems. In this context, the development of sustainable pavement solutions is further constrained by the poor mechanical behavior of locally available or problematic soils, such as expansive soils, which limits their direct use in structural road layers. Therefore, it is essential to evaluate the effectiveness of ecological stabilization techniques in improving the structural performance, load-bearing capacity, and long-term durability of these materials, enabling their integration as functional components in sustainable pavement systems (Barmade et al., 2023). Another important research direction related to the structural performance assessment of ecologically stabilized road layers involves the characterization of their time-dependent mechanical behaviour under traffic loading. Since such materials-particularly those incorporating stabilized soils or biocomposites based on agro-industrial by-products (Popa et al., 2023; 2025) often exhibit viscoelastic properties, their response cannot be fully described using purely elastic models. In this context, the application of rheological models, such as the Zener viscoelastic model (Bratu, 2020), becomes essential for evaluating their dynamic response under harmonic excitation, enabling a more realistic prediction of their in-service performance.

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