

Structural Integrity Characterization of Chemically Stabilized Full-Depth Reclamation Base Layers

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ABSTRACT: Base stabilization is a crucial process for enhancing the structural condition of pavements by improving key engineering properties such as shear strength, durability, and stiffness modulus. This technique addresses challenges associated with weak or problematic soils, extending roadway service life and improving resilience against vehicular loads and environmental variations. A field investigation and a construction project were conducted on CSAH-14 in Wright County, Minnesota, to evaluate the effectiveness of various proprietary additives in stabilizing a Full-Depth Reclamation (FDR) base layer. In 2021, five test sections were constructed: four sections stabilized with additives - three ionic stabilizers and one enzyme-based product—and one untreated control section. The Minnesota Department of Transportation (MnDOT) conducted periodic Falling Weight Deflectometer (FWD) testing to monitor the long-term structural integrity of the stabilized sections. FWD data collected during October 2024, and April 2025 will be analyzed to backcalculate the elastic moduli (stiffness) of individual pavement layers based on pavement deflection measurements. The primary objective of this research is to estimate the elastic modulus of the underlying Full-Depth Reclamation (FDR) base layer and other pavement layers using multiple backcalculation software, including ELMOD, BAKFAA, and MODULUS. This study also sought to compare the performance and accuracy of these tools in evaluating pavement structural properties.

KEYWORDS: Backcalculation, Full-Depth Reclamation (FDR), Base stabilization, Proprietary additives, Falling Weight Deflectometer (FWD), Elastic Modulus and stiffness.

1 INTRODUCTION

When foundation layers of pavements do not provide enough support, several improvement methods can be used (Chauhan et al., 2008). One common method is to remove and replace the weak soil, but this process can be costly and difficult, especially when good-quality replacement materials must be brought from outside the area (Abu-Farsakh et al., 2015; Senol et al., 2006). Traditional stabilizers like lime, fly ash, and Portland cement are widely used to improve the properties of local soils through physical or chemical processes, but their effectiveness depends on the type of soil (Little and Nair, 2009). Base stabilization helps improve the strength and performance of road foundations, especially in weak or frost-prone soils, by increasing important characteristics such as shear strength, durability, fatigue resistance, and stiffness. Stabilizers can be grouped into two types: non-proprietary materials such as cement, fly ash, lime, asphalt emulsion, recycled materials; and proprietary commercial products. While many studies have been done on non-proprietary stabilizers, more research is still needed to fully understand how proprietary products perform in both lab and field settings.

Backcalculation is a fundamental nondestructive technique used in pavement engineering to estimate the in-situ elastic moduli of pavement layers based on surface deflection data collected from a Falling-Weight Deflectometer (FWD). The FWD simulates traffic loading by applying a transient load to the pavement surface and measuring the resulting deflection basin using geophones placed at various offsets. These measured deflections are then compared with theoretical deflections computed from a forward model based on layered elastic theory. Through an iterative optimization process, the elastic moduli of each layer are adjusted until the computed deflections closely match the measured ones. As an inverse problem, backcalculation can yield multiple valid solutions, making it necessary to validate results with engineering judgment and known material properties. Various software tools such as ELMOD, BAKFAA, and MODULUS use numerical algorithms to implement this approach.

The objective of this study is to comprehensively evaluate structural performance of Full-Depth Reclamation (FDR) base layers stabilized with various proprietary additives by

estimating the elastic moduli of individual pavement layers using Falling Weight Deflectometer (FWD) data. This study aims to assess and compare the effectiveness of multiple backcalculation software tools - ELMOD, BAKFAA, and MODULUS - in determining pavement layer stiffness. By analyzing FWD-derived deflection basin parameters (e.g., Maximum Deflection, Surface Curvature Index, Base Damage Index, and Base Curvature Index), the research also seeks to quantify the long-term impact of stabilization treatments on pavement resilience and durability.

2 FIELD SITE DESCRIPTION

A field-testing site was set up on road CSAH-14 in Wright County, Minnesota, to carry traffic loads equal to 1,500,000 equivalent single axle loads (ESALs) over a planned 32-year design life, assuming a traffic speed of 55 mph (89 km/h). The subgrade strength with a measured by R-value of 12 was used for design purposes. The project involved rebuilding an 8-kilometer (8000-meter) stretch of road with a pavement structure consisting of an 8-inch (203.2 mm) Full-Depth Reclamation (FDR) base and a 5.5-inch (139.7 mm) warm-mix asphalt (WMA) surface layer. For evaluation, five test sections were built, each 24 feet (7.3 meters) wide and 1000 feet (305 meters) long, separated by 300-foot (91.44-meter) gaps. Four sections were treated with proprietary chemical stabilizers, including three ionic stabilizer types and one enzyme-based stabilizer, all blended into the FDR layer. One section was left untreated to serve as a control. The layout and dimensions of the test sections are shown in Figure 1.

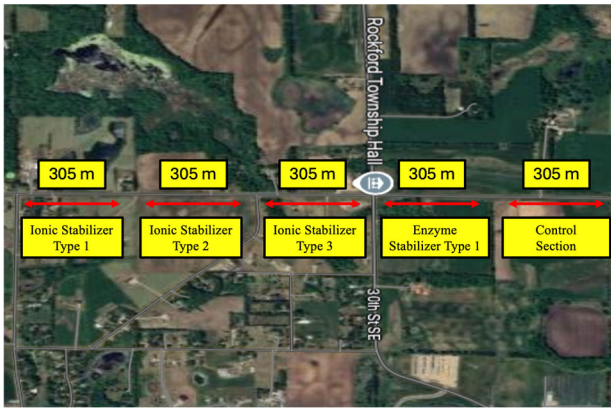


Figure 1 Layout and dimension of field evaluation site at wright county, MN (Ahmed et al. 2025)

3 FWD DATA COLLECTION

Falling-Weight Deflectometer (FWD) tests were used to assess the structural condition of the pavement layers by measuring their deflection response to a controlled load, simulating the impact of a passing vehicle. FWD tests were conducted at different intervals (November 2021, September 2022, June 2023, and October 2024) to monitor the long-term performance of the pavement sections. The data was collected using the trailer-mounted FWD device shown in Figure 2 provided by the Minnesota Department of Transportation (MnDOT). The FWD device has a rigid loading plate with a diameter of 11.8 inches (299.7 mm). To measure deflection, nine geophones are strategically positioned at various distances from the center of the loading plate: 8 inches (203 mm), 12 inches (305 mm), 18 inches (457 mm), 24 inches (610 mm), 36 inches (914 mm), 48 inches (1219 mm), 60 inches (1524 mm), and 72 inches (1829 mm) (Jibon et al. 2024, Ahmed et al. 2025). For this study, a load equivalent to 9,000 pounds (40 kN) was considered.



Figure 2 MnDOT Falling-Weight Deflectometer Device

4 TEMPERATURE CORRECTION METHODOLOGY

Temperature significantly affects FWD deflection measurements, particularly near the center of loading due to the viscoelastic nature of asphalt (Calhoun et al., 2022). Equation 1 is the temperature adjustment formula for the FWD deflection values.

$$D_{adj} = D \times 10^{(C_0 + A \times r) \times (T_{bells} \times H_{ac})} \dots \dots \dots (1)$$

where

r = Radial distance from load plate center
 A = Regression constant (-5.47x10⁻⁸)

C₀ = Regression constant (4.65x10⁻⁵)

T_{bells} = Pavement temperature at 1/3 depth predicted by BELLS3

H_{ac} = Asphalt layer thickness in mm

The number of sensors requiring correction was determined using Equation 2 that considers dependence on the asphalt layer thickness (Kim and Park, 2002). Sensors located within the specified radial distance, as defined by the equation, were subjected to temperature correction. For this study, the first three sensors were temperature corrected.

$$D_{eff} = 4.75 \times H_{ac} - 413 \dots \dots \dots (2)$$

where

D_{eff} = Effective radial distance (mm)

H_{ac} = Asphalt layer thickness (mm)

The BELLS3 model was used to estimate the internal asphalt temperature at 1/3 depth, because this better matched the routine testing methods used than other models, as shown in Equation 3 (Lukanen et al. 2000).

$$T_{bells} = 0.95 + 0.892 \times T_{surf} + \log_{10}(H_{ac}/3) - 1.25 \times (-0.448 \times T_{surf} + 0.621 \times T_{prev} + 1.83 \times \sin(hr18 - 15.5)) + 0.042 \times T_{surf} \times \sin(hr18 - 13.5) \dots \dots \dots (3)$$

where

T_{surf} = Pavement surface temperature (°C)

T_{prev} = Average air temperature from the day before testing (°C)

H_{ac} = Thickness of asphalt pavement layer (mm)

sin(hr18 - 15.5) = 18-hour sine function with 15.5 variation

sin(hr18 - 13.5) = 18-hour sine function with 13.5 variation

5 DEFLECTION BASIN PARAMETER ANALYSIS

The FWD deflection basin was used to assess the structural condition and load-bearing capacity of pavement layers by analyzing deflection responses at varying distances from the applied load. Figure 3 and 4 shows values of the temperature-corrected FWD deflection basin parameter based on October 2024 and April 2025 FWD data. It was found from the analysis of both years' FWD data, collected 3.5 years and 4 years after construction, that the control section (represented by the red line) exhibited higher deflection values compared to the stabilized sections, highlighting its lower stiffness and reduced structural capacity. Among the stabilizers, Ionic Stabilizer Type 2 (represented by the blue line) demonstrated the lowest deflection values across the sensor distances, suggesting that it provides the highest level of stiffness enhancement to the base layer obtained from the October 2024 FWD data.

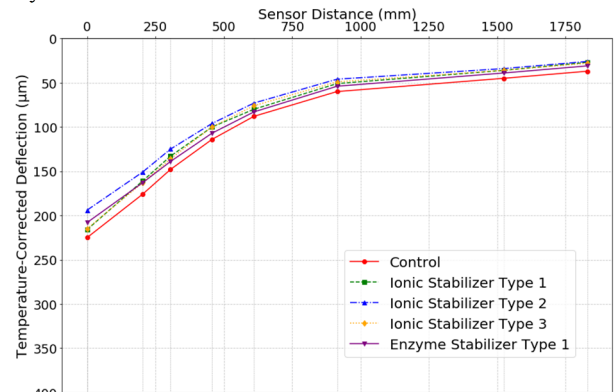


Figure 3 Comparison of FWD Deflection Basin Parameters Across Stabilized and Control Sections – October 2024

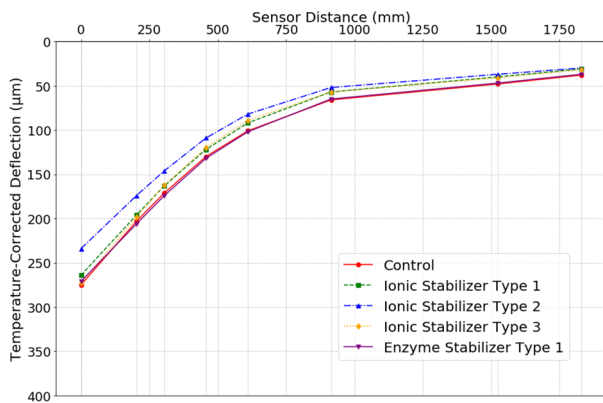


Figure 4 Comparison of FWD Deflection Basin Parameters Across Stabilized and Control Sections – April 2025

6 BACKCALCULATION SOFTWARES

6.1 ELMOD

ELMOD, developed by Dynatest®, is a specialized software package for evaluating flexible and rigid pavements. It uses an Equivalent Thickness and Finite-Element method with MET as its backcalculation technique. ELMOD operates through an iterative process and uses a fixed interface model in which the subgrade is treated as the reference layer. It can support up to four layers (not including the rigid layer) and uses deflection data from five sensors to achieve accurate results (William, 1999).

6.2 MODULUS

MODULUS, developed by the Texas Transportation Institute, is a backcalculation program that uses WESLEA as its forward calculation subroutine based on multilayer linear elastic theory. It offers two analysis modes: Full Analysis, which allows users to define modulus ranges and seed values for up to three layers, and Material Types, which assigns moduli and Poisson’s ratios. The program supports up to eight load drops and seven geophone locations, with direct compatibility for DYNATEST FWD data. MODULUS includes an adaptive weighting system that detects nonlinear subgrade behavior and filters out unreliable sensors. It requires specific geophone spacing and automatically calculates depth to bedrock. A pattern search algorithm is used to match measured and calculated deflection basins, ensuring quality control throughout the analysis. (William, 1999).

6.3 BAKFAA

The BAKFAA program developed by the Federal Aviation Admin (FAA) is a tool primarily intended for use with rigid and flexible pavement structures. Utilizing a Layered Elastic Theory approach, it applies LEAF as its backcalculation technique. This program includes an iterative approach for nonlinear evaluation and implements a non-applied layer interface model. It supports variable layers, with moduli values required as inputs, with acceptable moduli values that must be within a specified range. The convergence methodology is based on the squared error sum, and the error metric is designed for accuracy, making BAKFAA suitable for diverse backcalculation needs (Ahmed, 2010).

7 RESULT AND ANALYSIS

Three backcalculation software tools - ELMOD, MODULUS, and BAKFAA - were utilized to estimate the elastic moduli of the asphalt, base, and subgrade layers using Falling Weight

Deflectometer (FWD) data collected in October 2024 and April 2025. The asphalt layer modulus values derived from all three programs revealed consistent trends across the five test sections. Sections treated with Ionic Stabilizer Type 1, Ionic Stabilizer Type 2, Ionic Stabilizer Type 3, and Enzyme Stabilizer Type 1 exhibited notably higher stiffness compared to the untreated control section. This trend, depicted in Figures 6 through 8 and Figures 15 through 17, underscores the effectiveness of stabilization treatments. Although BAKFAA generally yielded slightly higher modulus values than ELMOD and MODULUS, the differences were minimal and did not affect the overall interpretation. All three tools exhibited strong agreement in ranking the relative performance of stabilization techniques.

For the base layer, the outputs from ELMOD, MODULUS, and BAKFAA consistently differentiated between stabilized and untreated sections, with the treated areas demonstrating significantly higher modulus values. Figures 9 through 11 and Figures 18 through 20 show that Ionic Stabilizer Type 2 and Enzyme Stabilizer Type 1 sections attained the highest base stiffness across all three software outputs. This consistent ranking reinforces the reliability of the backcalculation results and supports the conclusion that base stabilization markedly enhances structural capacity.

With respect to the subgrade layer, the backcalculated modulus values were in close agreement across all software tools, reflecting the uniform subgrade conditions at the test site. The subgrade moduli displayed minimal variation and were largely unaffected by surface or base treatments, further confirming the robustness of the backcalculation process for this layer.

In summary, comparative analysis of ELMOD, MODULUS, and BAKFAA reveals a high level of consistency in estimating pavement layer moduli and evaluating the structural improvements resulting from chemical stabilization. The findings confirm that stabilized sections outperformed the control section - particularly in terms of asphalt and base layer stiffness - thereby validating the structural benefits of the applied treatments.

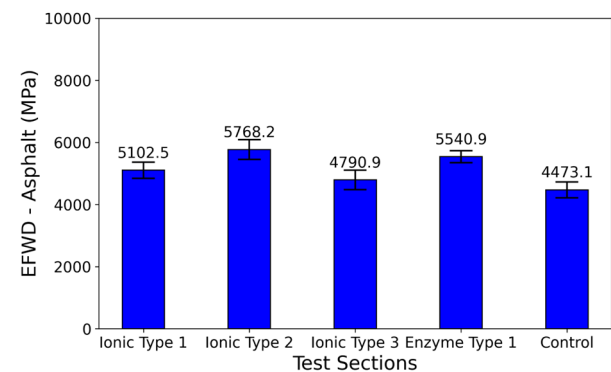


Figure 5 FWD Asphalt Layer Elastic Modulus based on October 2024 – ELMOD

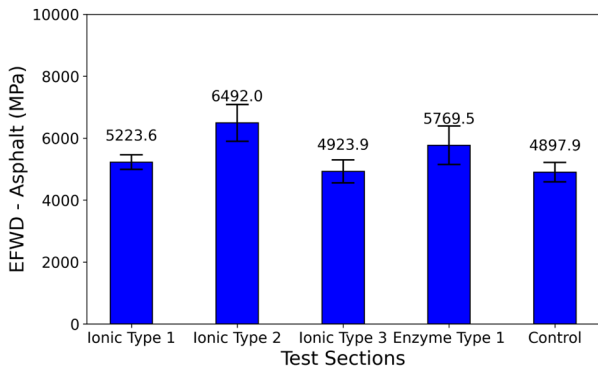


Figure 6 FWD Asphalt Layer Elastic Modulus based on October 2024 – MODULUS

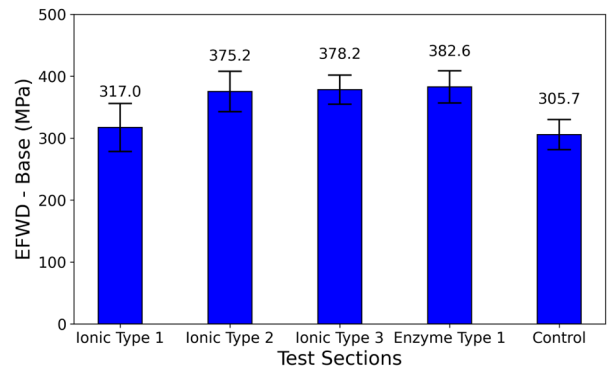


Figure 10 FWD Base Layer Elastic Modulus based on October 2024 – BAKFAA

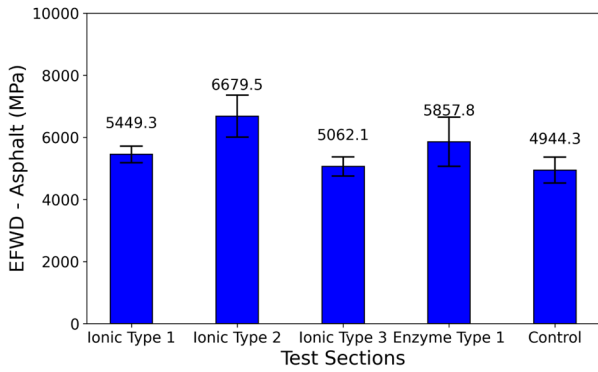


Figure 7 FWD Asphalt Layer Elastic Modulus based on October 2024 – BAKFAA

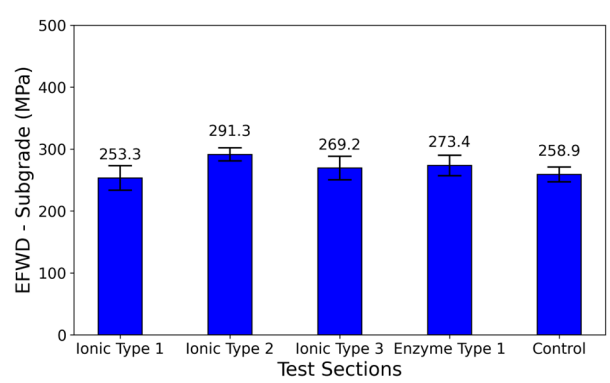


Figure 11 FWD Subgrade Layer Elastic Modulus based on October 2024 – ELMOD

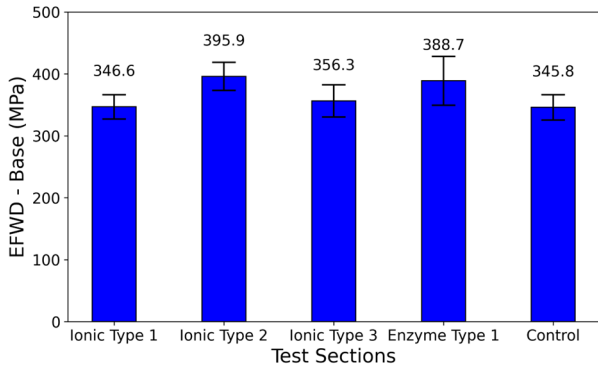


Figure 8 FWD Base Layer Elastic Modulus based on October 2024 – ELMOD

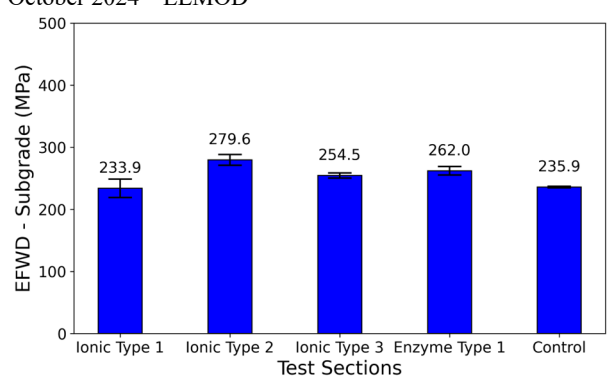


Figure 12 FWD Subgrade Layer Elastic Modulus based on October 2024 – MODULUS

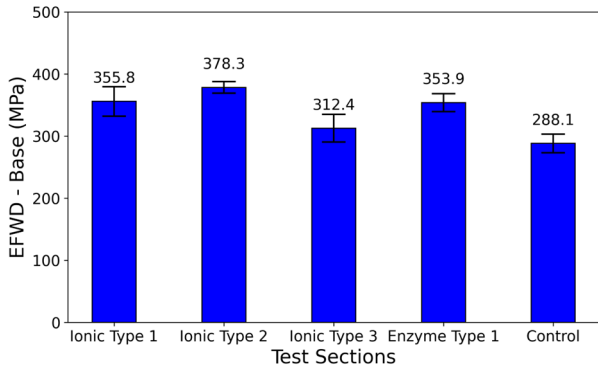


Figure 9 FWD Base Layer Elastic Modulus based on October 2024 – MODULUS

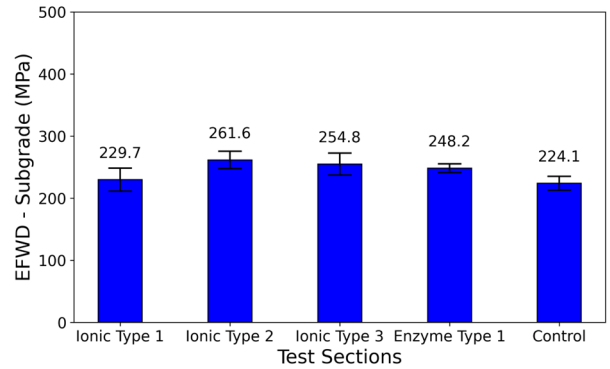


Figure 13 FWD Subgrade Layer Elastic Modulus based on October 2024 – BAKFAA

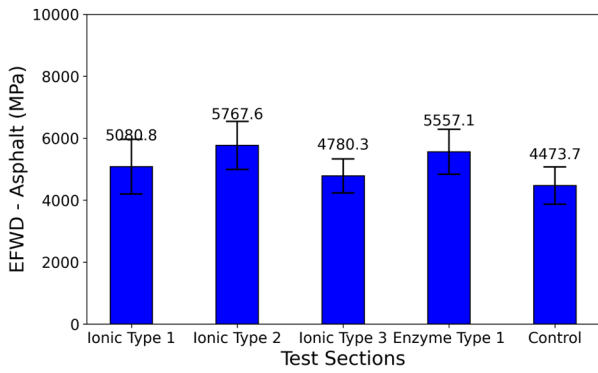


Figure 14 FWD Asphalt Layer Elastic Modulus based on April 2025 – ELMOD

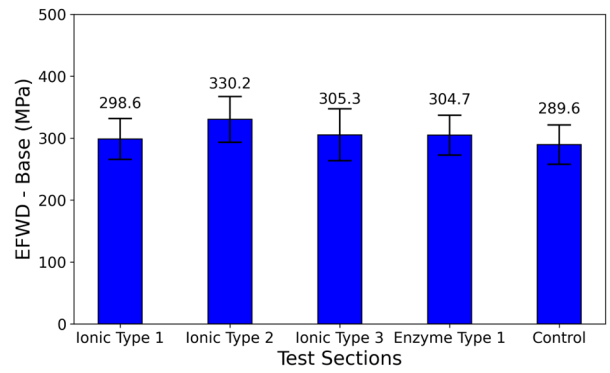


Figure 18 FWD Base Layer Elastic Modulus based on April 2025 – MODULUS

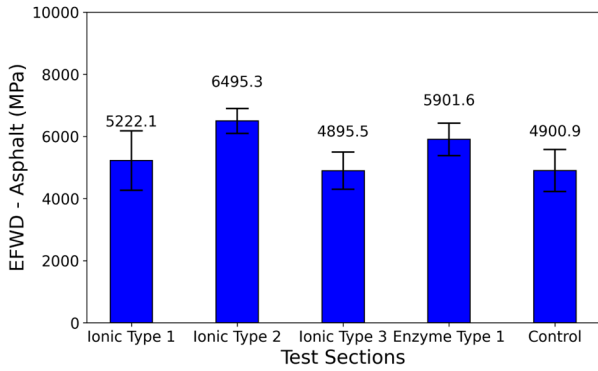


Figure 15 FWD Asphalt Layer Elastic Modulus based on April 2025 – MODULUS

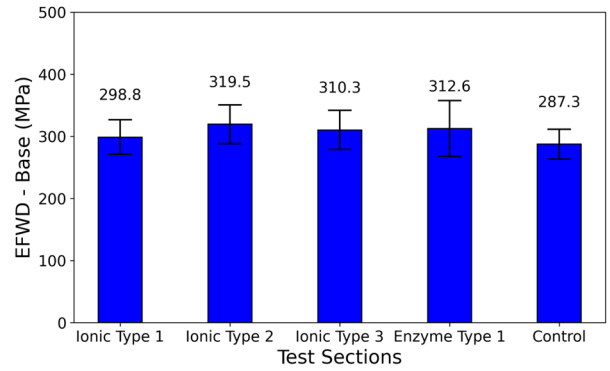


Figure 19 FWD Base Layer Elastic Modulus based on April 2025 – BAKFAA

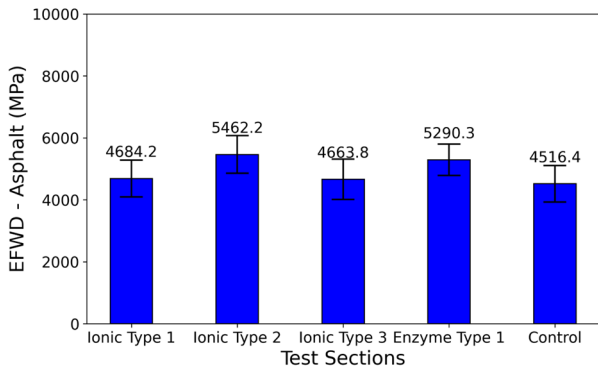


Figure 16 FWD Asphalt Layer Elastic Modulus based on April 2025 – BAKFAA

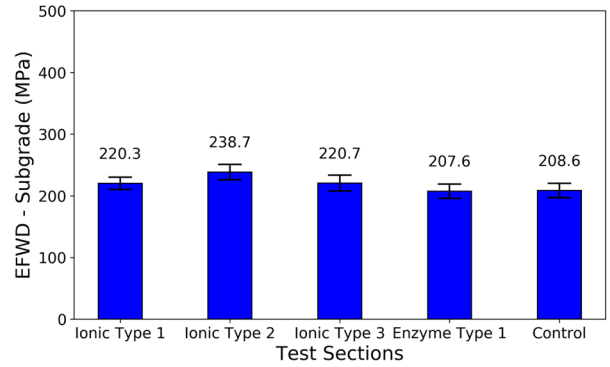


Figure 20 FWD Subgrade Layer Elastic Modulus based on April 2025 – ELMOD

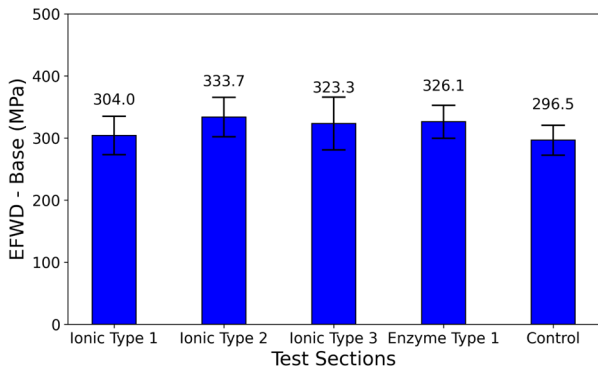


Figure 17 FWD Base Layer Elastic Modulus based on April 2025 – ELMOD

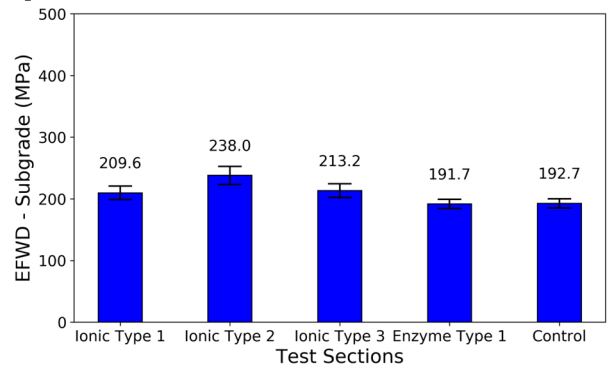


Figure 21 FWD Subgrade Layer Elastic Modulus based on April 2025 – MODULUS

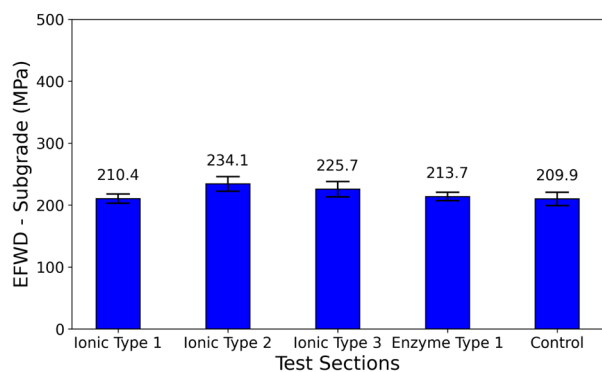


Figure 22 FWD Subgrade Layer Elastic Modulus based on April 2025 – BAKFAA

8 CONCLUSION

This study demonstrated that use of chemically stabilized Full-Depth Reclamation (FDR) base layers can significantly enhance pavement structural performance, as evidenced by backcalculated modulus values derived from FWD testing using ELMOD, MODULUS, and BAKFAA software. Stabilized sections - particularly those treated with Ionic Type 1 and Enzyme Type 1 additives - consistently exhibited higher asphalt and base moduli than the untreated control, validating the effectiveness of these stabilization treatments. The strong agreement in modulus estimation among all three software tools, and performance ranking underscores the reliability of the backcalculation methodologies. Deflection basin parameters such as D_0 , SCI, BDI, and BCI also confirmed the improved structural response of the stabilized sections. Subgrade modulus values remained consistent across test sections, indicating limited influence from surface treatments and confirming uniform subsurface conditions. Collectively, these findings provide compelling evidence that proprietary chemical stabilizers contribute to long-term structural improvement in FDR base layers and offer practical value for pavement design, evaluation, and maintenance planning.

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