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INFLUENCE OF SUBGRADE TREATMENT TYPE ON THE SEASONAL PERFORMANCE OF LOW-VOLUME ASPHALT PAVEMENT STRUCTURES

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Abstract. This study investigates the seasonal structural behaviour of flexible pavement structures constructed on subgrades with varying types of treatment. Eight road sections in Lithuania, featuring natural subgrades or soils stabilised with lime, cement, or hydraulic road binder (HRB), were evaluated using Falling Weight Deflectometer (FWD) testing during thawed and recovered states. Structural condition was assessed using deflection-based indices: the Surface Curvature Index (SCI), Base Damage Index (BDI), and Base Curvature Index (BCI). Seasonal changes were quantified, and Wilcoxon signed-rank tests were applied to assess the statistical significance of deflection differences. The results revealed that the untreated subgrades experienced the largest seasonal softening, with BCI increases of up to 45%. Cement stabilization provided the most effective mitigation, limiting the BCI to 14% and preserving the stability of SCI. Lime-treated sections showed a dosage-dependent improvement, while HRB treatment yielded results comparable to high-percentage

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lime stabilisation. The study confirms that the type and dosage of subgrade treatment significantly influence pavement resistance under freeze-thaw conditions and highlights the importance of evaluating the geometry of the deflection bowl to correctly interpret structural indicators. These findings contribute to improved mechanistic understanding of seasonal load response in flexible pavements and inform best practices for subgrade stabilisation.

Keywords: BCI, BDI, deflection bowl indices, falling weight deflectometer, flexible pavement, subgrade stabilisation, seasonal variation, SCI.

Introduction

Subgrade plays a critical role in the structural integrity and performance of pavements, roads, and railways. The bearing capacity and susceptibility to the hydrothermal influence of the subgrade have a predominant effect on the long-term performance of the pavement structure (Žalimienė et al., 2020). As a load-bearing layer, the subgrade must demonstrate resilience to the effects of environmental factors, including temperature fluctuations, moisture variations, and freeze-thaw cycles. These factors contribute to seasonal changes in the physical properties of the subgrade, which can lead to substantial deformation or failure of the infrastructure over time. A substantial body of research has identified spring thaw as the predominant cause of deterioration in pavements subjected to frost penetration. This phenomenon has been identified as the main cause of structural damage, including the formation of fatigue cracks, permanent structural deformations, and the rapid development of pavement roughness (White & Coree, 1990; Sylvestre et al., 2019). Given that spring thaw is the dominant cause of pavement deterioration in frost-affected regions, its significance becomes even more pronounced in the context of climate change. With increasing variability in precipitation and extreme weather events, subgrade soils are subjected to more frequent wet-dry and freeze-thaw cycles (Kandalai et al., 2023).

Freezing in pavement structures and subgrade soils occurs when the pore water in the soil freezes due to subzero temperatures, forming ice lenses at the freezing front. The process of capillary action, in which ice lenses attract additional water from the surrounding soil, causes the frost zone to penetrate deeper into the subgrade. The freezing process continues until the heat flow becomes insufficient to maintain further freezing. The soil may undergo a loss of density during the thawing process, further compromising the stability and performance of the pavement structure. A substantial body of research has been dedicated to the examination of seasonal variations in the characteristics of subgrade soils and unbound layers, with a particular emphasis on their response to moisture content and temperature. The prevailing focus of these studies is on laboratory testing and modelling based on multilayered elastic theory, coupled with mechanistic-empirical prediction of pavement performance. Laboratory experiments have demonstrated a strong correlation between soil moisture and the resilient modulus of the subgrade, with the resultant formation of permanent deformations. This phenomenon is particularly evident in conventional pavement structures comprising unbound base layers, which distribute the load less effectively compared to bound layers (Rahman et al., 2019; Rahman et al., 2023). Even minor fluctuations in soil moisture content can profoundly impact its deformability, potentially reducing the resilient modulus by up to 70% (Kern et al., 2021). Soils with a high fine particle content exhibit heightened sensitivity to the effects of water and frost due to their substantial surface area, which allows greater water retention compared to coarser soils. During the freezing process, the water present in these fine-grained soils undergoes a phase transition, converting into ice. This process exerts pressure on the structure of the surrounding soil. Bearing capacity in clay and silty soils can be reduced by up to a factor of two due to the impact of moisture, which often becomes the predominant cause of pavement structural deterioration (Janoo & Berg, 1990; Chu et al., 2023). Furthermore, excess moisture has been shown to have a detrimental effect on the resilient modulus of unbound base layers (Cary & Zapata, 2011). Furthermore, accelerated testing of instrumented pavement structures demonstrated that moisture increases both the resilient and permanent strains in unbound layers (Erlingsson, 2010; 2012). Consequently, the aforementioned factors contribute to the acceleration of damage accumulation in pavements during the critical spring thaw period.

To address the aforementioned challenges, a variety of soil treatment methods have been employed to improve the stability and resilience of the subgrade. Soil stabilisation techniques, including the incorporation of lime, cement, bituminous compounds, or geosynthetics, have emerged as prominent methods to increase soil bearing capacity and mitigate seasonal variations. The most prevalent hydraulic binders, i.e., lime and cement, undergo a chemical reaction with soil particles, resulting in the formation of cementitious compounds, also referred to as the pozzolanic reaction. This reaction helps reduce the sensitivity of the soil matrix to water and frost, thus enhancing its stiffness. In addition to traditional stabilising agents, fly ash has also proven effective in significantly enhancing the stiffness and long-term durability of treated subgrade layers, making fly ash a viable alternative in subgrade improvement strategies (Zimar et al., 2022). Research by Behnood and Olek (2020) demonstrated that stabilisation techniques, including cement-treated soils and flowable fill, led to a substantial reduction in settlement under cyclic loads, thus improving subgrade performance. This finding was based on full-scale laboratory-based instrumented pavement structures. Furthermore, an increase in the thickness of the stabilised subgrade layer has been shown to have a positive impact on the fatigue life of both the asphalt and the base layers (Solanki et al., 2009; Solanki & Zaman, 2017). The improved resilient modulus resulting from subgrade stabilisation is associated with an extension of the fatigue life of the pavement, underscoring the importance of stabilisation thickness in pavement design. Ghanizadeh et al. (2024) further highlighted that stabilisation not only extended the rutting and fatigue life of pavements, but also emphasised that the optimal content of additives and proper stabilisation thickness played a key role in improving pavement longevity, particularly for subgrade types with higher resilient moduli. In summary, the findings support the conclusion that binder-based stabilisation methods are essential to improve the performance and lifespan of flexible pavements, particularly in challenging soil conditions.

Although experience, laboratory tests, and modelling clearly demonstrate the benefits of subgrade soil stabilisation to improve pavement structure performance, there is still limited information on how different stabilisation methods influence pavement load response behaviour under seasonal fluctuations in hydrothermal conditions. The objective of this study is to assess the structural behaviour of pavement structures using falling weight deflectometer (FWD) measurements, thus providing valuable insights into how different subgrade treatments affect the pavement response to load.

1. Site description

For the study, eight sections of regional roads with typical three-layer flexible pavement structures were selected, located in different regions of Lithuania (Figure 1). Each pavement structure is designed for relatively low loads up to 0.18×10^6 ESAL. All road sections were relatively new, constructed between 2019 and 2020.

Figure 1. Selected road sections

The selection of specific sections related to the design load and the resulting composition of the pavement structure is based on the understanding that, due to the relatively thin thickness of the base and HMA layers, there is a lower load distribution effect, resulting in higher stresses in the subgrade. In such structures, permanent deformation in the subgrade is the predominant structural damage caused by traffic loads (Chittoori et al., 2012; Selsal et al., 2022). Pavement structures consist of a 6–12 cm HMA layer, a 15–25 cm unbound base layer of crushed stone and a 23–40 cm sub-base layer of gravelly sand, the total thickness of pavement structures ranges from 55 to 65 cm. Natural subgrade soils are predominantly composed of silty sand (SM) and low plasticity clay (CL). In five out of the eight road sections, the upper part of the subgrade is stabilised with hydraulic binders – lime, cement, or hydraulic road binder – in amounts ranging from 4% to 8% of the soil mass. The pavement structure in the remaining three road sections is constructed on compacted natural subgrade soils. The summarised parameters of the pavement structures of the road sections under study are presented in Table 1.

Table 1. Pavement structures of the selected road sections

Road Section	Design load, 10^6 ESAL	Pavement structure	Subgrade soil type (frost susceptibility class)	Type of soil treatment additive, content, and layer thickness	Frost depth, m	Depth of groundwater table, m
I	0.0	AC 16 PD (70/100) (10 cm) Crushed aggregate 0/32 (20 cm) Gravely sand (35 cm)	SP (F1), SM (F3)	-	1.40	1.30
II	0.10	AC 16 PD (70/100) (10 cm) Crushed aggregate 0/32 (20 cm) Gravely sand (25 cm)	GM (F2), CL (F3)	-	1.40	–
III	0.09	AC 16 PD (70/100) (10 cm) Crushed aggregate 0/32 (15 cm) Gravely sand (40 cm)	SM (F3), CL (F3)	-	1.30	–
IV	0.09	AC 16 PD (70/100) (10 cm) Crushed aggregate 0/45 (20 cm) Gravely sand (35 cm)	CL (F3)	Cement, 8%, 30 cm	1.50	–
V	0.18	AC 11 VN (70/100) (4 cm) AC 22 PN (70/100) (8 cm) Crushed aggregate 0/45 (20 cm) Gravely sand (23 cm)	CL (F3)	Lime, 3% 30 cm	1.40	–
VI	0.17	AC 11 VN (70/100) (4 cm) AC 22 PN (70/100) (8 cm) Crushed aggregate 0/45 (20 cm) Gravely sand (33 cm)	SM (F2)	Lime, 4%, 30 cm	1.40	–
VII	0.01	AC 16 PD (70/100) (6 cm) Crushed aggregate 0/45 (20 cm) Gravely sand (39 cm)	CL (F3)	Lime, 5%, 30 cm	1.60	–
VIII	0.04	AC 16 PD (70/100) (6 cm) Crushed aggregate 0/45 (25 cm) Gravely sand (35 cm)	SM (F3), CL (F3)	Hydraulic road binder, 4%, 30 cm	1.40	3.40

2. Methodology for measuring and evaluating the structural behaviour of pavement structures

2.1. Bearing capacity measurements

To assess how the bearing capacity of the pavement structure and its seasonal variation due to hydrothermal conditions are influenced by the subgrade soil treatment method, measurements were performed using a falling weight deflectometer (FWD). The FWD measurements were planned according to the data collected from road climate stations, with the objective of falling within the critical thawed state and the period of neutral hydrothermal conditions (recovered state). Each road section was investigated twice, corresponding to two distinct seasonal conditions: the thawed and the recovered states. Measurements during the thawed state were carried out between 2 and 10 April, coinciding with the onset of positive temperatures within the frost-affected depth, whereas measurements during the recovered state were conducted between 13 and 17 September.

A trailer-mounted FWD “PRIMAX 2500” (Figure 2) was used for the measurement of deflection, with sensors placed at specific distances from the 150-millimeter radius load plate. These distances corresponded to 0, 200, 300, 450, 600, 750, 900, 1200, 1500, 1800, and 2100 mm. A target load of 50 kN was applied. At each test location, three consecutive load drops were applied to improve repeatability and to account for potential seating effects of the loading plate, thereby ensuring reliable and representative deflection measurements. Deflections obtained from the third drop were used for the analysis. The test was carried out within a single traffic lane, with a 25-meter interval (comprising 21 measurement points within each road section) between the wheel paths. It is assumed that the area between the wheel path is not affected by vehicle loads; therefore, the pavement structure bearing capacity parameters determined depend only on the material properties of the pavement structure layers, the natural ageing process, installation practices, and hydrothermal conditions, which is the most important aspect in the scope of this study. Furthermore, the air, surface and pavement temperature were recorded during the test.

Figure 2. Falling weight deflectometer "PRIMAX 2500"

2.2. Analysis of structural behaviour

The FWD deflection basin indices were analysed to investigate the structural behaviour of the pavement during the spring thaw and recovered state periods. The indices considered in this study included deflection bowl, Surface Curvatures Index (SCI), Base Damage Index (BDI), and Base Curvature Index (BCI) (see Table 2). The SCI, calculated as the deflection difference between the centre of the FWD load plate and a sensor located 200 mm away, provides insight into the stiffness and integrity of the upper layers of a flexible pavement structure, particularly the asphalt layer. BDI, defined as the deflection difference between 300 mm and 600 mm from the centre of the FWD load plate, serves as an index for identifying the stiffness of the base layers of flexible pavement structures. The BCI, defined as the difference between deflections at 600 mm and 900 mm from the centre of the load plate, serves as a sensitive indicator of subgrade stiffness.

Table 2. Deflection basin indices used for structural evaluation of pavement structures (adapted from Doré et al., 2009)

Deflection basin index	Equation	Description
SCI	$SCI = d_0 - d_{200}$	Curvature of the inner part of the deflection basin, indicating the stiffness of the upper part of the pavement
BDI	$BDI = d_{300} - d_{600}$	Curvature of the middle part of the deflection basin, indicating the stiffness of the unbound base and sub-base
BCI	$BCI = d_{600} - d_{900}$	Curvature of the outer part of the deflection basin, indicating the stiffness of the subgrade top part

Seasonal changes in each deflection-derived index were evaluated using paired two-sided Wilcoxon signed-rank tests. The Wilcoxon test is a nonparametric statistical method that compares the median of the differences between two dependent samples; in this case, the thawed-state and recovered-state observations recorded at the same FWD test locations. This Wilcoxon test was selected as the Shapiro–Wilk test and visual inspection of Q–Q plots indicated that the deflection data deviated from a normal distribution ($|p| < 0.05$). For each road section, the deflection index values obtained at identical test locations during the thawed and recovered states were paired to form matched samples. The non-zero paired differences were ranked by their absolute values, and the signed ranks were summed to obtain the Wilcoxon statistic (W), which was then evaluated against its exact sampling distribution (for $n \leq 25$). A two-tailed significance level of $\alpha = 0.05$ was adopted for all statistical tests.

Figure 3 shows the measured deflection bowls for every road section in both the thawed and recovered (reference) states. Each curve represents the mean response; the dotted curves denote the minimum to maximum range observed during each season, giving a first impression of structural variability. Across the eight sections, the thawed state bowl lies consistently above and, therefore, exhibits larger deflections than the recovered state bowl, confirming that seasonal moisture and freeze-thaw action reduce the composite stiffness of the pavement system. The vertical separation between the two seasonal curves, however, differs markedly between the treatment groups and changes as a function of radial offset.

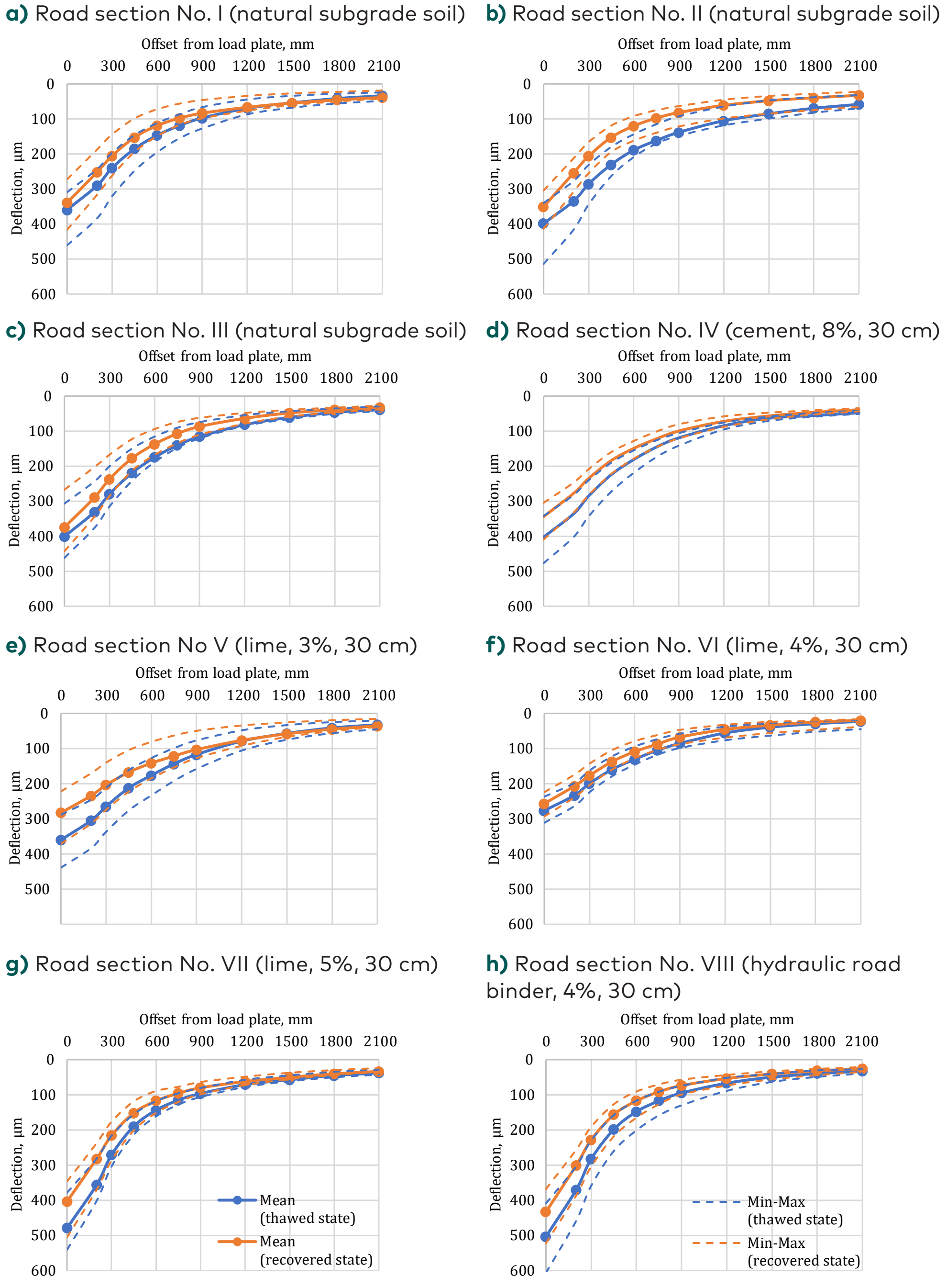

Figure 3. Deflection bowls of the selected road sections

Untreated subgrades (Sections I–III) display the most pronounced seasonal gap. The thawed curve starts roughly 80–120 µm higher at the load centre (d0) and remains visibly elevated through the entire offset range to 2.1 m. The cement-treated subgrade (Section IV, 8% cement) shows the smallest seasonal divergence. The thawed and recovered curves nearly coincide beyond about 600 mm. The lime-treated subgrades (Sections V–VII, 3–5% lime) occupy an intermediate position. With 3% lime the thawed curve still rises 70 µm above the recovered one at d_0 and remains noticeably higher out to 900 mm. As the lime content increases to 4% and 5%, the seasonal gap narrows, yet a discernible offset persists in the 300–900 mm zone. The progressive tightening of the two curves suggests that the efficiency of lime improves with dosage, though not to the level achieved by cement. Hydraulic-road-binder (HRB, Section VIII, 4%) behaves similarly to the higher-dosage lime sections. The thawed-state bowl is only modestly above the recovered curve at large offsets, indicating that HRB provides some mitigation of deep layer softening; nevertheless, the central deflection remains sensitive to moisture. Further, more detailed analysis based on the deflection bowl indices – SCI, BDI and BCI – is provided in Chapter 3.

3. Results and discussion

3.1. Seasonal variation in subgrade stiffness

This section analyses the seasonal behaviour of BCI across road sections with different subgrade treatments, highlighting the impact of stabilisation on the resilience of the subgrade. The distribution of the BCI index in each road section during thawed and recovered states and the seasonal changes expressed as a percentage difference are presented in Figure 4.

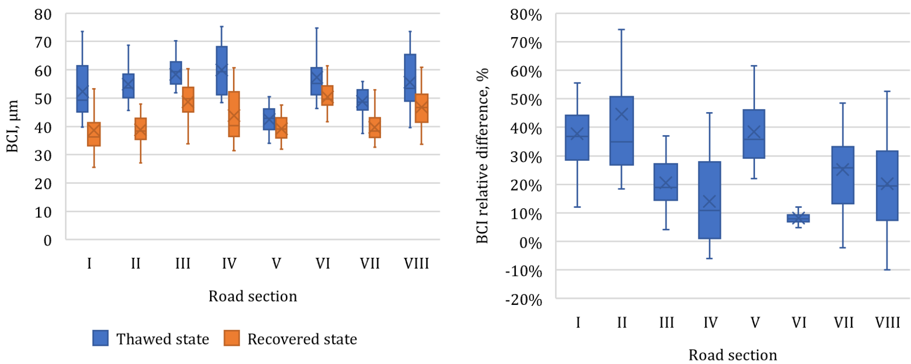

Figure 4. Distribution of BCI during thawing and recovered states (left) and seasonal percentage change (right)

In road section I, which features an untreated subgrade, the BCI increased from an average of 38.55 μm in the recovered state to 52.25 μm in the thawed condition, reflecting a 38% seasonal increase. This indicates a substantial reduction in the stiffness of the subgrade during thaw periods. A similar trend was observed in road section II, also constructed on an untreated subgrade, where BCI increased from 38.82 μm to 54.97 μm, amounting to a 45% increase. These results suggest that untreated soils are particularly susceptible to moisture-induced weakening and exhibit notable structural degradation during thawing conditions. Road section III, also built on untreated subgrade, experienced a less pronounced yet still notable seasonal BCI increase of 21%, increasing from 48.74 μm in the recovered state to 58.38 μm in the thawed state. A smaller relative change compared to sections I and II may be attributable to local variations in subgrade soil properties or differences in drainage efficiency, which can influence the depth and extent of thaw weakening.

In contrast, road section IV, which incorporates 8% cement-treated subgrade, demonstrated a considerably lower seasonal fluctuation. The BCI increased by only 14%, from 50.48 μm in the recovered state to 57.36 μm in the thawed state. This relatively moderate change implies that cement stabilisation effectively limits structural softening in the subgrade, likely due to improved moisture resistance and increased stiffness of the treated soil matrix.

Road section V, constructed with a 3% lime-treated subgrade exhibited a BCI increase of 43.81 μm to 59.98 μm, representing a seasonal change of 38%. This level of fluctuation is comparable to that observed in untreated sections, suggesting that the lime content may have been insufficient to achieve a meaningful resistance to seasonal weakening. This result may also reflect a suboptimal compatibility between lime and native soil, as the efficacy of lime stabilisation is highly dependent on the mineralogical and granulometric characteristics. However, sections VI and VII, treated with 4% and 5% lime, respectively, showed progressively better performance. Section VI increased from 42.16 μm to 51.25 μm (22%), while section VII increased from 44.08 μm to 50.81 μm (15%). These results suggest a dosage-dependent improvement in seasonal resilience, with higher lime contents that more effectively limit the loss of stiffness.

Section VIII, constructed in a subgrade treated with 4% hydraulic road binder (HRB), demonstrated behaviour comparable to the higher lime dosages. Its BCI increased from 47.28 μm to 53.34 μm, an increase of 13%. This indicates that HRB-treated soil offers significant structural stability through seasonal cycles, limiting thaw-induced deflection in the subgrade region.

When grouped by treatment type, a clear gradient of seasonal performance emerges. The untreated sections experienced the highest seasonal increases in BCI (21–45%), revealing their low resistance to moisture and frost effects. The lime-treated sections showed a strong dosage effect: 3% treatment was insufficient, but 4 to 5% lime reduced the seasonal increase in BCI to 15 to 22%, showing intermediate performance. Cement treatment achieved the best control of seasonal variation, with a BCI increase of just 14%. HRB performed similarly to cement, suggesting its potential as an effective alternative stabilisation method.

To corroborate the descriptive findings, a paired two-sided Wilcoxon signed-rank test was applied to the BCI values for the thawed and recovered states at each road section. All sections returned statistically significant increases in BCI at the 5% significance level, confirming that seasonal softening of the subgrade layers is a widespread phenomenon. The test returned statistically significant results for all eight sections at the $\alpha = 0.05$ level, confirming that the increases in BCI during the thawed period were not due to random variation. The untreated sections I, II, and III exhibited the lowest p-values (between 5.96×10^{-5} and 6.10×10^{-5}), which along with the highest seasonal increases in BCI (21–45%) indicating a consistent and strong seasonal effect.

Similarly low p-values (between 5.96×10^{-5} and 6.90×10^{-5}) were obtained for the 3–5% lime-treated sections (V–VII), confirming statistically significant seasonal differences in all three cases. However, the magnitude of BCI increase varied notably: section V (3% lime) exhibited the highest seasonal increase at 38%, while sections VI and VII (4% and 5% lime) showed smaller increases of 22% and 15%, respectively. This pattern indicates that although all lime treatments were statistically significant, higher lime content more effectively suppressed seasonal weakening of the subgrade. This pattern indicates that despite the application of lime treatment, all sections exhibited statistically significant seasonal changes in subgrade stiffness (BCI); however, higher lime content more effectively suppressed the magnitude of this seasonal weakening.

The cement-treated section IV showed a higher, but still significant, p-value ($p = 1.2 \times 10^{-3}$). This indicates that cement does not completely eliminate the influence of the hydrothermal regime on the bearing capacity of the subgrade, but considering the BCI increase of just 14%, it is the most effective of the treatment types studied.

Section VIII, treated with 4% hydraulic road binder, exhibited a statistically significant increase in BCI during the thawed state ($p = 3.67 \times 10^{-4}$). However, the magnitude of this increase was relatively low at 13%, indicating that HRB treatment, along with cement stabilisation, most effectively mitigates the impact of seasonal hydrothermal conditions on subgrade bearing capacity among all treatments investigated.

These results align with the descriptive findings and reinforce the conclusion that subgrade soil treatment does not completely eliminate seasonal variations in the bearing capacity of the soil. However, subgrade treatment, particularly with cement, hydraulic road binder or sufficiently dosed lime, reduces the seasonal weakening of the lower pavement structure as reflected by the BCI.

The comparative analysis of the results indicates that subgrade treatment significantly influences the seasonal performance of pavement structures in terms of BCI. The untreated subgrades showed the highest susceptibility to seasonal weakening, as evidenced by large increases in BCI during the thawed period. The cement subgrades markedly improved seasonal stability, while low-percentage lime treatment did not appear to yield a clear benefit. HRB and high-dosage lime also contributed significantly to seasonal stability.

3.2. Seasonal variation in unbound base layers stiffness

This section examines the magnitude and variability of BDI in road sections featuring different subgrade soil treatments and evaluates the effectiveness of stabilisation in reducing seasonal susceptibility. The distribution of the BDI index in each road section during thawed and recovered states and the seasonal changes expressed as a percentage difference are presented in Figure 5.

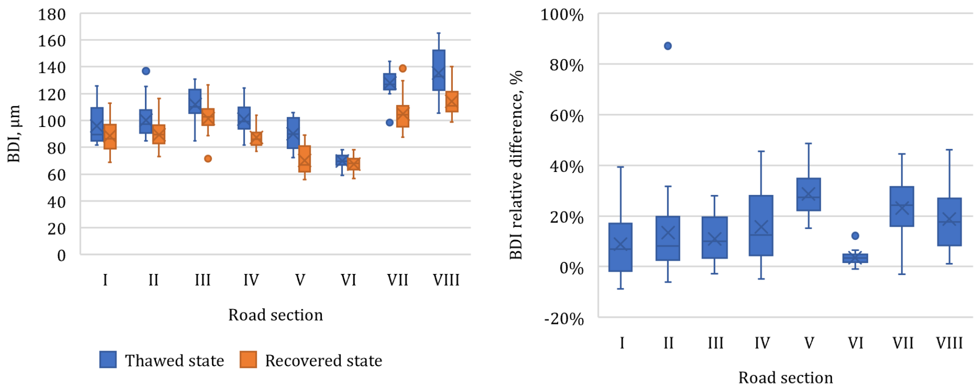

Figure 5. Distribution of BDI during thawing and recovered state periods (left) and seasonal percentage change (right)

In road section I, constructed on untreated subgrade, the average BDI increased from 88.64 μm during the recovered state to 95.85 μm in the thawed condition, indicating a seasonal growth of approximately 9%. Although moderate in absolute terms, this change signifies a noticeable loss of stiffness in the base layer due to increased moisture and reduced bearing capacity during the thaw period. Road section II exhibited a more pronounced response, with BDI increasing from 89.30 μm to 100.30 μm, resulting in a seasonal increase of 13%. The relatively higher sensitivity in section II, compared to section I, may be attributed to local variability in base material composition or drainage performance, which can exacerbate moisture infiltration during thaw cycles.

In road section III, the BDI increased from 101.52 μm in the recovered condition to 111.94 μm in the thawed state, amounting to a seasonal increase of 11%. Although this being slightly lower than the change observed in section II, the elevated absolute values suggest that the base layer in this section is inherently more deformable, regardless of season, possibly due to lower initial compaction or suboptimal material gradation.

The cement-treated subgrade in road section IV of the road showed a comparatively higher seasonal change in BDI than expected. The index increased from 87.46 μm to 100.76 μm, reflecting a 16% increase. Although the absolute values are within the same range as those observed in the untreated sections, the relative increase raises questions about the uniformity or thoroughness of cement stabilisation in this case. It is possible that field implementation factors, such as mixing efficiency or curing conditions, limited the effectiveness of the treatment, allowing seasonal softening to occur despite the presence of cement.

Road section V, with 3% lime treatment, demonstrated the highest BDI sensitivity among all sections. The BDI increased from 70.17 μm in the recovered condition to 89.95 μm during thaw, an increase of 29%. The relatively low initial BDI in the recovered state implies a stiffer base layer during optimal conditions; however, the large seasonal fluctuation reveals a structural vulnerability under thawed conditions. Section VI (4% lime) showed a smaller increase of 17% (74.96 μm to 87.58 μm), while section VII (5% lime) increased by just 9% (74.08 μm to 80.58 μm). The data clearly demonstrate a dose-dependent improvement in seasonal performance, with a higher lime content providing better resistance to seasonal moisture softening.

Section VIII, built on subgrade treated with 4% hydraulic road binder, experienced a BDI increase of 13%, from 79.49 μm to 89.91 μm. This result is comparable to the performance of the 5% lime section and somewhat better than the 4% lime section, suggesting that HRB treatment offers a stabilising effect in the upper base region during thaw conditions.

To assess the statistical significance of seasonal differences in BDI, paired, two-sided Wilcoxon signed rank tests were performed for all road sections. The results showed statistically significant increases in BDI between the thawed and recovered states in all sections at the 5% significance level. Section I, which featured an untreated subgrade, returned a p-value of 1.25×10^{-2}, still significant but higher than those of other untreated sections, which along with BDI change of 9% suggesting a relatively smaller or more variable seasonal effect. Sections II and III, also untreated, had lower p-values (4.19×10^{-4} and 1.41×10^{-4}, respectively). Considering the change in the BDI, which amounts to 13 and 11% respectively, it indicates a more consistent seasonal weakening in the unbound base layers. Section IV, treated with 8% cement, produced a p-value of 2.81×10^{-4}, which along with BDI change of 16% confirms that even stabilised structures experience statistically significant thaw-related softening.

Sections V (3% lime) and VIII (4% hydraulic road binder) both returned p-values of 5.96×10^{-5}, suggesting pronounced and highly consistent seasonal changes in BDI. However, the relative change in the BDI for Section V, at 29%, was significantly larger than that for section VIII, with a change of 13%.

Sections VI and VII, treated with 4% and 5% lime, also showed a strong significance ($p = 1.87 \times 10^{-4}$ and 9.22×10^{-5}, respectively) in BDI differences. However, the relative change in BDI indicates that lime dosage has an impact on the magnitude of seasonal variation, since at lime content of 3, 4 and 5% the relative change in BDI is 29, 17 and 9%, respectively.

These results corroborate the descriptive findings and highlight the sensitivity of BDI to thaw effects in the unbound base layers. Although all stabilisation treatments reduced absolute BDI levels to some extent, statistical tests confirm that only higher lime contents or HRB treatment begin to approach the performance of cement in limiting seasonal softening.

When viewed by treatment category, a clear pattern emerges. Untreated sections consistently showed 9–13% seasonal increases in BDI, reflecting moderate but persistent base layer softening. The cement treatment resulted in a slightly higher increase in this case, though this may be project-specific. Lime treatment at 3% was least effective, producing the highest increase in BDI in all sections, but increasing the dose to 4–5% significantly improved seasonal performance. HRB treatment showed behaviour comparable to high-dosage lime, suggesting that it may be a viable alternative to increase base resilience under freeze–thaw conditions.

Overall, the BDI results reinforce the need for sufficient stabilisation of the subgrade to control the loss of seasonal stiffness in the upper base. Among the solutions investigated, higher lime dosages (≥4%) and HRB proved effective in moderating increases in BDI, while cement stabilisation, despite a moderate change in BDI, still outperformed all alternatives of untreated and low lime content when viewed in the context of complete structural response. These findings highlight the importance of dosage optimisation and soil–binder compatibility when selecting stabilisation strategies to improve seasonal durability.

3.3. Seasonal variation in asphalt layers stiffness

Asphalt layers are less directly influenced by subgrade behaviour; therefore, SCI is generally expected to exhibit less seasonal variation. However, freeze-thaw cycles can still influence the structural response of the upper layers due to indirect effects such as moisture accumulation, frost heave, or loss of support from underlying weakened layers. This section evaluates how SCI responded seasonally across pavement sections with different subgrade stabilisation methods. The distribution of the SCI index in each road section during thawed and recovered states and the seasonal changes expressed as a percentage difference are presented in Figure 6.

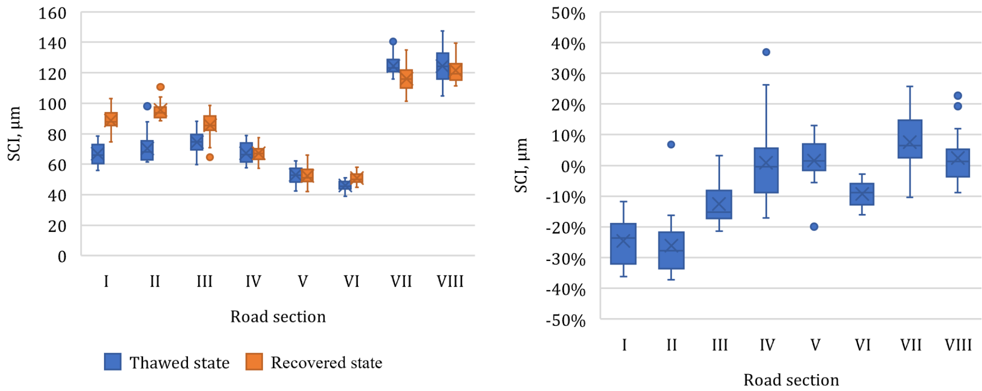

Figure 6. Distribution of SCI during thawing and recovered states (left) and seasonal percentage change (right)

In road section I, constructed on untreated subgrade, the SCI decreased from an average of 88.85 μm during the recovered (reference) state to 66.88 μm during the thawed condition. This represents a seasonal reduction of 25%. Road section II showed similar behaviour. The SCI decreased from 95.50 μm to 70.48 μm, resulting in seasonal drop of 26%. Road section III showed a somewhat smaller decrease in SCI, from 85.63 μm to 74.62 μm, corresponding to a 13% reduction. Although the results seem contradictory, when looking at the deflection basins in these sections, it is seen that during the thawing period the deflection bowls shift by approximately the entire radial offset, i.e. the deflection basin flattens, but the overall bearing capacity of the pavement structure is clearly reduced. That may lead to a reduction in the SCI, not because the asphalt is stiffer, but because the load spreads more widely and deeper, increasing d_{300} disproportionately relative to d_0. This suggests that the SCI indicator should also not be analysed without considering the shape of the entire deflection bowl.

In road section IV, with an 8% cement-stabilized subgrade, SCI remained virtually unchanged between seasons, decreasing marginally from 67.10 μm to 67.22 μm. The seasonal difference was only 1%, suggesting exceptional structural stability in the upper layers. This result supports the conclusion that cement stabilisation not only improves the lower structural layers but also contributes to uniform load distribution and reduced stress concentrations near the surface, likely due to improved subgrade stiffness and reduced moisture-induced deformation.

Road section V, constructed on a 3% lime-treated subgrade, experienced a slight increase in SCI from 52.25 μm to 52.99 μm, which represents seasonal increase of

2%. The nearly negligible change suggests that although the lime treatment may not have significantly improved the deeper structural layers, it helped maintain stability in the upper pavement structure during thawing.

Section VI (4% lime) exhibited a more pronounced decrease in SCI of 9% (50.76 µm to 46.06 µm), while section VII (5% lime) showed an increase of 8% (115.99 µm to 124.44 µm). This could suggest a shift of deflection bowl by approximately the entire radial offset, similarly to that for sections I–III with untreated subgrade soil.

Section VIII, constructed with 4% hydraulic road binder, experienced a 3% increase in SCI, from 121.47 µm to 124.46 µm, suggesting greater structural stability in the upper layers.

In general, the SCI results confirm that the response of the asphalt layer during thaw is indirectly influenced by the subgrade and base performance. Treatments that provide deeper structural support – especially cement stabilization – contribute to the preservation of surface curvature and load distribution. However, SCI should not be interpreted in isolation; rather, it should be analysed in conjunction with deflection bowl shape and complementary indices such as BDI and BCI to accurately assess seasonal pavement behaviour.

Conclusions

This study assessed the seasonal structural response of flexible pavements based on Falling Weight Deflectometer (FWD) measurements collected from eight road sections with different subgrade treatments. The analysis focused on deflection-based indices – Base Curvature Index (BCI), Base Damage Index (BDI), and Surface Curvature Index (SCI) – to quantify stiffness changes between thawed and recovered (reference) states. The results confirm that seasonal weakening is significant and measurable in all pavement systems, with the degree of deterioration closely related to the type and effectiveness of subgrade stabilisation.

Pavements with untreated subgrades exhibited the most severe seasonal weakening effect. BCI increased by 38 to 45%, BDI increased by 9 to 13% and SCI decreased by 13 to 26%, clearly indicating a weakening across all structural layers. In these sections, the deflection bowls shifted significantly throughout the radial offset during the thawing period, reflecting the decrease in subgrade stiffness.

On the contrary, the cement-stabilised subgrade (8% cement) demonstrated good seasonal stability. The BCI increase was limited to 14%, BDI increased by 16%, and SCI remained nearly unchanged (a 1% decrease), indicating that cement effectively preserved the structural continuity of both lower and upper pavement layers during thawing period.

Lime-treated sections showed dosage-sensitive behaviour. At 3% lime, BCI increased by 38% and BDI by 29%, indicating that this dosage was not sufficient to prevent seasonal softening. However, higher dosages – 4% and 5% lime – reduced the seasonal BCI increases to 15–22% and BDI to 9–17%, demonstrating a clear improvement in structural resilience with increased additive content.

The section treated with 4% hydraulic road binder (HRB) exhibited comparable seasonal stability to high-dosage lime. BCI increased by 13%, BDI by 13%, and SCI rose slightly by 3%, suggesting that HRB offers an alternative stabilisation approach under frost-susceptible conditions.

Statistical analysis based on the Wilcoxon signed-rank test was conducted to estimate statistical significance in seasonal differences of BCI and BDI. Statistical analysis showed that seasonal differences were statistically significant ($p < 0.05$) across all road sections, regardless of the type and quantity of binder.

For BCI, statistically significant seasonal differences were found in all sections, with p-values ranging from 5.9×10^{-5} to 1.2×10^{-3}. The untreated and 3% lime sections (I–III, V) exhibited the lowest p-values (5.9×10^{-5}–6.9×10^{-5}). The cement-treated section (IV) returned $p = 1.2 \times 10^{-3}$, while the HRB-treated section (VIII) showed $p = 3.7 \times 10^{-4}$.

For BDI, all sections also demonstrated statistically significant seasonal differences, with p-values ranging from 5.9×10^{-5} to 1.3×10^{-2}. The untreated sections (I–III) produced $p = 1.3 \times 10^{-2}$, 4.2×10^{-4}, and 1.4×10^{-4}. The cement-treated section (IV) showed p = 2.8 × 10−-4. Lime-treated sections returned $p = 5.9 \times 10^{-5}$, 1.9×10^{-4}, and 9.2×10^{-5} for 3%, 4%, and 5 % lime contents, respectively. The HRB-treated section (VIII) had $p = 5.9 \times 10^{-5}$.

Accordingly, it can be stated that in the studied roads, the subgrade treatment does not completely eliminate the seasonal variation in the bearing capacity of the unbound base layers and subgrade due to changes in hydrothermal conditions. However, the type and amount of binder affect the magnitude of the bearing capacity fluctuations as can be seen from the relative change in BCI and BDI.

Finally, the observed reduction in SCI during thaw conditions – most pronounced in untreated and low-lime content sections – should not be misinterpreted as surface stiffening. Instead, it reflects deflection bowl flattening due to weakened subgrade support, which disproportionately increases deflection at 200 mm offset relative to the deflection at load plate centre.

The findings clearly demonstrate that cement-treated subgrades provide the best protection against seasonal stiffness loss, while properly dosed lime and HRB treatments can offer meaningful but lesser improvement. These results highlight the critical role of the type and dosage of subgrade stabilisation in ensuring long-term pavement performance under freeze-thaw conditions and support the use of deflection bowl indices as sensitive, interpretable indicators of seasonal structural behaviour.

Disclosure Statement

The authors confirm that they do not have any competing financial, professional, or personal interests from other parties.

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