Evaluation of Elastic Modulus Evolution of Cold In-place Recycling during early curing

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Abstract

Cold in-place recycling (CIR) presents environmental and technical benefits by reusing existing asphalt pavement, reducing the use of virgin aggregates, and minimizing emissions during rehabilitation. Despite these advantages, aspects such as stiffness development, spatial variability, and temperature effects remain under-implemented in routine CIR quality control. This study evaluates the evolution of the elastic modulus in the CIR layer during early curing, using light weight deflectometer (LWD) tests under real construction conditions in Québec, Canada. Elastic modulus values were backcalculated with BackCAP software and corrected to a reference temperature of 25 °C to reduce variability associated with temperature differences. Tests were carried out at multiple time intervals (0, 1, and ≈24 hours) and locations, both longitudinally and transversely. Results showed an increase in elastic modulus over time, attributed to curing effects, and revealed spatial heterogeneity—especially across the width of the lane and at specific chainages. The outer wheel path consistently displayed higher stiffness, suggesting the influence of traffic-induced compaction. The findings reinforce the importance of spatially distributed modulus measurements and thermal correction for reliable assessment of mechanical performance at early ages. Integrating LWD testing and temperature-adjusted backcalculation into CIR quality control can improve assessment consistency. It is recommended to exclude the first 150 meters of the test section to account for equipment calibration zones. The ability to quantify modulus gain within 24 h enables agencies to optimize traffic-opening schedules and adjust compaction or moisture control, improving long-term pavement durability and reducing maintenance costs. Future research should apply advanced statistical methods to enhance the reliability and generalizability of recycled pavement performance assessments.

Initial considerations

Cold-in-place recycling (CIR) is recognized for its environmental and technical advantages, particularly its ability to reuse in-situ materials, reduce the demand for virgin aggregates, and lower greenhouse gas (GHG) emissions during road rehabilitation[1-4]. By limiting material transport and energy consumption, CIR contributes to sustainable pavement management practices. Beyond these environmental benefits, effective early-age quality control directly influences the service life of recycled layers, reducing the frequency of future maintenance interventions and the associated life-cycle costs and emissions.

CIR techniques utilize stabilizing agents such as foamed asphalt and modified emulsions to produce bitumen-stabilized materials (BSM), composed mainly of reclaimed asphalt pavement (RAP), supplemented with 1–3% bitumen, up to 1% cement, and sufficient moisture to optimize workability[5]. These mixtures offer improved structural performance, especially through strength development during curing, as confirmed by both laboratory and field studies[3, 6]. However, for maintenance and operations managers, the key question is not only how stiffness develops, but how quickly reliable stiffness can be verified so that traffic can be opened sooner, premature distress avoided, and long-term durability assured.

Despite these advancements, key performance aspects, such as the evolution of stiffness over time and its sensitivity to spatial and thermal variation, remain poorly explored in CIR practice and limits its widespread use. A critical parameter in evaluating structural behaviour is the elastic modulus, widely assessed trough deflection-based technique such as the falling weight deflectometer (FWD) and the light weight deflectometer (LWD). These methods provide reliable, non-destructive modulus estimations, but their integration in CIR for monitoring curing and quality control remains limited. The LWD offers practical

advantages for routine quality control and quality assurance (QC/QA) due to its portability, cost-effectiveness, and rapid operation capabilities[7]. Integrating rapid LWD testing and temperature-corrected backcalculation into construction practice can give agencies an early indication of stiffness gain, allowing immediate adjustments in compaction, moisture management, or traffic-opening schedules that extend pavement life and reduce the need for subsequent maintenance.

Although thermal correction of modulus data is critical for thermosensitive materials such as BSM, especially during the early stage of curing, it remains largely overlook in many studies. Chan et al. (2009) incorporated temperature normalization in their analysis, but such practices are not yet standardized in CIR evaluation protocol[3]. Furthermore, the effects of spatial variability, both longitudinally and transversely, on CIR performance are rarely addressed, despite its implications for pavement uniformity and long-term service life.

This study aims to investigate the evolution of the elastic modulus in CIR layers under real construction conditions, considering spatial variability and surface temperature during early curing, in order to better understand stiffness development and improve quality control practices.

CIR rehabilitation operations

The CIR rehabilitation of National Road 170 in Rivière-Éternité, northern Québec (Canada), covered a 2.8 km segment. The existing pavement, with an average thickness of 145 mm thick (ranging from 110 to 175 mm), was milled and repurposed using CIR, reducing the need for virgin materials. Figure 1 presents the project area along with the designated test locations (chainage).

Figure 1. General view of the project to rehabilitee National Road 170 in Rivière-Éternité (Québec), showing the chainages where the tests were carried out (in grey).
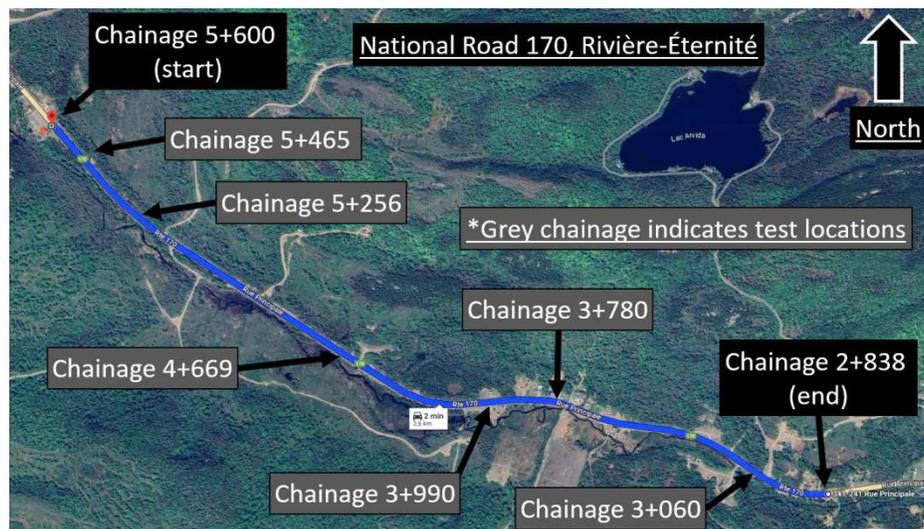
The CIR rehabilitation started at Chainage 5+600, processing one lane per day over a 2-day period, totaling 2.8 km. Traffic was alternately managed, ensuring continuous flow throughout the operations.

Figure 2 illustrates the road conditions before and after rehabilitation. The existing pavement displayed distresses, including rutting and cracking. During the first day of operations, traffic circulated on the

original surface, while on the second day, it was shifted onto the newly recycled lane, highlighting the quick operational turnaround of CIR.

Figure 2. View of original and after cold-in-place recycling road condition

Prior to the CIR process, preparatory steps were implemented to ensure optimal conditions. The pavement surface was cleaned to remove debris and allow effective milling. Milling depth was carefully adjusted to preserve the existing structural base and ensure uniform depth along the roadway.

The CIR process (Figure 3a) started with uniform cement spreading (Figure 3b), followed by milling and simultaneous mixing with a bituminous emulsion heated to 50 °C (Figure 3a). The reclaimed and stabilized mix was then placed using a paver (Figure 3a) and compacted with pneumatic and vibratory rollers to reach the target density (Figure 3c). The entire operation was executed at a constant speed to ensure material uniformity.

Figure 3. Cold-in-place recycling process: a) overall view of the recycling train, b) cement spreader and, c) pneumatic and steel drum rollers used for compaction
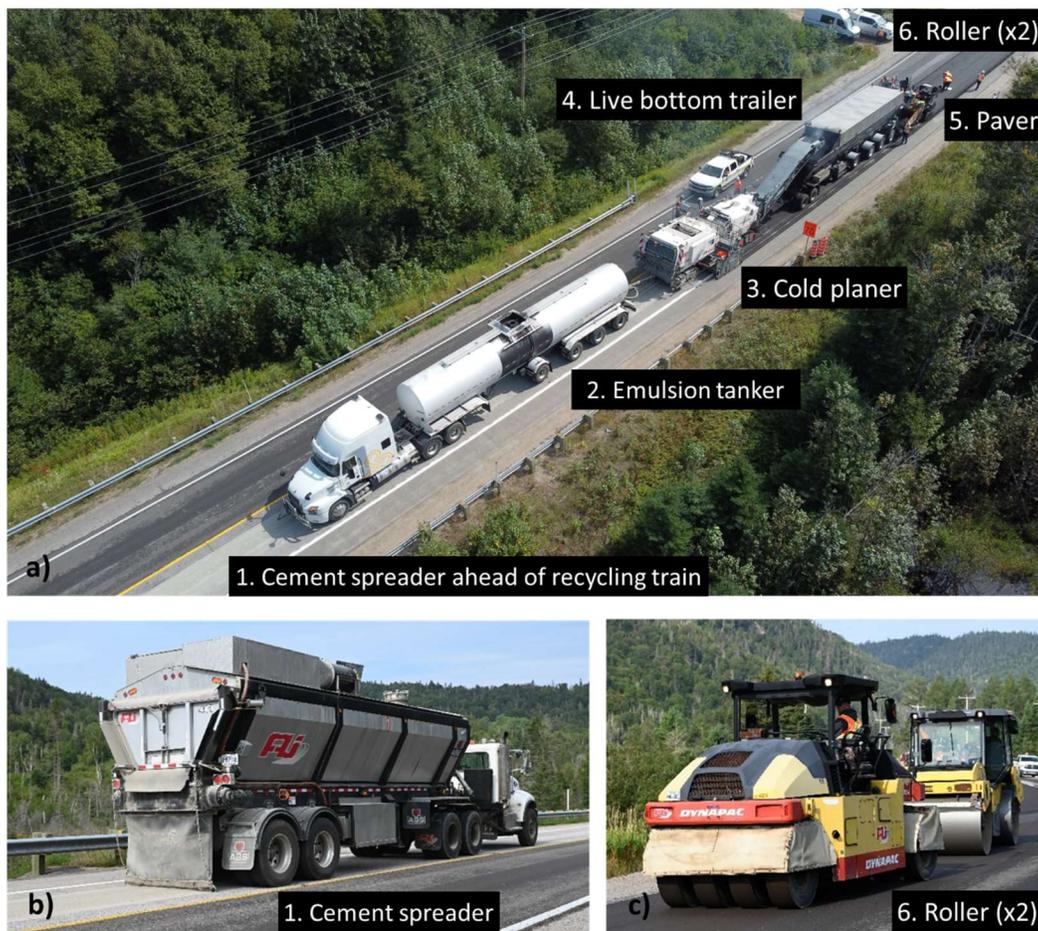
Experimental campaign

Methodology

All measurements were conducted on the west direction lane due to constraints related to traffic management and construction activities. During compaction, density control was performed to ensure that the appropriate density was reached. Once the target compaction was achieved, LWD tests were conducted at the same chainages to evaluate the surface modulus. These values were subsequently used to backcalculate the elastic modulus of CIR layer. At each of the six chainages (S1 to S6), four LWD tests were performed transversely across the lane, as illustrated in Figure 4 (-1 to -4). The first point was positioned 610 mm from the centerline, followed by three additional points spaced at 914 mm intervals.

Figure 4. Field layout of transversal testing points for LWD measurements, showing spacing from centerline and marked test positions

At each testing location, a minimum of ten LWD drops were performed (at least five at a drop height of 406 mm and five at 813 mm) to evaluate the surface modulus. A 200 mm diameter loading plate was employed, ensuring deflection values remained within the acceptable range of 150 to 2200 μm. Prior to each test sequence, surface temperature was measured adjacent to the testing point using an infrared thermometer. Testing was carried out at three distinct time intervals: immediately after compaction (0 h), after one hour (1 h, except at S6), and after 24 hours (total of 68 LWD tests). Some measurements could not be completed due to restrictions imposed by traffic management and ongoing construction activities.

Backcalculation of the CIR layer modulus was performed using the BackCAP software[8], which integrates the finite element method (FEM) through the CAP3D tool[9]. The solution minimizes the squared differences between measured and calculated deflections using gradient-based optimization algorithms, such as Gauss-Newton or Levenberg-Marquardt[8, 10]. The modeled pavement structure comprised a 100 mm CIR layer over a semi-infinite subbase. Initial screening revealed that data from chainage S1 differed from other locations. This point was located approximately 135 m from the start of the work zone, an area typically used as a buffer section for equipment calibration and operation adjustments. Given the potential variability in material properties within this segment, data from S1 were excluded from the analysis to maintain consistency.

To allow comparison between test points, the elastic modulus values were adjusted to a reference temperature of 25 °C using the correction model proposed by Chen et al. (2000), as shown in Equation 1[11].

$$E_{T_W} = E_{T_c}/[(1.8\,T_W + 32)^{2.4462} \times (1.8\,T_c + 32)^{-2.4462}]$$ Equation (1)

Where: E_{T_W} = modulus at the adjusted temperature; E_{T_c} = modulus at the temperature measured in the field survey; T_W = adjusted temperature (25 °C); T_c = temperature measured (°C) during the field survey.

Results and discussion

Influence of temperature on elastic modulus

Figure 5 presents the elastic modulus values of the CIR layer before and after temperature correction. At 0 h, the average surface temperature was 31 °C (standard deviation: SD = 7 °C; range: 19–41 °C). At 1 h, the average increased to 34 °C (SD = 3 °C; range: 30–39 °C). After 24 h, the average temperature decreased to 27 °C (SD = 5 °C; range: 18–34 °C). Without correction, the average elastic modulus was 222 MPa at 0 h (SD = 83 MPa), 269 MPa at 1 h (SD = 62 MPa), and 515 MPa after 24 h (SD = 260 MPa).

After applying the correction to a reference temperature of 25 °C (Chen et al., 2000: Equation 1), the average modulus values were 337 MPa at 0 h (SD = 213 MPa), 445 MPa at 1 h (SD = 133 MPa), and 567 MPa at 24 h (SD = 292 MPa). The temperature correction reduced the variability associated with the thermal fluctuation, although some residual dispersion remains, likely associated with the curing process.

The increase in modulus with temperature correction (e.g., from 222 to 337 MPa at 0 h) reflects the expected temperature sensitivity of the material. Additionally, the progressive increase in modulus over time is attributed to curing advancement. In mixtures containing bituminous emulsion and Portland cement, higher curing temperatures accelerate stiffness development[12]. Thus, curing-related effects likely contributed to the observed variability, especially at early ages.

Figure 5. Variation in average elastic modulus at different curing times (0 h, 1 h, and ≈24 h) without (w/o) and with (w) temperature correction (values in gray: standard deviation)
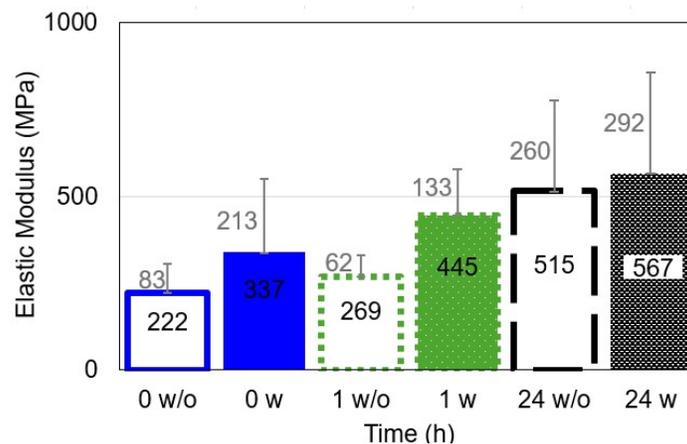

Spatial heterogeneity on elastic modulus, longitudinal variations along the roadway

The longitudinal variability of the roadway was evaluated based on the elastic modulus values measured ≈24 hours after compaction, as illustrated in Figure 6. Due to traffic management, the testing times were as follows: S2 at 26 h, S3 at 23 h, S4 at 23 h, S5 at 22 h, and S6 at 20 h.

S3 and S5 showed the lowest average modulus values (< 500 MPa: Figure 6), suggesting potential issues such as insufficient compaction, moisture fluctuations, or variability in recycled materials. These contrasting sections provide insights into factors affecting mechanical performance across the pavement structure. Moreover, the results from S3 (23 h) and S5 (22 h) were similar, likely due to comparable curing

times, material characteristics, and consistent construction practices. This uniformity highlights the importance of strict quality control during execution.

Figure 6. Elastic modulus variation along different chainage points of roadway (values in grey: SD)
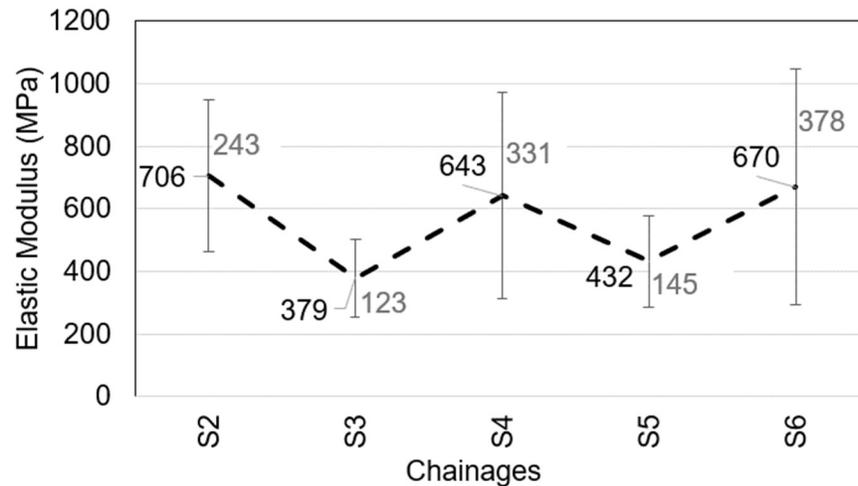
On the other hand, S6 (670 MPa), S4 (643 MPa), and S2 (706 MPa) exhibited similar average values (Figure 6), suggesting a stabilization of mechanical properties likely due to material homogeneity or consistent construction conditions. However, the differences in curing times (20 h for S6, 23 h for S4, and 26 h for S2) may have influenced the results.

Spatial heterogeneity on elastic modulus, transversal variations along the roadway

Figure 7 presents the average elastic modulus at four transversals locations (-1 to -4) after 0 h, 1 h, and ≈24 h of curing, based on measurements form five chainages (S2 to S6) and corrected for temperature.

Location 4 (outer wheel path) consistently exhibited the highest stiffness (430 MPa at 0 h, 502 MPa at 1 h, and 704 MPa at ≈24 h), likely due to vehicle-induced densification. Location 1 (inner wheel path) showed the second-highest values (338, 491, and 584 MPa, respectively), possibly benefiting from better confinement and compaction. In contrast, intermediate Locations 2 and 3 had lower and similar values (≈300 MPa at 0 h, ≈400 MPa at 1 h, and just > 500 MPa at 24 h).

These results suggest that localized factors such as traffic loading, material placement, compaction variability, and confinement influence stiffness distribution across the section. Over time, stiffness differences tend to diminish, indicating increasing material homogeneity as curing progresses. This highlights the importance of considering transversal variability in quality control and performance evaluation, particularly in early stages, when local variations are more pronounced. These effects, as demonstrated by Clauß and Wellner (2022), can affect internal stress distributions and the overall service life of pavements[13].

Figure 7. Variation of elastic modulus across transversal locations over time (SD: values in gray)
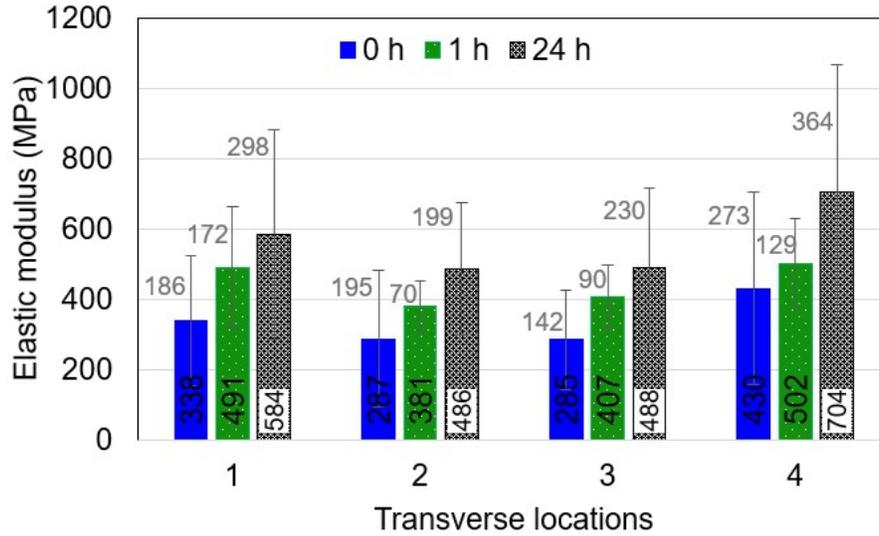

Elastic modulus evolution during early curing stages

Figure 8 illustrates the evolution of the elastic modulus over early curing times (0, 1, and ≈24 h), with and without temperature correction. A total of 749 backcalculated modulus values were analyzed.

An increase in stiffness was observed (from 337 or 222 MPa at 0 h to 445 or 269 MPa at 1 h, and 567 or 515 MPa at ≈24 h) regardless of temperature adjustment (w curve in Figure 8). This trend confirms that curing is the main factor driving stiffness gain, though temperature and humidity also influence results (w/o curve in Figure 8).

Figure 8. Elastic modulus at different curing times without (w/o) and with (w) temperature correction
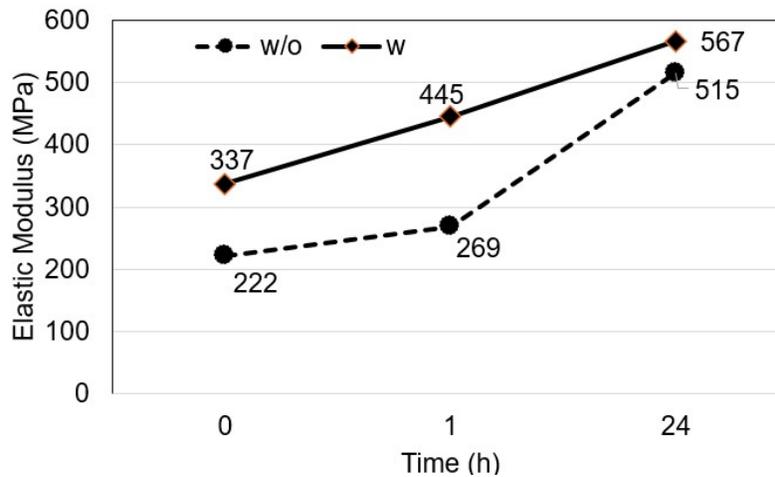
The thermal correction (w curve) in Figure 8 reduces environmental variability, allowing the effects of curing to be more clearly isolated. Unger Filho et al. (2020) reported stiffness increases from 1,000–2,000 MPa to 3,500 MPa over a curing period of 28–56 days, while Chan et al. (2009) reported modulus values

near 1,100 MPa after two months. Both emphasize the critical role of curing in improving mechanical performance.

Temperature correction improves reliability by ensuring that modulus values accurately reflect intrinsic behaviour of the material. However, further research (for example, laboratory characterisation) is needed to better understand the interaction between curing and environmental factors, especially given the thermosensitive nature of CIR materials.

Early-stage evaluations (within 24 h) are especially valuable, as they provide a practical quality-control tool for agencies and contractors. By integrating rapid LWD testing with temperature-corrected BackCAP backcalculation during construction, field teams can verify stiffness gain and identify localized weaknesses (e.g., low-modulus zones such as S3 and S5) before traffic opening. Furthermore, linking early modulus verification to agency maintenance programs supports a more sustainable pavement network: fewer premature repairs translate into reduced life-cycle greenhouse-gas emissions, lower aggregate consumption, and minimized disruption to road users. These findings therefore move beyond laboratory investigation, offering a framework for specification updates and long-term performance monitoring that directly supports sustainable road maintenance practices.

Conclusion

This study investigates the factors influencing the elastic modulus of cold in-place recycled (CIR) pavement layers, with a focus on mechanical behaviour and the impact of environmental variability. To minimize the influence of temperature fluctuations during field evaluations, thermal correction was applied, allowing elastic modulus values to be standardized to a reference temperature. This approach improves the consistency of comparisons, particularly in regions subject to wide thermal variation.

Tests revealed spatial heterogeneity in both longitudinal and transversal directions, with notable differences at specific chainages and along the outer wheel paths. These findings highlight the importance of distributed measurements across the pavement surface to assess structural uniformity and detect localized variations.

The evolution of the elastic modulus over time, measured at approximately 0, 1, and 24 hours after construction, reflects the influence of the curing process on stiffness development. Monitoring mechanical behaviour at early stages provides useful data on the initial stabilization of the material.

For quality control purposes, the implementation of transversal and longitudinal measurements along the test section is recommended. The use of tools such as BackCAP software, which incorporates load and temperature normalization, contributes to more consistent and reliable modulus evaluation. In addition, integrating periodic LWD testing during construction, supported by laboratory validation, strengthens the assessment of mechanical behaviour. It is also recommended that the first 150 meters of the job site be excluded from quality control analyses to allow proper calibration of the construction equipment.

To ensure the robustness and generalizability of the findings, the application of advanced statistical methodologies is imperative. These approaches facilitate a deeper understanding of spatiotemporal variability and enhance the reliability and scientific rigor of mechanical performance evaluations in recycled pavement layers.

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