Design and Field Implementation of Pavement Instrumentation System for Monitoring High-RAP Warm Mix Asphalt Performance

Omran Maadani, PhD. (Corresponding Author)
Senior Research Officer
Resilient and Sustainable Infrastructures (RSI)
National Research Council Canada (NRC)
1200 Montreal Road, M-20, Ottawa, Ontario K1A 0R6 Canada
Phone: (613) 9798313
Email: omran.maadani@nrc-cnrc.gc.ca

Mehran Farashah, Ph.D., P.Eng., PMP
Transportation Asset Management Engineer
Transportation Infrastructure Asset Management, Public Works
Email: Mehran.Farashah@york.ca

Kerolus Khalil, PMP, P.Eng
Senior Project Manager
Capital Delivery – Transportation
Capital Infrastructure Services, Public Works
Email: kerolus.khalil@york.ca

Nasir Aslam C.E.T.,
Project Lead (Lead Designer) York Region
Planning & Design Coordinator
Nasir.aslam@york.ca

Paper prepared for the session {SO - Innovation in Roadway/Embankment Materials and Geotechnical Engineering}
2026 Transportation Association of Canada (TAC) Conference & Exhibition
Winnipeg, Manitoba

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the National Research Council of Canada (NRC), Low Carbon Built Environment (LCBE) for their financial support and guidance and to York Region for their in-kind contributions and strong collaboration throughout the project. The authors also acknowledge Engtec for their support with Falling Weight Deflectometer (FWD) testing, and Viola, the subcontractor, for their continuous assistance during and after construction activities.

Special recognition is extended to NRC technical officers Nirob Ahmed and Antal Prigli for their valuable technical guidance, support, and contributions to the successful implementation of the field instrumentation program.

ABSTRACT

This paper presents the design and implementation of a cost-effective pavement instrumentation system developed to evaluate the structural and environmental behaviour of asphalt pavement sections. The system design considers pavement layer configuration and material composition to guide sensor selection, layout, and data acquisition strategies. Particular emphasis is placed on capturing the effects of seasonal variations in temperature and moisture on pavement response.

The monitoring system incorporates both static and dynamic measurement capabilities to assess early-age pavement performance, including initial deformations, stresses, and corresponding asphalt temperatures. In addition, the system enables evaluation of the impact of high asphalt temperatures on the structural integrity and performance grade of asphalt binders.

The instrumentation includes moisture sensors and thermocouples to quantify environmental gradients within the pavement structure, along with sensors to measure structural responses under traffic loading. The system was implemented across five full-scale pavement sections in York Region, including four trial sections and one control section, as part of a research program aimed at maximizing the use of Reclaimed Asphalt Pavement (RAP) in Warm Mix Asphalt (WMA). RAP contents ranged from 20–30% in surface mixes and 30–40% in base mixes, exceeding current Ontario municipal specifications.

This paper details the instrumentation design, sensor selection, installation procedures, a unique temperature-dependent testing protocol, and the data management framework developed to support reliable long-term monitoring. The testing protocol captures the viscoelastic response of PG 64-28 warm-mix asphalt by evaluating pavement performance across critical high-temperature and representative in-service conditions. Field results demonstrate strong sensitivity of pavement response to temperature variations and traffic speed, confirming the effectiveness of the system. The proposed approach provides a practical framework for implementing in-situ pavement instrumentation in full-scale projects

Keywords: Sustainability, Pavement Instruemnation, Smar Roads, Reclaimed Asphalt Pavement

INTRODUCTION

The use of Reclaimed Asphalt Pavement (RAP) has become a key strategy in advancing sustainable pavement construction in Canada. RAP consists of recycled materials obtained from the milling or removal of existing asphalt layers, which are then processed and reused in new asphalt mixtures, including Warm Mix Asphalt (WMA). The growing interest in RAP is driven by the need to reduce both the environmental footprint and the economic cost of road construction while maintaining or enhancing pavement performance. Given that asphalt concrete constitutes more than 90% of Canada's paved road network, the potential for resource conservation through RAP utilization is substantial.

The incorporation of RAP in asphalt mixtures offers significant environmental and economic benefits. By reducing the demand for virgin aggregates and asphalt binders, both energy-intensive materials, RAP contributes to lower energy consumption, decreased greenhouse gas emissions, and reduced reliance on landfills. Previous studies (Zhao et al., 2021; Arshad et al., 2018 and Ma et al., 2022) have shown that increasing RAP content can lead to measurable reductions in construction costs while supporting sustainability objectives. In addition, the use of recycled materials aligns with broader efforts to promote circular economy practices within the transportation infrastructure sector.

Despite these advantages, the performance of RAP-containing mixtures remains a critical concern, particularly in cold regions such as Canada. The presence of aged asphalt binder in RAP can increase mixture stiffness, which may negatively affect resistance to cracking under low temperatures and repeated freeze–thaw cycles (Baaj, 2018). Seasonal variations in temperature and moisture further complicate pavement behaviour, influencing both the mechanical response of materials and long-term durability. As a result, there is a need for a comprehensive field evaluation to better understand how high RAP contents perform under real service conditions.

To address these challenges, this study focuses on the development and implementation of a full-scale pavement instrumentation system (Maadani, et al., 2014 and Robin and Wei, 1997) designed to monitor both structural and environmental responses of RAP containing WMA mixtures. The system enables continuous measurement of key parameters such as stress, strain, temperature, and moisture within the pavement structure. By capturing both static and dynamic responses under traffic loading and environmental variations, the system provides valuable insight into the in-situ performance of high RAP mixtures.

This paper presents the design, installation, and application of an in-situ pavement instrumentation system across multiple pavement sections incorporating varying reclaimed asphalt pavement (RAP) contents that exceed the limits specified in the current Ontario municipal specifications (OPSS 1151, 2020), constructed in York Region, Ontario.

The objective is to evaluate the feasibility and performance of high RAP usage in WMA mixtures and to assess the influence of environmental conditions and traffic loading on pavement behaviour. The findings from this study aim to support the development of improved design practices and guidelines for the sustainable use of RAP in asphalt pavements, particularly in cold climate regions.

PROJECT SCOPES AND OBJECTIVES

The scope of this project involves evaluating the feasibility and benefits of incorporating Reclaimed Asphalt Pavement (RAP) in road construction. The study focuses on identifying opportunities to enhance pavement durability, reduce construction costs, and minimize environmental impacts associated with conventional asphalt materials.

The primary objective is to develop and implement a comprehensive experimental program for full-scale trial sections to monitor the structural and environmental behaviour of RAP-blended mixtures. This includes the application of a unique testing protocol developed in this study, supported by collaboration with municipal agencies, contractors, and consulting partners.

Through a combination of in-situ monitoring and advanced laboratory testing, the project aims to quantify the performance of RAP mixtures and assess the feasibility of higher RAP contents in asphalt applications. The study also seeks to evaluate the interaction between material properties, traffic loading, and environmental conditions.

In addition, the project aims to establish best practices and develop design guidelines to support the broader adoption of RAP in asphalt pavement construction. These outcomes are intended to assist municipal agencies in implementing more sustainable, cost-effective, and performance-driven pavement solutions.

PRE-CONSTRUCTION ACTIVITIES

The design of a cost-effective pavement monitoring system requires careful consideration of structural and environmental data needs while ensuring reliable long-term performance. Instrumentation was selected to accurately monitor pavement response under varying traffic and environmental conditions, including changes in temperature and moisture that influence pavement behaviour.

The monitoring system incorporates reliable environmental and structural sensors, including moisture sensors and Type T thermocouples connected through a 12-pair Type T thermocouple cable, allowing up to twelve independent temperature measurements using a single cable. This configuration reduces installation complexity, cabling requirements, and overall instrumentation costs while providing continuous temperature profiles and frost penetration measurements. The system is powered by solar panels with rechargeable battery storage, eliminating the need for grid electricity and enabling economical, uninterrupted monitoring at remote sites.

The field experimental program was developed in collaboration with the Ontario Road Builders' Association (ORBA), the Ontario Asphalt Pavement Council (OAPC), and York Region. Five test sections representing different pavement structures and RAP contents were selected, with construction, instrumentation installation, and quality control carried out jointly by York Region, the project contractor, and the research team to ensure consistent and reliable field data collection

Test sections

Five pavement sections within York Region were selected for instrumentation, as summarized in Table 1. Sensors were installed along both the inner and outer wheel paths of the slow lane to monitor pavement structural responses under traffic loading, as well as daily and seasonal variations in environmental conditions.

Table 1 summarizes the characteristics of the instrumented test sections, including asphalt mixture types, reclaimed asphalt pavement (RAP) content, traffic conditions, pavement layer configurations, and site identification. The study consists of four trial sections incorporating different RAP percentages and one control section for performance comparison.

Evotherm M1 was used as a warm mix asphalt (WMA) additive at a dosage of 0.3% by weight of binder. It was incorporated into both the surface and binder courses of Sections 1 and 5, the binder course of Section 2, and the surface course of Sections 3 and 4. ReLIXER rejuvenator was applied at a dosage of 0.3 kg/tonne of asphalt mixture in the surface course of Section 2 and the binder courses of Sections 3 and 4.

Table 1: Section details

Location	Mix Type		WMA Thickness, mm	Instrumentation Site Number
130m North of Commerce Valley Drive to Hwy 7	Surface Course	SP12.5 FC2 PG64-28 0%RAP	210	1 (Control Section)
	Binder Course	SP25 PG64-28 10%RAP		
Hwy 7 to 16th Avenue	Surface Course	SP12.5 FC2 PG64-28 30%RAP	210	2
	Binder Course	SP25 PG64-28 10%RAP		
16th Avenue to Major Mackenzie Drive (1st Box)	Surface Course	SP12.5 FC2 PG64-28 0%RAP	180	3
	Binder Course	SP25 PG64-28 40%RAP		
16th Avenue to Major Mackenzie Drive (2nd Box)	Surface Course	SP12.5 FC2 PG64-28 0%RAP	180	4
	Binder Course	SP25 PG64-28 30%RAP		
Major Mackenzie Drive to Elgin Mills	Surface Course	SP12.5 FC2 PG64-28 20%RAP	180	5
	Binder Course	SP25 PG64-28 10%RAP		

Infrastructure

Instrumentation Boxes

Instrumentation boxes were constructed and installed at each test site to house the data acquisition systems and associated components. These installations were carried out by York Region in collaboration with the project contractor. Each instrumentation box includes the required data logging equipment and accessories, along with two conduits (100 mm in diameter) to route cables from the embedded pavement sensors to the data acquisition system.

Power supply

A solar-powered energy system was installed by the National Research Council (NRC) to provide reliable power to the instrumentation system at each site. The system also supports wireless communication, enabling remote access to the data loggers for continuous monitoring and data retrieval.

INSTRUMENTATION PLAN

The instrumentation plan was developed to monitor the structural and environmental behaviour of pavement layers under both traffic loading and climatic conditions. Structural responses, including stresses and strains within pavement layers, are measured using embedded pressure cells and strain gauges installed during construction (Gancalves, et al., 2003).

To capture environmental influences, moisture sensors and thermocouples are incorporated to monitor variations in moisture content and temperature throughout the pavement depth. These measurements enable the assessment of environmental gradients and their impact on material performance. Thermocouple arrays are also used to determine frost depth and track freeze–thaw cycles at each site.

Selection of sensors

The sensors and data acquisition system were selected based on the study objectives and the conditions of the constructed pavement sections. The instrumentation was designed to monitor structural responses and environmental conditions affecting pavement performance.

Sensors were installed to measure deformation, strain, pressure, moisture, and temperature. These measurements were used to evaluate the effects of environmental conditions and varying RAP contents on pavement behavior and long-term performance

Structural response

The structural response of the pavement system was evaluated by measuring stress and strain within the asphalt layers, including the warm mix asphalt (WMA), and the underlying granular base under both static and dynamic loading conditions.

Current pavement design methodologies identify tensile strain at the bottom of the asphalt layer as a critical parameter for evaluating pavement performance. Accordingly, four asphalt concrete strain gauges (AST1000-6) were installed at each test site to measure tensile strain responses at the bottom of the asphalt layer.

The deformation behavior of the unbound pavement layers, particularly volumetric deformation, was monitored using two deformation sensors (SCS-015) installed at each site. Data collected from these sensors were used to quantify permanent deformation and estimate the resilient modulus of the pavement layers.

In addition, stresses transmitted through the pavement structure to the unbound layers were monitored using four pressure cells (LPTPC09-9-S-1.0) installed at each site to measure both vertical and horizontal stress components. These measurements provide valuable insight into load distribution, stress transfer mechanisms, and the overall structural behavior of the pavement system under traffic loading.

Environmental response

The selection of these sensors was based on their ability to monitor key environmental parameters that influence pavement performance. Each site was instrumented with one 12-pair Type T (copper–constantan) thermocouple cable, providing temperature measurements at 12 locations throughout the pavement depth, and two moisture sensors embedded within the pavement structure.

The temperature and moisture data are essential for evaluating the effects of climatic conditions on pavement material behavior and for interpreting pavement responses under traffic loading. These measurements also provide valuable information for assessing the long-term performance of the pavement structure.

Data acquisition systems and accessories

This section provides an overview of the data acquisition system deployed across the five instrumented pavement sections, including the data loggers, communication devices, and power supply. It also describes the data collection strategy and sampling frequencies adopted to capture both the structural response of the pavement under traffic loading and environmental variations, including temperature and moisture.

The collected data are classified into two categories: dynamic and static measurements. Dynamic measurements are acquired to capture the real-time structural response of the pavement under traffic loading. These measurements are collected during scheduled field testing, which requires the presence of the research team on site and high-frequency data acquisition. Static measurements are used to

monitor the long-term behaviour of the pavement structure, including the accumulation of permanent deformation under repeated traffic loading. Environmental parameters, including pavement temperature and moisture content, are also monitored as part of the static data collection program. These measurements are recorded four times per day to support the evaluation of the temperature sensitivity of asphalt concrete and the moisture-dependent behaviour of the resilient modulus (Mr). Each instrumented section is equipped with two data loggers: (a) one DT85 data logger for static data acquisition and (b) one MX16901B data logger for dynamic data acquisition. Remote communication is provided through a RUT956 industrial router equipped with a SIM card, while the power supply consists of a solar panel coupled with a battery storage system regulated by a GENASUN GV-10 charge controller.

The data acquisition system was designed to satisfy the objectives of this project by continuously monitoring both the structural and environmental responses of the pavement system. As described in the previous section, the selection and configuration of the sensors were based on the pavement structure, anticipated loading conditions, and environmental exposure. Appropriate sampling frequencies were established according to the operating characteristics of each sensor and the expected loading scenarios, and these parameters were incorporated into the data logger programming.

The overall system architecture, including the connections between the sensors, data loggers, communication devices, and power supply, is illustrated in Figure 1. Static measurements, including temperature, moisture content, stress, frost depth, and permanent deformation are collected using the DT85 data logger. These measurements are automatically recorded four times per day according to a predefined schedule programmed into the data acquisition system. The recorded data are transmitted remotely via the RUT956 communication module to a central data storage facility at the National Research Council (NRC) headquarters in Ottawa, Canada, where they are archived, quality-checked, and processed for subsequent analysis.

Dynamic measurements are collected using the MX16901B data logger during controlled field testing involving a calibrated test truck with known axle loads representative of typical traffic conditions in York Region, as well as during Falling Weight Deflectometer (FWD) testing. The dynamic response is obtained from four asphalt strain gauges installed at the bottom of the asphalt layer, four pressure cells installed within the pavement structure, and two deformation sensors embedded in the granular backfill. These measurements are acquired at sampling frequencies ranging from 1,200 to 1,400 Hz to accurately capture transient pavement responses under moving wheel loads.

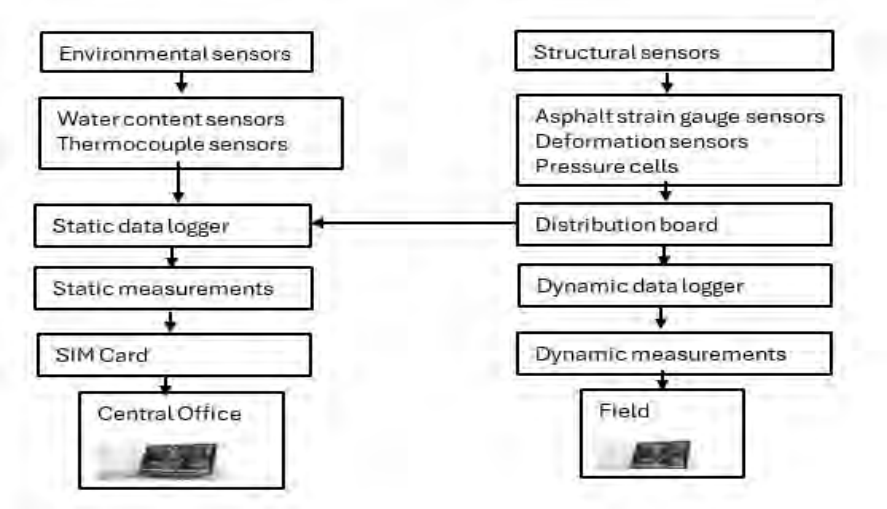


Figure 1: Instrumentation master flow chart

Sensors Layout

This section presents the layout of the five sensor types used in the instrumented pavement sections: soil moisture content sensors (M), asphalt strain transducers (S), total earth pressure sensors (P), soil compression sensors (D), and thermocouple sensors (T). A typical plan view illustrating the spatial arrangement of these sensors is shown in Figure 2.

Figure 3 presents a representative vertical cross-section of the pavement structure, including the detailed positioning of all sensors within the different pavement layers. The pavement structures constructed in York Region, Canada, consist of RAP-blended asphalt concrete surface layers with thicknesses of 180 mm and 210 mm, as summarized in Table 1. The cross-section also illustrates the placement of sensors relative to layer interfaces to ensure accurate monitoring of both structural and environmental responses.

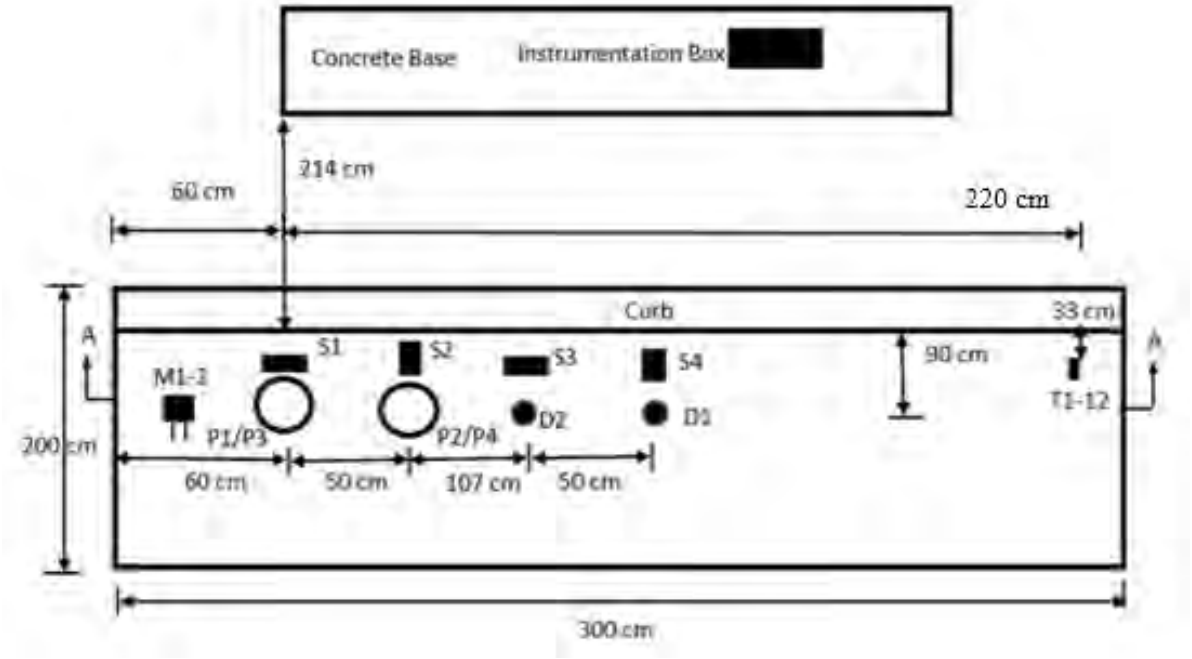


Figure 2: Plan view of all sensors

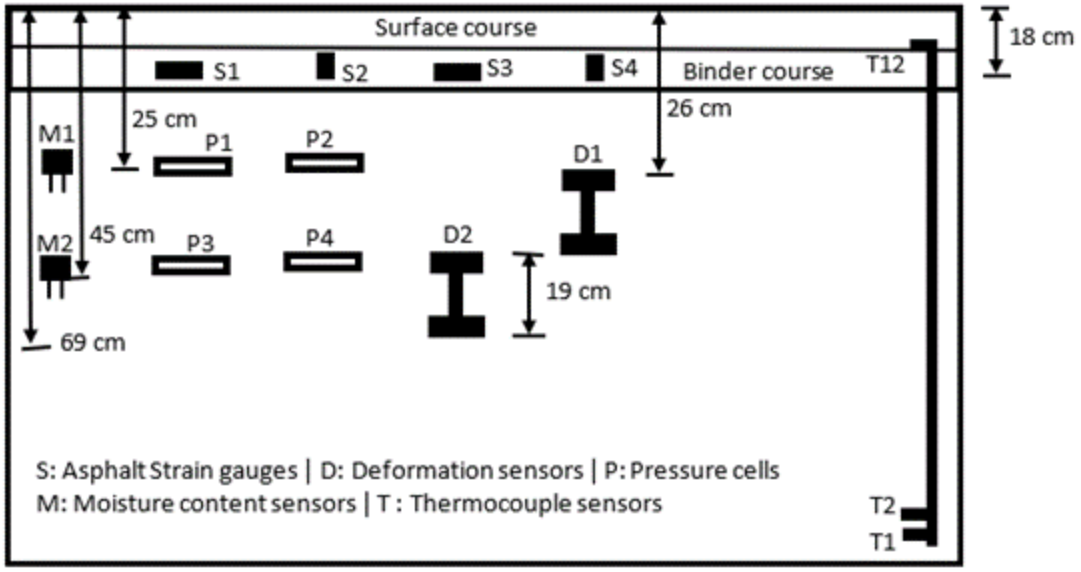


Figure 3: Vertical cross section A-A -Section 3

POST CONSTRUCTION ACTIVITIES

Monitoring program

A comprehensive monitoring protocol was developed to capture both static and dynamic pavement responses during and after construction. The structural and environmental performance of the instrumented pavement sections will be monitored over two years to assess the influence of seasonal variations and long-term environmental effects.

Throughout the monitoring period, static data will be collected remotely using the installed data acquisition system. In addition, three scheduled field visits per year will be conducted to collect dynamic data using a calibrated test truck and a Falling Weight Deflectometer (FWD).

Immediate post-construction testing evaluated the response of the pavement system under different asphalt temperature conditions, including the maximum Performance Grade (PG) temperature (64°C), one grade above the PG temperature, and typical in-service temperatures (25–40°C). A unique testing protocol was developed to account for the temperature-dependent viscoelastic behavior of PG 64-28 warm-mix asphalt (WMA), enabling performance evaluation across both critical high-temperature and representative in-service conditions. The tests assessed load transfer mechanisms, deformation characteristics, and stress distribution within the pavement structure and underlying layers. At elevated temperatures, reduced asphalt stiffness can diminish the load-distributing capability of the surface layer, increasing stress transfer to the underlying layers. This testing phase also evaluated the adequacy of the selected PG 64-28 binder under high-temperature conditions immediately after construction.

Environmental and Seasonal Effects

The monitoring program also investigates the influence of environmental variability on flexible pavement performance. This includes daily and seasonal fluctuations in temperature and moisture, as well as freeze–thaw cycles. These factors are expected to significantly affect pavement life, stiffness, and deformation behaviour.

In addition, the study examines the potential impacts of climate change on freeze–thaw depth progression throughout the pavement structure using thermocouple measurements installed at multiple depths.

Static data collection

Static data collection forms the basis of long-term pavement performance evaluation. Initial measurements of environmental conditions, stress, and deformation are recorded immediately after construction to establish baseline conditions. These baseline data provide an essential reference for all subsequent analyses.

Following the initial measurement phase, data are collected biweekly over a two-year monitoring period and transmitted to the central data management facility at the National Research Council (NRC). The static monitoring program includes:

- Establishment of baseline conditions for all structural and environmental sensors
- Measurement of permanent deformation accumulation over time under traffic loading
- Evaluation of layer-specific contributions to pavement deformation using embedded sensors
- Remote data retrieval through a programmed acquisition system and communication modem
- Periodic road surface profile surveys to quantify surface deformation
- Biannual longitudinal and transverse survey measurements to assess overall pavement deformation
- Visual inspections to identify surface distress, including cracking
- Continuous monitoring of temperature and moisture variations within the pavement structure

Dynamic data collection

Dynamic testing is conducted using both a calibrated test truck and a Falling Weight Deflectometer (FWD), supported by the dynamic data acquisition system. These tests are performed immediately after construction completion and repeated three times per year over the two-year monitoring period.

Dynamic testing is carried out under varying pavement surface temperatures and truck speeds to evaluate the influence of thermal conditions and loading rate on pavement response. The initial FWD testing phase provides baseline deflection basin measurements, which serve as a reference for future comparisons.

During FWD testing, loads are applied directly above the locations of embedded sensors, including pressure cells, asphalt strain gauges, and deformation sensors. All test locations are pre-marked to ensure repeatability and consistency across monitoring events.

For test truck operations, controlled passes are conducted along the designated wheel paths, which are clearly marked on the pavement surface. Each pass is used to capture synchronized sensor responses across the instrumented network.

Data management

Field experiments were conducted to evaluate the performance of the instrumented pavement sections. Pavement performance was assessed by analyzing the mechanical response of the roadway under the combined influence of environmental conditions, material properties, traffic loading, and construction practices. The purpose of this section is to define a standardized procedure for managing and processing data collected from the instrumented pavement systems.

File storage and naming conventions

Data are retrieved remotely by the instrumentation team and stored on secure National Research Council (NRC) systems. A backup copy of all collected data is maintained using dedicated project storage media (e.g., external drives) to ensure data security and redundancy.

Data are organized in a structured directory system, where each pavement section is assigned a dedicated folder. This structure facilitates efficient data retrieval, processing, and long-term archiving.

Data Testing and Quality Control

Prior to final storage and analysis, weekly datasets are subjected to quality control procedures. These checks are performed to identify and correct potential errors in the recorded data. Common issues include:

- Instrument malfunction
- Values below the measurement range
- Values exceeding the measurement range
- Signal noise and data irregularities

Noise reduction is performed using signal processing techniques, including Fast Fourier Transform (FFT) filtering where appropriate.

Data conversion

All field data are initially recorded in voltage format. These raw signals are then converted into engineering units using calibration equations provided by NRC and/or sensor manufacturers. This conversion process ensures consistency and accuracy across all datasets, enabling meaningful comparison and analysis of pavement responses.

TYPICAL RESULTS AND ANALYSIS

Environmental data

One of the key objectives of this study was to evaluate the influence of temperature and moisture variations on the structural response of different pavement layers. Temperature and moisture gradients were continuously monitored throughout the pavement depth using thermocouples and moisture sensors.

All five test sections are located in regions subject to seasonal frost penetration. To capture freeze–thaw behaviour, each site was instrumented with 12 thermocouples installed at different depths to monitor frost development and propagation within the pavement structure.

Moisture content profiles

Volumetric water content was measured using water content reflectometers based on the Time Domain Reflectometry (TDR) principle. These measurements were converted to gravimetric water content using established calibration relationships.

Typical moisture profiles obtained during the first few months after construction are presented in Figure 4. The results indicate greater variability in the lower portion of the backfill layer (approximately 12–20%) compared to the upper portion (approximately 8–16%). This variation reflects the influence of subgrade conditions and drainage characteristics on moisture distribution within the pavement structure.

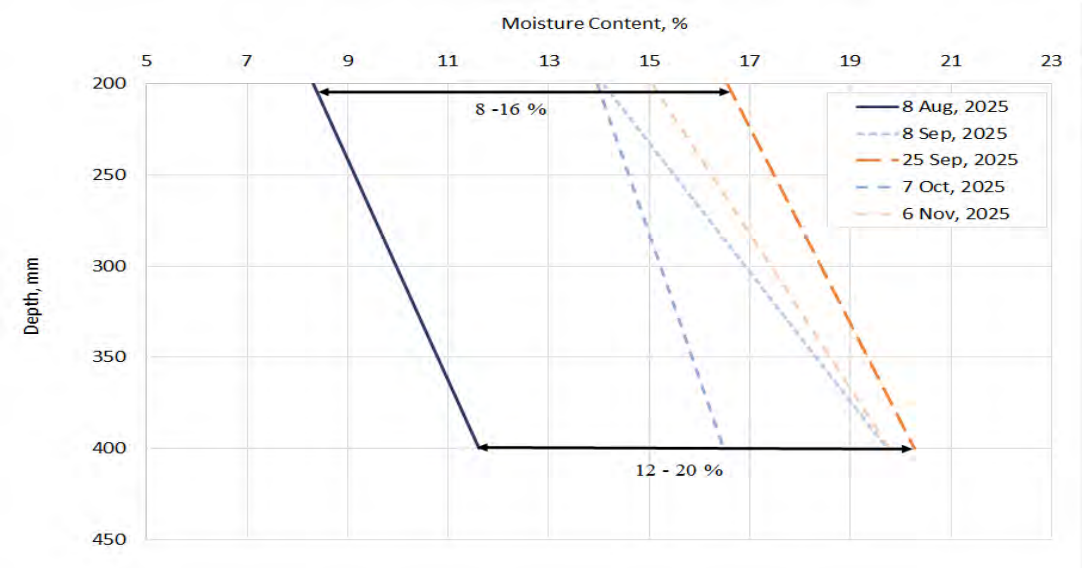


Figure 4: Moisture content profile

Temperature profile

Temperature data were recorded on a daily basis throughout the monitoring period (four years) to capture both seasonal and long-term thermal behaviour of the pavement system. Representative temperature profiles for both bound (asphalt) and unbound layers are presented in Figure 9.

The results show consistent thermal gradients across the pavement structure, with similar temperature variation trends observed in both material types. These measurements also allow identification of freezing conditions and the depth of frost penetration during winter periods.

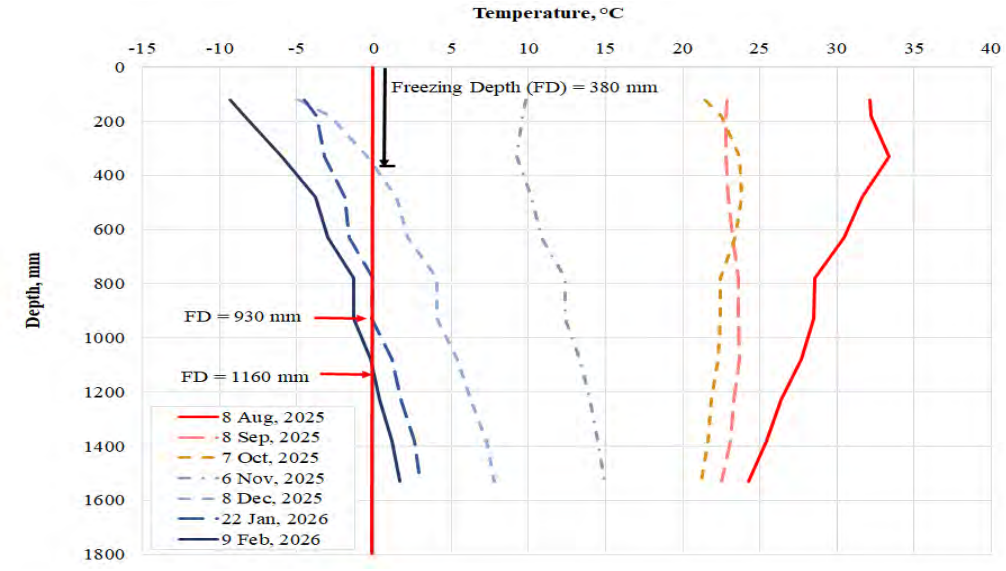


Figure 5: Temperature profile and freezing depth

Freeze and thaw diagram

The progression of freezing fronts within the pavement structure was evaluated using temperature data obtained from thermocouples installed at multiple depths. The onset of freezing was defined as the point at which recorded temperatures crossed the 0°C threshold within the backfill layer.

By tracking this transition over successive days, the development and propagation of the freezing front were determined and plotted as a function of depth, as shown in Figure 6. This process enables continuous monitoring of freeze–thaw cycles and their influence on pavement performance over time.

The resulting freeze–thaw diagrams also provide a basis for evaluating the potential influence of RAP content on thermal response and frost susceptibility within the pavement structure.

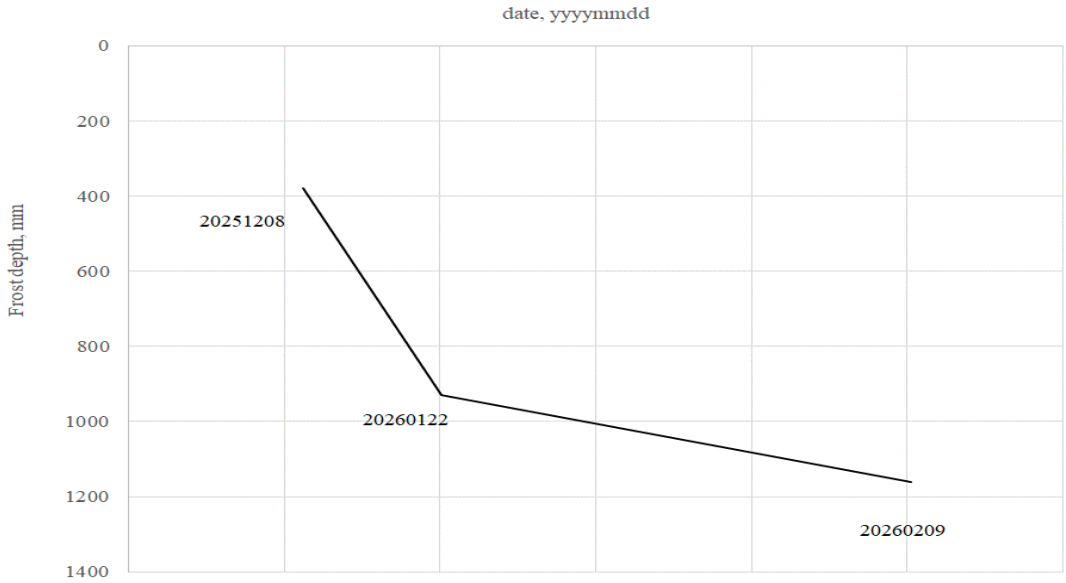


Figure 6: Typical freeze cycle for 2025-2026 in York region

Typical Results: Truck test –Structural Behaviour

A comprehensive field instrumentation system was designed and implemented to monitor the structural behaviour of pavement systems under combined mechanical and environmental loading. The system captures real-time pavement responses under traffic loads, temperature variations, moisture changes, and seasonal effects across five full-scale pavement sections with varying RAP contents. The monitoring program focused on three key aspects:

- Road–vehicle interaction
- Material behaviour under different RAP contents
- Influence of environmental and seasonal variations

General Structural Response

Asphalt binders and mixtures are highly temperature-sensitive materials. In this study, PG 64-28 binder was used across all five test sections, with varying RAP percentages as summarized in Table 1. A dedicated a field testing protocol was developed to evaluate the structural response of the modified asphalt mixtures under controlled field loading conditions.

The testing program specifically targeted the viscoelastic behaviour of asphalt mixtures across a range of temperatures, including high-temperature conditions (approximately 60° C), intermediate service conditions, and low-temperature conditions (approximately 25° C). These tests allowed evaluation of the transition from viscous-dominated to more elastic material behaviour and its effect on pavement structural response.

Speed Impact

Figure 7 presents the response of pressure sensors under a three-axle test truck operating at different speeds on top of the base course layer and 70 mm below the bottom of the base course. The results indicate that pressure values at low speed (approximately 5 km/h) are significantly higher by up to 127% compared to those recorded at higher speed (60 km/h).

This increase in response at lower speeds is attributed to longer tire–pavement contact times, which result in higher stress accumulation within the pavement structure. Prolonged loading duration enhances densification of the asphalt layer and increases the likelihood of permanent deformation, particularly under high-temperature conditions.

As traffic speed increases, the contact duration decreases, resulting in reduced stress accumulation and lower permanent deformation potential. Although the applied load magnitude remains constant, the reduction in contact time leads to a decrease in rutting susceptibility.

These findings highlight the critical influence of low-speed traffic conditions, particularly creep loading (near-zero speed), which is common in areas such as intersections, bus stops, and traffic signals where rutting-related distress is more likely to develop.

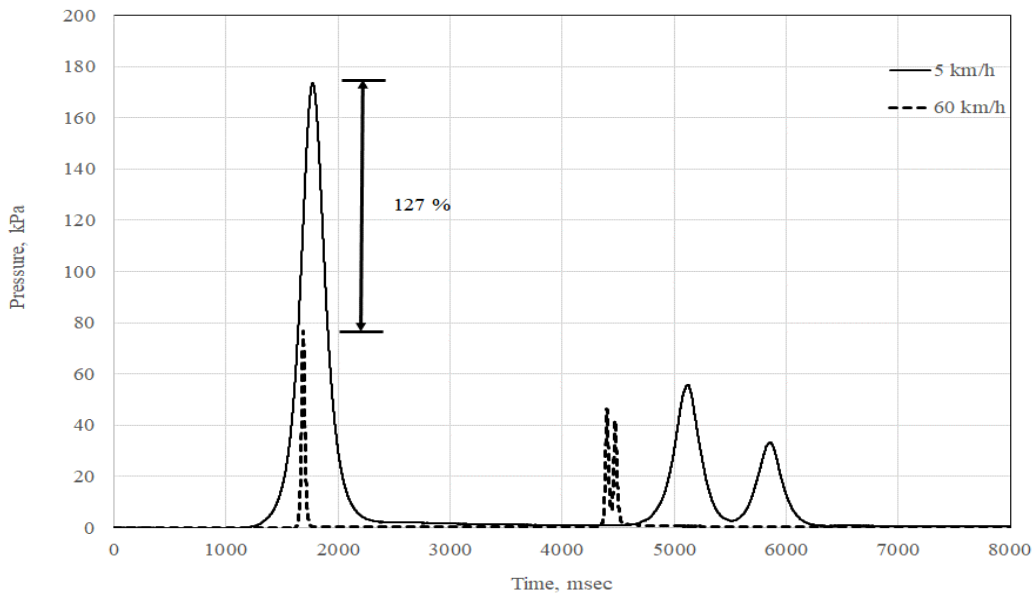


Figure 7: Speed impact on pressure cells located at depth of 70 mm below the bottom base course of WMA

Temperature Impact

Temperature has a significant influence on the stiffness and load distribution capacity of asphalt materials. At elevated temperatures, the reduced stiffness of asphalt concrete diminishes its ability to effectively distribute loads to underlying layers, increasing stress concentrations within the pavement system.

Figure 8 illustrates the response of a three-axle truck travelling at constant speed of 60 km/h over pressure sensors located at 70 mm below the bottom base course of WMA, and it was carried out at different asphalt temperatures. The results show substantially higher stress levels at elevated temperatures (60°C) compared to lower temperatures (20°C). This behaviour is consistent with the temperature-dependent viscoelastic nature of asphalt materials.

The observed stress magnitudes are higher than those reported in previous studies, indicating that reduced stiffness at high temperatures may significantly affect load transfer mechanisms and increase the demand on underlying granular layers. This condition increases the susceptibility of the pavement to permanent deformation (rutting), particularly under heavy traffic loading.

These findings also emphasize the importance of considering high-temperature performance when determining the appropriate timing for opening newly constructed pavements to traffic.

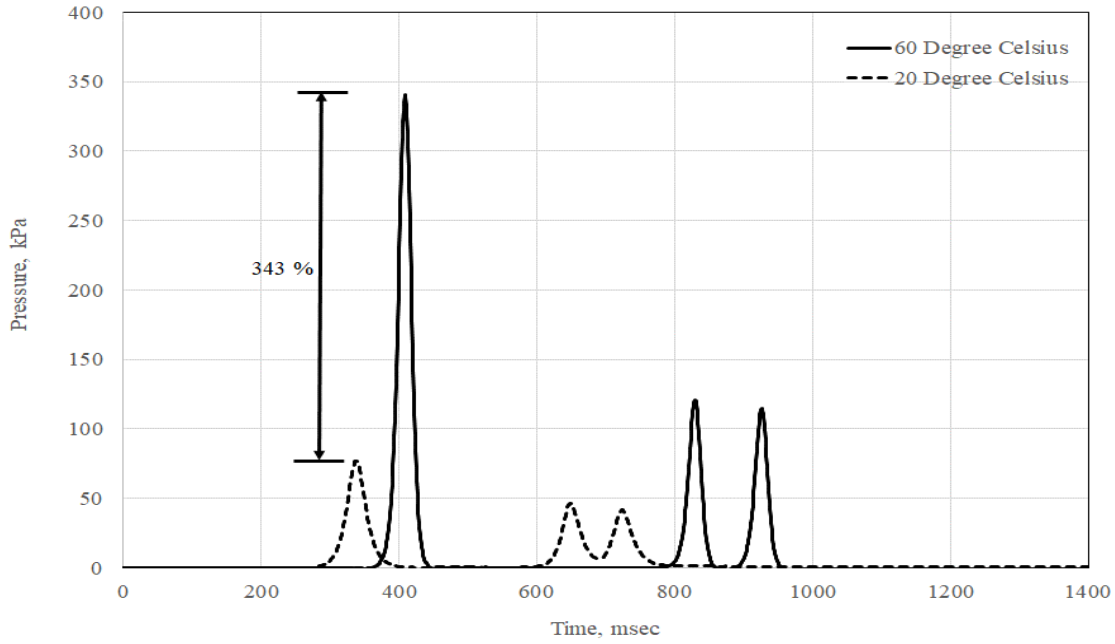


Figure 8: Asphalt temperature impact on pressure cells located at a depth of 70 mm below the bottom base course of WMA

RAP Usage Impact

Figure 9 compares the structural response of pavement sections containing different RAP contents (10 and 40 %) in the base layer. The results indicate that increasing RAP content improves load distribution characteristics within the pavement system.

At lower RAP contents, the material exhibits more flexible behaviour, concentrating stresses and transmitting higher loads to the underlying layers. This behaviour increases the risk of rutting and fatigue cracking (Rizk et al., 2023)..

In contrast, higher RAP content results in a stiffer mixture that behaves more like a system, promoting more uniform load distribution across the pavement structure. This improved load-spreading capability reduces stress concentration in deeper layers and enhances overall structural efficiency.

These findings suggest that optimized RAP incorporation can contribute positively to pavement structural performance when properly designed and balanced with temperature and binder characteristics

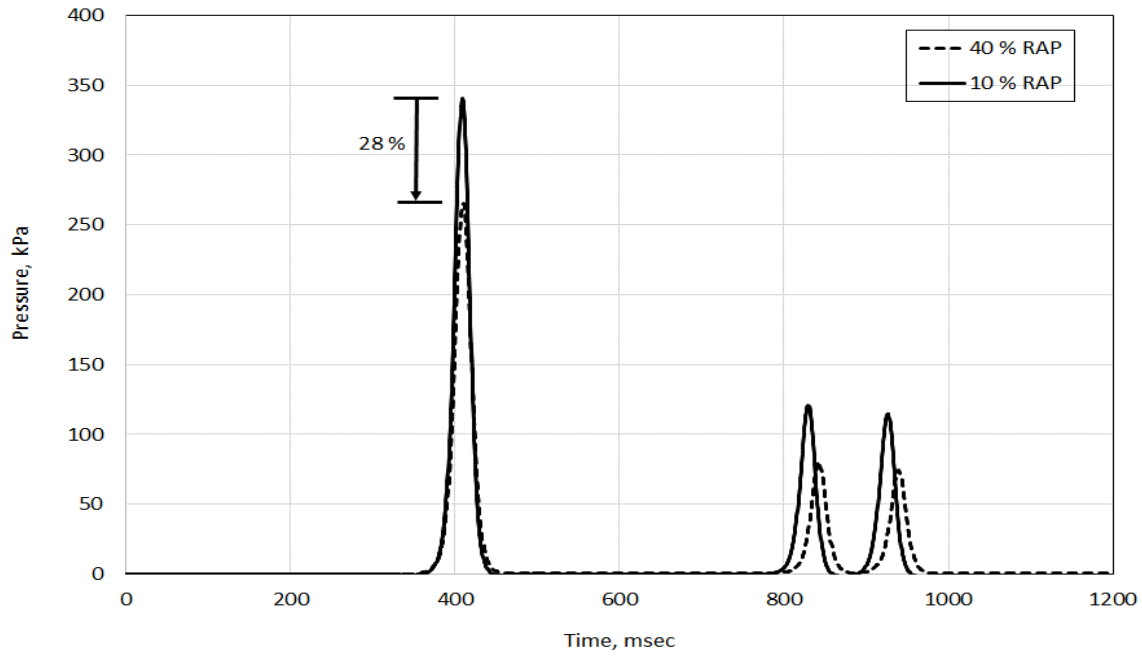


Figure 9: The structural response of different RAP content on pressure cells located at depth of 70 mm below the bottom base course of WMA

CONCLUSIONS:

This study presents the development, design, and implementation of a practical and cost-effective field instrumentation system for monitoring pavement performance. The collected field data will support further laboratory investigations and contribute to a more comprehensive evaluation of RAP-blended asphalt mixtures.

The results demonstrate that simple and inexpensive thermocouple-based measurements can effectively be used to develop freeze–thaw profiles, providing a practical alternative to conventional resistivity-based probes.

Field measurements revealed high levels of stress and strain under both traffic loading and environmental influences, highlighting the importance of in-situ monitoring for capturing realistic pavement behaviour.

The findings also emphasize the significant influence of traffic speed and the timing of pavement opening to traffic on structural performance, particularly under high-temperature conditions.

Finally, the results indicate that higher RAP content in base course materials can improve load distribution within the pavement structure compared to lower RAP contents, suggesting potential structural benefits when RAP is properly designed and implemented.

RECOMMENDATIONS:

Based on the findings of this study, the following recommendations are made:

- Long-term monitoring should be continued for a minimum period of two years to fully capture seasonal effects, freeze–thaw cycles, and long-term pavement performance behaviour.
- Additional field studies should be conducted to further validate the performance of high RAP content mixtures under different climatic and traffic conditions.
- Thermocouple-based temperature monitoring is recommended as a cost-effective alternative for freeze–thaw characterization in pavement systems.
- Future implementations should consider the influence of traffic speed and loading duration when evaluating early-age pavement performance and opening-to-traffic decisions.
- Higher RAP content in base layers should be further investigated to optimize structural performance and material efficiency in asphalt pavement design.

Data Availability Statement

All data and models are available except the codes generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

References

1. Arshad, A., K.,; Awang, H.,; Shaffie, E., ; Hashim, W., and Abd Rahman, Z., 2018. Performance Evaluation of Hot Mix Asphalt with Different Proportions of RAP Content. E3S Web of Conferences 34, 01026
2. Baaj, H. (2018). Evaluation of the impact of silo storage on thermal cracking of hot mix asphalt with RAP. Transportation Association of Canada Annual Conference Proceedings.
3. Gancalves, F. P.; Ceratti, J. A. P. and Bica, A. V. D., 2003. The use of embedded stress cells for monitoring pavement performance. Geotechnical Testing Journal, Vol. 26, No.4.
4. Maadani, O.; Abd El Halim, A. and Mostafa, N., 2014. Instrumentation for monitoring pavement performance in cold regions. Journal of cold regions engineering. 10.1061/(ASCE)CR. 1943-5459.000087, 04014017. American Society of Civil Engineers
5. Ma, X., Wang, J., and Xu, Y., 2022. Investigation on the Effects of RAP Proportions on the Pavement Performance of Recycled Asphalt Mixtures. Frontiers in Materials. www.frontiersin.org. Volume 8, Article 842809.
6. Rizk, A., Baaj, H., & Carter, A. (2023). Cracking and rutting performance of asphalt mixtures incorporating RAP and RAS. Transportation Association of Canada Annual Conference Proceedings.
7. Robin, M. A. and Wei, Z., 1997. Construction instrumentation and load testing of the Danish Road testing. National Research Council U. S. Transportation Research Board, Meeting, 76. Washington D. C.
8. Ontario Provincial Standard Specification, OPSS 1151, 2020.. (2020).: Material Specification for Superpave and Marshall Hot Mix Asphalt. Ontario Ministry of Transportation, Toronto, ON.
9. Zhao, Y., ; Goulias, D., and Peterson, D., 2021. Recycled Asphalt Pavement Materials in Transport PavementInfrastructure: Sustainability Analysis & Metrics. Sustainability Journal 2021, 13, 8071. https://doi.org/10.3390/su13148071