Using Sensing Technology for Pavement Performance Monitoring in Edmonton, Alberta

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Paper prepared for presentation at the Innovations in Pavement Management, Engineering and Technologies session

2023 TAC Conference & Exhibition, Ottawa, ON

ABSTRACT

Pavements in cold regions are continuously under the influence of extreme climates, in addition to variable and ever-increasing traffic loads. Consequently, various types of structural failures can occur depending on specific circumstances and construction features. Thus, a well-planned pavement maintenance strategy must take place throughout the years to reach the designed service life and even sustainably extend the pavement structure's lifetime. An accepted and widely practiced process for continuous monitoring of the pavement conditions is collecting environmental and performance data using sensors installed in different pavement structural layers. In fact, the embedded instrumentation in the pavements can be an effective tool for capturing data such as temperature, moisture, and the induced stresses and strains within the pavement structure, allowing professionals in the field to determine the appropriate maintenance approach based on the collected information. This paper is divided into two main parts. The first part aims to provide a literature review on the sensors used for the instrumentation of pavements. Based on the review of different case studies, this study shows various applications of pavement sensors and their significance for analyzing pavement conditions. The second part of this study focuses on the instrumentation of a test section which was constructed in July 2022 in Edmonton, Alberta. This part mainly discusses the construction and instrumentation of the smart road test section and the application of artificial intelligence to predict the pavement performance based on the captured data.

Keywords: Pavement evaluation; Pavement response; Sensor type; Smart road; Instrumentation.

1. INTRODUCTION

The transportation network of a country represents its level of development as well as its living standards [1]. In order to achieve a high standard of living and proper support for social development and economic growth, a country must rely on well-functioning transportation networks [1]. For example, the greater part of the Canadian Transportation System is composed by road networks and ground transportation. In accordance with Statistics Canada [2], in 2020 there were 1,042,718 kilometers of public road assets in Canada, which could be divided in 597,701 kilometers of local roads, 115,575 kilometers of arterial roads, 115,121 kilometers of rural highways and 52,722 kilometers of highways. As can be inferred, pavements are structures which play a crucial role in Canada’s transportation and development.

Paved road networks are the main transportation system used by communities in general for linking people to their jobs and activities as well as delivering products to customers. As stated by Transport Canada [3], road transportation is the most dominant mode for moving freights and passengers in Canada, with nearly 25 million road vehicles registered and more than 1.1 million two-lane equivalent lane-kilometers of public road. Moreover, trucks are responsible for transporting approximately 90% of all goods and services on Canadian roads [4]. Additionally, Singer [5] pointed out that in the year of 2022 Canada’s population increased by more than one million people hitting just under 39.6 million, which indicates a growth of 2.7%, a rate not seen since 1957. It brings to attention the fact that, as the country is becoming increasingly more populated and urbanized, significant pressure has been placed on the existing infrastructure [3]. Therefore, to protect the road infrastructure and its associated benefits to society, there is a critical need for good pavement design and maintenance practices in Canada [4].

It is important to acknowledge that pavement structural design has significantly evolved in Canada going from a process which relied on experience to one using empirical, mechanistic-empirical and mechanistic principles [4]. To develop a final pavement design that will represent the most cost-effective one and will also meet the needs of users, many aspects must be considered, such as traffic loads, soil type, unit cost, service life, and also climate change impacts [6].

Road pavements are divided into two categories: flexible pavement and rigid pavement [7]. Flexible pavements are commonly utilized for low to medium volume roads, but also for high volume roads and airfield runways, whereas rigid pavements are mainly used in areas with high volume traffic [7]. As can be seen in Figure 1, flexible pavements are characterized for transmitting the wheel load stresses to the underlying layers by a point load transfer, while rigid pavements take most of the load in the pavement layer itself having much lower stress being transferred to the lower layers [7]. In Canada, flexible pavement represents 64% of federal, provincial, and territorial network and 76% of municipal roads [8]. As shown in Figure 1, a flexible pavement is basically composed of four layers: asphalt concrete layer, which can be divided in binding layer (bulk of the Hot Mix Asphalt structure, responsible for distributing the load) and wearing layer (surface in direct contact with traffic loads, responsible for taking the brunt of traffic wear), granular base course (GBC), granular subbase course (GSBC) and subgrade, also called roadbed [9]. However, in Alberta, Canada, according to the Alberta Transportation and Utilities – Pavement Design Manual [10], Alberta flexible pavement structures are mainly composed of asphalt layer, GBC and subgrade. Occasionally, the presence of a GSBC is required, but its presence solely relies on an economic analysis to demonstrate potential cost savings.

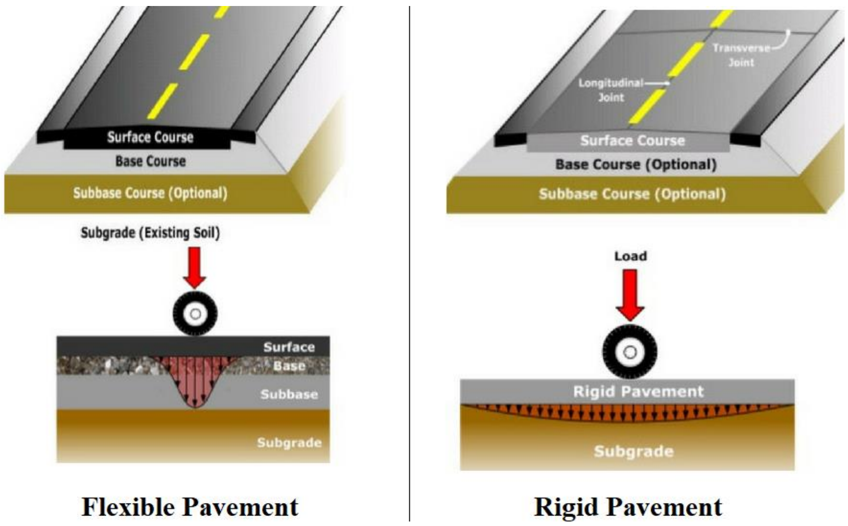

Figure 1. Flexible and rigid pavement layers and load distribution [11]

When considering Alberta, and Canada in general, climate is of extreme significance for a pavement design, specially under constant seasonal temperature variations. For instance, the air temperature in Edmonton, capital of Alberta, can get as high as 35°C in the Summer and lower than -35°C in the Winter [12]. This high air temperature, which can be aggravated with the increase in average temperature due to climate change [13], makes the asphalt materials more prone to rutting or permanent deformation [8].

Pavements in cold regions are subjected to a unique set of challenges due to the harsh environmental conditions, facing consequences such as frost-heave, which can be considered as a weathering process due to the freeze-thaw cycles [14]. In other words, throughout the freezing period, there is an accumulation of moisture in the soil, which later expands perpendicularly to the direction of the heat flow; this expansion exerts upward pressure on the pavement, often causing severe cracking. Seasonal frost areas, such as Alberta, are susceptible to a weakening of the subgrade during the spring thaw period caused primarily by the melting of ice segregation in the subgrade layer [10]. In fact, freezing and thawing in regions under extreme climates are unavoidable events which affect the susceptible granular base and subgrade layers [15]. For instance, during winter, the penetration of frost depth causes differential frost heave on the pavement surface, as a consequence of temperature decrement below the freezing point of water [15]. The term frost heaves, as well described by the Alberta Pavement Design Manual [10], refers to a pavement surface bottom-up movement resulting from the formation of ice lenses in a frost susceptible subgrade. This surface heave negatively affects the ride quality of a road by altering its profile [16]. Furthermore, if the melted water from the ice lenses is excessive, the entire pavement structure can be weakened as a result of an increase of pore water pressure in the subgrade and a subsequent decrement in the load bearing capacity of the unbound layers during spring thaw [16].

In addition to environmental conditions, the variable and increasing traffic loads also play an important role in the performance of a pavement. As stated by Pais et al. [17], traffic intensity is primarily responsible for pavement problems due to the applied loads from vehicles. In fact, heavy traffic is the primary cause of pavement damage such as fatigue cracking and rutting [17]. When analyzing a pavement, it is important to understand that loads on the pavement surface produce two critical strains: the horizontal tensile strain at the bottom of the asphalt layer and the vertical compressive strain at the top of the subgrade layer [18]. On one hand, excessive horizontal tensile strain will cause cracking of the surface layer, and the pavement will distress because of fatigue; on the other hand, excessive vertical compressive strain will cause permanent deformation at the pavement surface due to overloading the subgrade, and the pavement will distress because of rutting [18].

In addition to taking precise data and reliable measures for achieving a successful pavement design, a well-thought maintenance plan must be developed to reach the pavement's designed service life and even extend its structure's lifetime. One way of achieving these goals is by installing pavement instrumentation, which, according to Tabatabaee & Sebaaly [19], can provide valuable insights into the behavior of a pavement under different traffic loads and environmental conditions. Given the constant advances in technology, nowadays software for numerical analysis and electronic sensors grants the conditions for a better approach regarding asphalt pavement monitoring [20]. In fact, to understand the pavements' behavior, test their materials and better model their performance, in place response collection and proper use is essential [21]. Additionally, as concluded by Al-Qadi et al. [22], pavement instrumentation is a workable tool to measure the pavement response to loading, as long as some practices are in place: proper calibration and installation, and good data management. Some of the data that must be collected, as stated by Al-Qadi et al. [22], are stresses, strains, deflection, temperature, and moisture. To gather this data, sensors are installed in or on the pavement surface. The measurement of these parameters permits the maturing of greater pavement response models, leading, consequently, to better pavement design approaches [22].

The use of sensors, data acquisition systems and other monitoring devices allow for the collection and analysis of meaningful information, in real-time or periodically. This information can be used to improve pavement design, construction, maintenance, and rehabilitation strategies. In fact, pavement instrumentation with sensing technologies represents a significant tool for understanding the pavement conditions, allowing for data control, remotely and continuously, with saving in time and no need for traffic interruption [23]. Moreover, this constant monitoring of pavement performance plays an important role in pavement management systems, since the knowledge of the pavement health conditions empower decision-makers to plan proper maintenance actions which will lead to road safety improvement and extension of these roads service lives [23].

In conjunction with pavement instrumentation, there is also an increase in the use of Artificial Intelligence (AI) to predict pavement performance. As stated by Marcelino et al. [24], prediction models are utilized to anticipate the future state of the pavement, aiding in the optimal distribution of funds for maintenance and repair purposes. In other words, the use of AI forecasting models allows for better planning and management of maintenance and repair activities related to pavement.

Therefore, the aim of this project is to present a recently constructed smart road with different types of sensors, and, based on the data collection combined with the use of artificial intelligence, predict pavement performance and generate enhanced pavement design and maintenance procedures.

2. OBJECTIVE

The main objective of this study is to provide an overview of a newly instrumented test section constructed in Edmonton, Alberta, Canada. For this test section, a new instrumentation system was designed and implemented with the purpose of monitoring the in-situ pavement response under the influence of heavy trucks under extreme weather conditions. The goal is to bring forward and discuss the conceptual philosophy and theories behind the use of these instruments aligned with the use of artificial intelligence to generate reliable and credible databases towards predicting pavement performance and enhancing mechanistic-empirical design models.

3. BACKGROUND

Pavement instrumentation has proven to be one effective and successful way of monitoring physical condition of the pavement structure [25]. It can be used to capture the pavement's response to traffic loading, such as axial strain and total pressure, as well as environmental parameters, such as soil moisture content and temperature. The main target is to determine the deflections in the pavement and its structure properties in addition to evaluating the factors affecting the pavement [25]. For instance, accurate values for strains and stresses in a pavement are essential for comprehending the pavement behavior and modeling its failure [26]. In fact, the utilization of pavement sensors permits continuous monitoring of pavement systems allowing for an integration between measurements and management systems leading to advanced maintenance and rehabilitation approaches [27]. However, to have a successful instrumentation of the pavement structure, the selection and installation of the sensors is essential for collecting quality data [28]. The sensing devices can be divided into two categories: structural and environmental sensors. Their application and design are presented in the following paragraphs.

3.1 Structural Sensors

Structural sensors are used to determine pavement responses under traffic loading and to measure the deflection and strain/stress distribution at a given depth in the pavement structure. In other words, tensile strain at the bottom of the asphalt layer, vertical compressive stress on top of the subgrade and pavement surface deflection can be the measured responses from the traffic loading [29]. To get this data, strain transducers and pressure cells are often installed at the required elevations within the pavement structure.

Strain measurement is of extreme importance for verifying the pavement condition and determining the right approach based on the information gathered. There is a well-established understanding that the development of bottom-up fatigue cracking and rutting distresses in a hot mix asphalt (HMA) layer is caused by the longitudinal and vertical strains at the bottom of this layer [30,31]. In fact, while high tensile strain at the bottom of the asphalt layer can cause fatigue failure, high shear strains in the asphalt layer and high compressive strains in the other layers can cause rutting and permanent deformations [19].

Horizontal asphalt strain transducer (HAST) is commonly used to measure the horizontal strains caused by the traffic loading [28]. It basically comprises a strip made of a sensitive material containing one to four active strain gauges connected in different bridge circuit configurations. The ends of this strip are linked to metal bars with rectangular cross sections acting as anchors, forming the letter *H* [19]. This device is usually installed at the bottom of the asphalt layer, and, as the load is applied, the anchor bars move, thus recording the strain applied to the strain gauge [28]. If the stiffness of the strip is similar to the asphalt layer's stiffness, the registered strain will be the same in the asphalt layer [19]. It is, therefore, important to choose the appropriate material and dimensions for both the strip and anchor bars. Figure 2 presents a typical HAST.

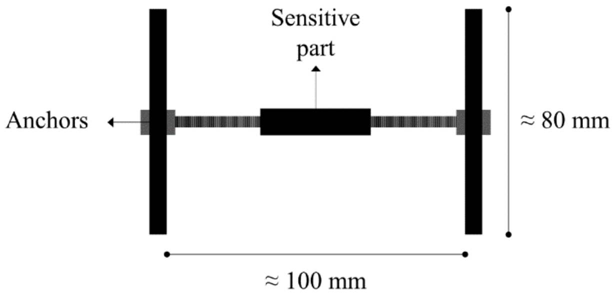

Figure 2. Horizontal Asphalt Strain Transducer [23]

Similar to HASTs, Vertical Asphalt Strain Transducers (VASTs) are generally installed in the bottom of the asphalt layer. They are responsible for measuring the vertical strain caused by repeated traffic loading in the asphalt layer [32]. The design of VASTs is comparable to HASTs in the sense that they contain a sensitive component positioned between two round plates [28]. The lower plate functions to secure the sensor, while the upper plate evenly distributes the load across the bar. HMA is poured between these two plates and compacted to achieve the desired density [32]. Additionally, a pointed stake is a characteristic of this sensor type, which can be inserted into the underlying layer. Figure 3 illustrates the diagram of the VAST.

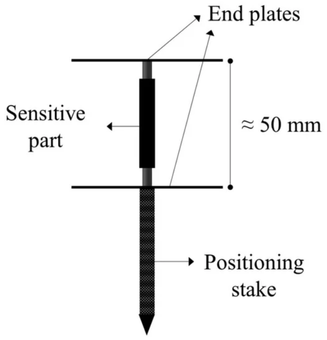

Figure 3. Vertical Asphalt Strain Transducer [23]

In addition to HASTs and VASTs, in which the response is determined by mechanical apparatus, there are other types of instruments that measure the strain by using electrical impulses. Some of them are Vibrating Wire (VW), Electric Resistance (ER) and Fiber Optic (FO) devices [28]. However, based on previous and ongoing studies, the most used sensors for measuring the strain/stress in the bottom of the asphalt layer are HASTs and VASTs.

Besides the strain measurement, another important response to the moving traffic loading is the dynamic vertical pressure [33]. A commonly used device to measure this pressure is the Earth Pressure Cell (EPC), and it is utilized to measure the vertical stresses in the three layers underneath the asphalt layer: Granular Base Course (GBC), Granular Subbase Course (GSBC) and subgrade [32]. As shown in Figure 4, the EPC device is made up of two round stainless-steel plates that are welded together along their edges and separated by a small gap that is filled with de-aired oil; when the pressure of the surrounding soil changes, it compresses the two plates, leading to a corresponding rise in the fluid pressure within the space; the semiconductor transducer then transforms this pressure into an electrical signal, which is transmitted as a change in voltage through a cable to the readout location [33].

Figure 4. Earth Pressure Cell [32]

As for determining the deflection throughout the pavement structure at different elevations, other devices can also be used, such as Linear Variable Differential Transformers (LVDTs), geophones and accelerometers [23]. Each one of them will perform based on different stimulation. For instance, after a moving traffic loading is applied, while geophones will generate the deflection by single-integrating the velocity signal, accelerometers will develop the displacement by double-integrating the acceleration signal on a specific point [19]. Although geophones and accelerometers are less intrusive than LVDTs, LVDT devices provide highly accurate measurements, since they have an infinite resolution [23].

3.2 Environmental Sensors

The pavement responses to traffic loading mentioned in the previous topic are directly influenced by environmental factors [29]. Thus, it is extremely important to measure these factors, which are moisture content and temperature at distinct depths within the pavement structure [29].

As pointed out by Tabatabaee & Sebaaly [19], the stiffness of the asphalt layers is directly affected by the temperature, which, as a result, impacts the pavement response. Therefore, to measure the temperature at different layers, the most commonly used devices are thermocouples, Resistance Temperature Detectors (RTDs) and thermistors [23]. As described by Weinmann et al. [34], a thermocouple is composed of a pair of wires twisted and soldered together. These wires are shielded and made of constantan and copper. A thermistor, on the other hand, which is a less costly element, is soldered onto a lead wire. Both the lead and the thermistor wires are dipped in epoxy to protect the ends from corrosion-related damage. As for the RTDs, typically, they are comprised of a slender wire, made of copper, nickel, or platinum, which is wound around a core composed of either ceramic or glass [23]. Figure 5 pictures a K-type thermocouple, an example of a temperature sensor device.

Figure 5. K-type thermocouple [23]

Further than the temperature sensors, moisture sensors are also essential in monitoring pavement performance, since an excessive moisture content can significantly impact both the performance and bearing capacity of pavement structures [35]. According to Barriera et al. [23], Time-Domain Reflectometry (TDR) probes are widely employed as the primary devices for measuring moisture content within pavement layers. Their principle of operation is based on time-domain reflectometry. This method entails transmitting an electrical pulse through a waveguide. The movement of the pulse through the waveguide varies according to the moisture level in the pavement. After traveling the length of the waveguide, the pulse is reflected back and detected by a receiver. The strength of the reflected pulse is ultimately proportional to the amount of moisture present in the pavement.

4. NEW TEST SECTION EXPERIMENT

4.1 Site Location

In July 2022, a smart road test section was built in Edmonton, Alberta, Canada, targeting the collection and analysis of more data with the use of modern sensors connected to a data logger. This new test section was constructed on the access road from Aurum Road to the Edmonton Waste Management Centre (EWMC). The location is deemed convenient and of significant interest due to the substantial daily circulation of approximately 1000 trucks within the area [16]. Figure 6 shows the location of this new test section.

4.2 Sensors Used

Both VASTs and HASTs, as shown in Figure 7(a) and (b), are responsible for measuring the axial strain under high-frequency (dynamic) loading. These sensors can resist the high temperature of asphalt mix during the pavement construction and be successfully used under vibratory roller compaction required for asphalt placement [36].

Figure 6. New test section location

The temperature sensors (thermistors) used in this test section are based on a 3k-Ohm NTC thermistor, as can be seen in Figure 7(c). These sensors can be installed on the surface or embedded in the pavement layers depending on the installation method. For the embedment temperature measurements, a polyvinyl chloride (PVC) tube was used, and a through-hole lug was also utilized for the surface measurements [37].

As for the soil moisture measurements, TEROS 10 moisture sensors were used to measure the volumetric water content of soil using stainless steel needles (Figure 7 (d)). By placing a ferrite core on the sensor cable, positioned 7.6 cm away from the sensor head, the sensor can be effectively isolated from any interferences in the system. This isolation ensures that potential noise from the system is avoided, resulting in clean and accurate data.

To measure the total pressure in earth fills and embankments, model 3500 EPCs were installed, as presented in Figure 7(e).

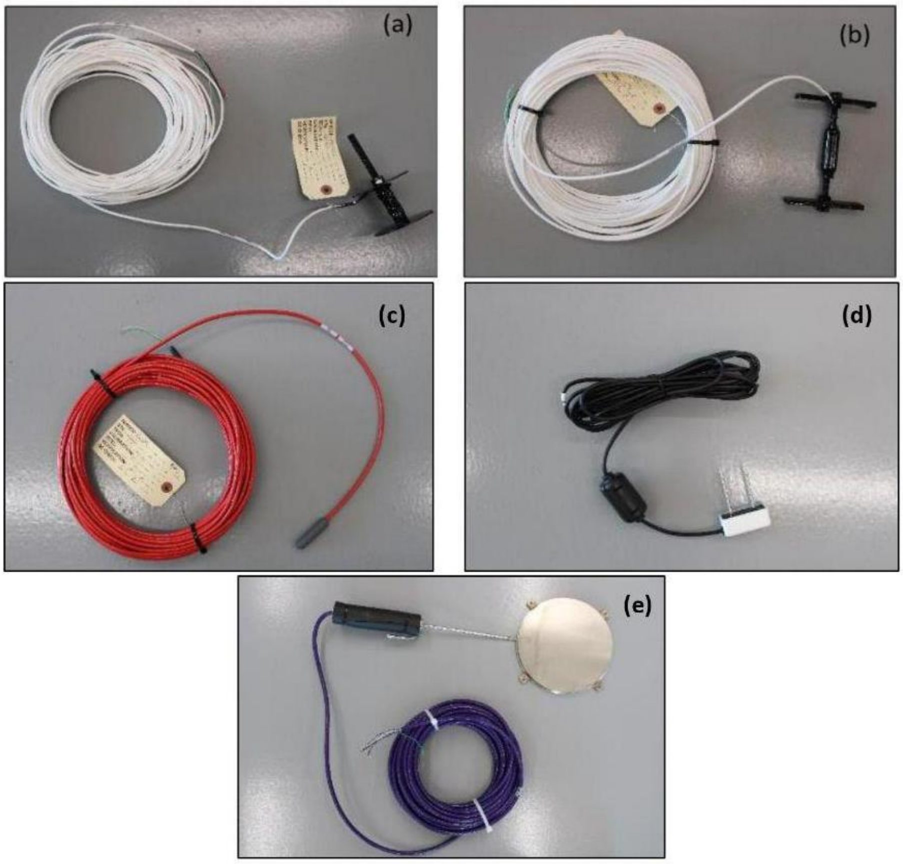

Figure 7: Sensors used: (a) Vertical Asphalt Strain Transducer (VAST); (b) Horizontal Asphalt Strain Transducer (HAST); (c) Thermistor; (d) Soil Moisture Sensor; (e) Earth Pressure Cell (EPC)

4.3 Instrumentation Plan

For this new test section, 36 sensors were used: 12 Horizontal Asphalt Strain Transducers (HASTs), 6 Vertical Asphalt Strain Transducers (VASTs), 6 thermistors, 6 soil moisture sensors (TEROS) and 6 Earth Pressure Cells (EPC). Figure 8 presents a plan view of the sensors' position and installation, and Figure 9, the cross sections with the sensors' elevation.

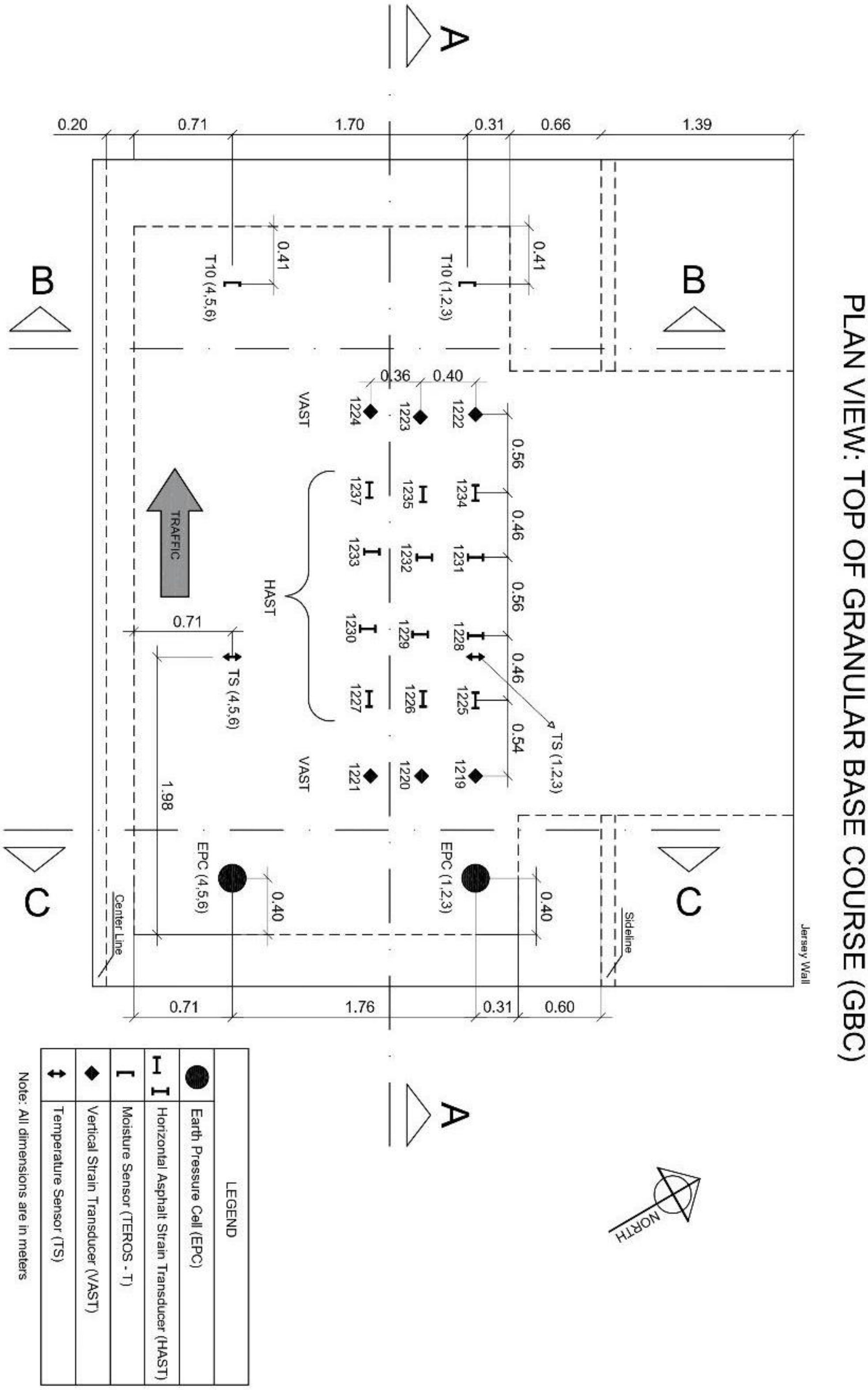

Figure 8. Instrumentation plan view (Top of GBC)

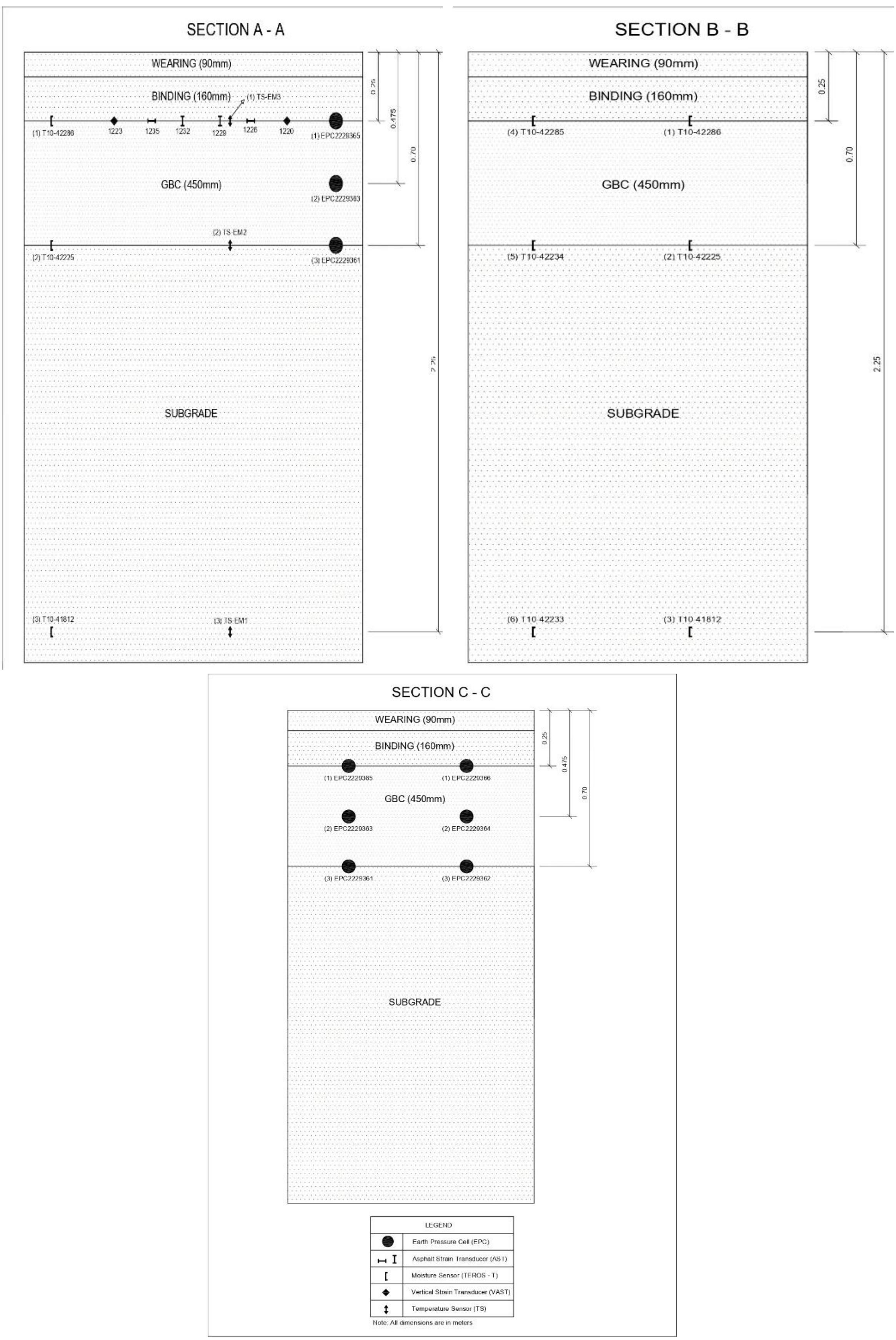

Figure 9. Cross Sections from the Plan View

4.4 Construction of the New Instrumented Test Section

Since the new instrumented section is located in an in-service road, to control the local traffic safety measures had to be taken with signage, traffic cones and flagging. After ensuring the safety procedures were in place, the construction started with the saw-cutting of the asphalt surface layer. The top pavement (asphalt) layer was then crushed using a concrete breaker and removed using a bucket attachment. After the removal of the entire surface layer, at the locations where the EPCs were to be installed, the GBC was excavated. For proper level installation of the EPCs, their spots were first filled with handfuls of sand before compacting manually with a steel tamper and checking with a water level. The first EPC was then inserted in place, 70cm from the top of the asphalt layer, before once again backfilling with sand and tamping. This process was repeated for the installation of the EPCs at the other two elevations namely the middle and the top of the GBC, at 47.5cm and 25cm from the top of the asphalt layer, respectively. In between EPCs, the elevation was prepared by backfilling with the GBC material and compacting with a vibratory plate compactor. Figure 10 shows the installation of the EPCs.

Figure 10. Installation of the EPCs: (a) Removing the existing base layer (b) sand filling and compacting with a tamper, (c) checking for levelness of compacted sand, (d) laying the pressure cells and (e) covering pressure cells with sand

The next step was the installation of the temperature and moisture sensors. For this part, four holes were drilled in their positions, according to the construction layout, to the required depth of 2.25m using a screw augur drill while sampling from the subgrade and the GBC material during the process. Once the holes were prepared, the next steps were to insert and install in place the moisture and temperature sensors at the three different elevations: in and on top of the subgrade, and on top of the GBC (225cm, 70cm and 25cm from the top of the asphalt layer, respectively). Figure 11 presents the installation of the moisture and temperature sensors.

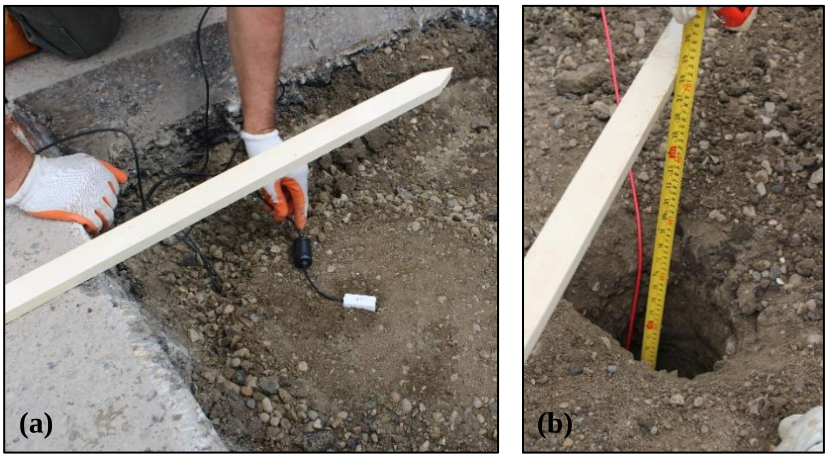

Figure 11. Installation of (a) the Moisture Sensors and (b) Temperature Sensors

After the installation of the EPCs, temperature and moisture sensors, the final layer of the GBC was prepared by backfilling with the original material, and with extra material where needed, before compacting the entire cut section using a vibratory plate compactor. Next, the exact locations for the VASTs and HASTs, as per the construction layout, were marked in place on the top of the GBC (25cm from the top of the asphalt layer) using a marking paint. They were then laid out accordingly and fixed using a mix of sand and asphalt emulsion. To secure the ASTs in place, asphalt mix was placed on top of them, before constructing the asphalt concrete layer. To connect the sensors to the data logger, shallow troughs were dug to serve as a channel for passing through the sensor cables. The installation of the HASTs and VASTs is presented in Figure 12.

Figure 12. (a) laying of vertical and horizontal asphalt strain transducers and (b) using hot mix asphalt to secure the transducers in place before resurfacing

With all the sensors in place, the test road was resurfaced with HMA, which was comprised of three layers with respective thicknesses of 100 mm, 100 mm, and 50 mm. Each asphalt layer was compacted with multiple passes of a smooth roller compactor at 152°C.

The final step was the installation of the data logger. A reinforced concrete pad with dimensions of 150 cm × 150 cm × 75 cm was constructed to place the data logger on top. As for the cable connections, trenches were dug, and the sensor cables were separated into two groups based on the connection plan provided by the manufacturer (BDI) and passed through conduits. After the concrete curing, the cabinet was then placed and anchored on the concrete pad. The cables were then connected to the data logging system based on the connection plan, and the ethernet and power cables were also connected.

4.5 Sample Data Collection

As previously mentioned, both environmental and structural sensors were used in the instrumented test section. Some of the data that has been collected is shown in Figures 13 to 15. Figure 13 depicts the temperature oscillation within 24 hours, while Figures 14 and 15 present a wave caused by a moving truck measured in a 2-second period.

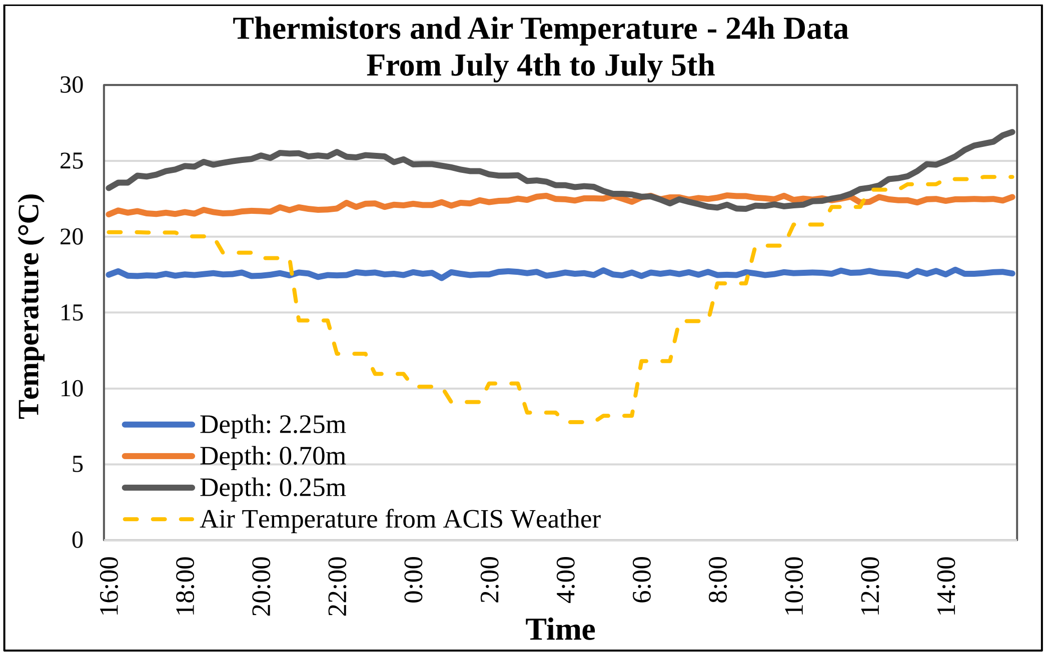

Figure 13. Soil Temperature Sample Data

As can be seen in Figure 13, the soil temperature measured by the sensor located in the upper (GBC) layer at the depth of 25 cm is higher and oscillates more as it is closer to the surface and more susceptible to changes. On the other hand, deeper sensors read lower and less changeable temperatures values.

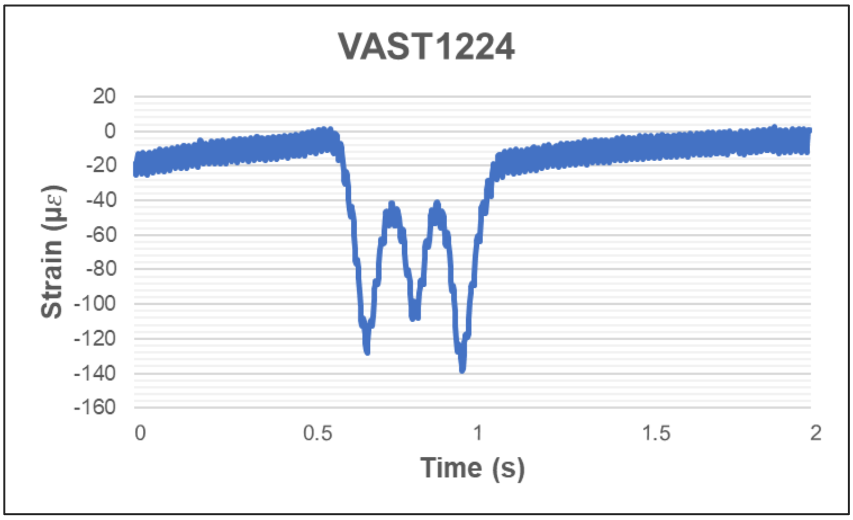

Figure 14. Vertical Strain Sample Data

It is important to mention that both measurements presented in Figures 14 and 15 were caused by a truck weighing 44,100 kg, as per the Weigh in Motion (WIM) Correlation set in place.

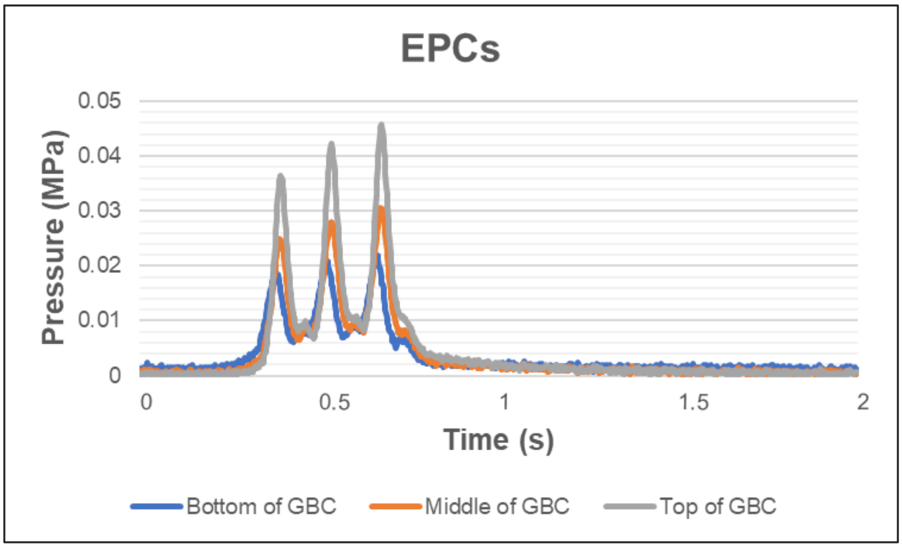

Figure 15. Earth Pressure Cell (EPC) Sample Data

As can be seen in Figure 15, the sensor located in the deeper location registered the lowest pressure value, while the highest value was measured by the sensor closer to the surface.

5. ARTIFICIAL INTELLIGENCE IN THE PREDICTION OF PAVEMENT PERFORMANCE

Assessing the condition of transportation infrastructure is an expensive, labor-intensive and time-consuming process. Many traditional road assessment methods utilize on-site measurements as well as visual inspection and interpretation [38]. Artificial intelligence (AI) technology can process and discover natural patterns in large amounts of data to make informed decisions based on better predictions, and it is gaining traction in pavement performance prediction [39,40].

Machine learning (ML) is a branch of Artificial intelligence. As shown in Figure 16, ML models can be divided into three groups: supervised learning, unsupervised learning, and reinforcement learning. There are different kinds of ML algorithms, including linear regression, nonlinear regression, gaussian process regression, support vector machine, decision trees, neural networks and so on. A detailed discussion on the ML algorithms is beyond the scope of this study, however more information can be found in references [41–43]. Unlike statistics, which aim to draw aggregate inferences from samples, machine learning aims to discover generalizable predictive patterns. Machine learning algorithms use computational methods to "learn" information directly from historical data or experience. Different machine learning algorithms have their own advantages, so the choice of machine learning algorithm is determined by the purpose of developing the model [39,40].

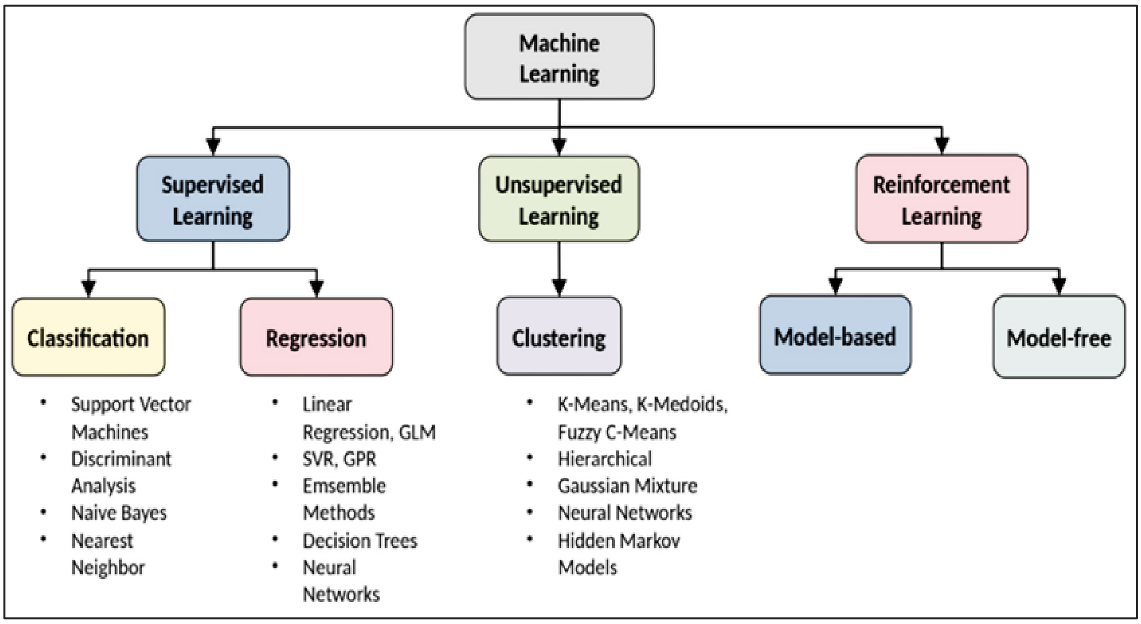

Figure 16. Summary of ML Algorithms [39]

Pavement performance is influenced by materials properties, traffic load, service life, environmental factors and so on. Machine learning models have been applied to estimating the resilient modulus (MR) of subgrade soil [44,45], the remaining service life (RSL) [46] and pavement deterioration conditions [47,48]. Ren et al. [44] applied artificial neural networks (ANN) to predict the MR of five common subgrade soil types in Canada after different freeze-thaw (FT) cycles, and data collected through laboratory testing. The number of FT cycles and moisture content of the soil were shown as the two main input parameters. Zhou et al. [49] build ANN models to investigate the dynamic responses of frozen subgrade soil exposed to FT cycles and assess the degeneration of the engineering properties of frozen subgrade soil induced by FT cycles. They found that the dynamic shear modulus-shear strain curve was significantly affected by the FT cycles, and the accumulated plastic strain rapidly increased at higher FT cycles. Kaya et al. [46] developed a network level ANN model to predict pavement performance and RSL for the flexible and composite pavement system. The international roughness index was used as a performance indicator and a build trigger for the repair decision process in RSL calculations. Based on two years of pavement performance data, the ANN model was trained to estimate the rutting, longitudinal cracking, transverse cracking and IRI for a given asphalt layer thickness, accumulated equivalent single axle load traffic, and age.

Deng et al. [47] applied the finite element model with AI algorithms to estimate the average deterioration degree of the pavement by considering the effect of aging and fatigue damage on the asphalt modulus, and the strength and weakness of the modulus were used as an indicator of the pavement condition. Wang et al. [50] used the ML algorithm, decision tree, to predict IRI. Pavement thickness, service age, average annual daily truck traffic, gator cracks, precipitation, temperature and so on have been used as input parameters, and this ML model outperformed the linear regression model given by the Mechanistic-Empirical Pavement Design Guide. The application of AI technology has made it possible for the pavement management system to change from passive to active, which is more efficient.

Although machine learning models are receiving increasing attention for improving pavement management, machine learning is a data-driven approach. Thus, it is not recommended to use machine learning models for other projects not included in the training set. For example, the model developed by Ren et al. [44] is applicable only to the five soil types included in the training set, and its accuracy may be greatly reduced if used to estimate the resilient modulus of other soils.

6. CONCLUSIONS AND FUTURE WORK

In this study, an overview of the sensors used for pavement instrumentation was presented, in addition to the instrumentation of a new test section in Edmonton, Alberta, by using different types of structural and environmental sensors. Information about the application of Artificial Intelligence (AI) for predicting pavement performance was also exhibited. The conclusions of this study are summarized as follows:

- Traffic characteristics and environmental factors act together to affect pavement health, performance, and serviceability.
- Pavement instrumentation is crucial for having a better understanding of pavement health and performance, leading to better maintenance and rehabilitation strategies.
- The measured temperature showed that the upper layer has a higher temperature value which oscillates more compared to values determined for the other layers.
- The pressure sensors showed that the pressure values are reduced at higher depth.

- AI can be of great assistance for pavement design and maintenance due to the fact that it adds accuracy to predicting pavement performance, allowing for more efficient management systems.

Based on the new instrumented test section constructed in Edmonton, Alberta, meaningful and significant information throughout the year, at different pavement temperatures and soil moisture contents, will be gathered, allowing for researchers to:

- Analyze the collected real-time field data and provide results to enhance the actual design and maintenance procedures.
- Perform AI to greatly evaluate the recorded data and, as a result, contribute to the evolution of actual rehabilitation and maintenance practices, and developing better pavement design procedures.

Acknowledgements

The authors would like to thank the Artificial Intelligence for Logistics (AI4L) program of the National Research Council (NRC) Canada for providing funding for this research. We would also like to thank the City of Edmonton and Edmonton Waste Management Centre (EWMC) for helping with the construction of the test section. Special thanks to Dr. Hamid Soleymani and Matthew Boutotte for all their assistance with the construction planning and arrangements.

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