Integrated Road Research Facility (IRRF): An Albertan Research Initiative

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Abstract

The Integrated Road Research Facility (IRRF) was founded in 2012 through an innovative partnership between the University of Alberta, Alberta Transportation, Alberta Recycling, the City of Edmonton and Canada Foundation for Innovation (CFI). The IRRF includes a fully-instrumented test road, located approximately 15 km east of downtown Edmonton. The test road has three major test sections that focus on evaluation of: 1) two road embankment materials: Tire Derived Aggregate (TDA) made from Passenger-Light-Truck-Tire (PLTT) and Off-the-Road (OTR) tires and PLTT-soil mixture; 2) flexible pavement performance in cold-climate conditions; and 3) insulated pavement sections using polystyrene boards, bottom-ash and TDA. The test road is unique in Canada and more than 8,000 tonnes of recycled tires were used in the construction of the road. The test road was instrumented with more than 250 pavement and geotechnical instrumentation during construction. Geotechnical instrumentation is used to monitor the TDA sections' compression behavior, internal temperature and drainage characteristics. Instrumentation in the insulation layer test section monitors temperature, moisture and frost penetration. Instrumentation in the pavement performance sections monitors the mechanistic responses of the pavement to both truck traffic and environmental conditions. This paper discusses details regarding the instrumentation design, installation procedure and data collection system for the three test sections. The results of Falling-Weight-Deflectometer (FWD) tests performed on finished subgrade for uniformity evaluation are also presented and discussed.

Word count: 248

1- Introduction

Sustainability and optimized life-cycle costs for highway infrastructure are of high interest for governments and highway agencies. To this purpose, Alberta Transportation initiated the evaluation of recycled and waste materials for use in road embankment construction. Albertans produce more than five million scrap tires every year; these tires are collected through Alberta's tire recycling program *(1)*. Scrap tires can be shredded to produce Tire-Derived Aggregate (TDA), a lightweight and free-draining fill material. TDA produced from Passenger and Light-Truck Tire (PLTT) has been successfully used as fill embankment in Canada in a number of small-scale pilot projects but a rigorous evaluation of TDA properties in relation to potential use as embankment fill in cold climates has not been undertaken *(2)*. The effect of freeze-thaw cycles and basics of how to construct with TDA to achieve maximum density and minimize long-term settlements have not been well documented. TDA's heat resistivity can be several times higher than soil, making this material a potential candidate for pavement insulation layer.

The primary use for recycled tires in Alberta for the past several years has been as leachate collection systems in rural landfills. As this market is becoming mature, it was necessary to look elsewhere for large volume consumption of recycled scrap tire. A pilot project was organized to investigate the use of TDA as roadway embankment construction materials. In addition to PLTT sources, heavy industry produces large volumes of Off-The-Road (OTR) tires. OTR tires have not been put to the test as fill materials, so a decision was made to include both PLTT and OTR material in the test road. Further, numerous challenges are faced every year regarding flexible pavement performance in cold climate conditions. The need to characterize the mechanistic response of pavement to traffic and environmental loads in Canada's extreme climate conditions provided the impetus to include a pavement performance monitoring test section along the test road.

As a result, the Integrated Road Research Facility (IRRF) was founded in 2012 based on a unique collaboration amongst academia, government and local private sector. The University of Alberta, Alberta Transportation, the City of Edmonton and Alberta Recycling formed a team, to construct and instrument a multi-million dollar test road in summer 2012. The project was made possible through extensive financial and in-kind support from the partners and matching funds from Canada Foundation for Innovation (CFI).

The new access road to the Edmonton Waste Management Center (EWMC) was selected as the candidate for the test road. A great deal of collaborative effort went into designing the various test sections of the test road. The final design included three main test sections: 1) a TDA fill embankment with three successive sections: PLTT, OTR and PLTT-soil mixture; 2) pavement monitoring; and 3) insulated sections, including PLTT, bottom ash and rigid polystyrene boards. The pavement monitoring test sections were located such that they would also serve as control sections for the TDA fill and insulated sections.

Based on the final design the required quantities of TDA were estimated. Over the span of two months, Liberty Tire Recycling Canada and CuttingEDGE Tire Recycling completed the production and quality assurance of the TDA from PLTT and OTR sources. TDA was transported and stockpiled near the project site in advance of construction, which started in May 2012. Approximately 8,000 tonnes of TDA (made from 825,000 tires), representing 10 percent of the scrap tires annually collected in Alberta, were used to construct the road.

Some of the challenges in planning and construction of the road included: developing tender documents and designs that dealt with an unknown construction material, accommodating different test sections along the road, placing and compacting the TDA fill material, and successfully installing the extensive instrumentation with long readout wire lead distances. The challenges were mitigated by diligent and cooperative coordination between the contractor, sub-contractor, consultant and the University of Alberta through weekly on-site meetings.

This paper introduces the IRRF's test road facility and its different test sections as a new research initiative in western Canada. The instrumentation layout and equipment, installation process and data acquisition system are discussed in detail. The authors believe that the instrumentation experience and the lessons learned from such a large-scale project and collaborative effort will provide invaluable insights for future projects. Future papers will deal with the monitored performance of the TDA fill, insulated and pavement sections.

2- Overview of IRRF's Test Road Facility

IRRF's test road facility is the new access to the EWMC, located on the eastern edge of Edmonton, about 15 km from downtown. Construction of the IRRF's test road started in May 2012 and was completed with Stage 1 of paving in August 2012. The test road is a two-lane road approximately 500 m long. The road (to be opened in 2014) is anticipated to carry 400 to 500 trucks per day. The pavement structure for the test road comprises 220 mm of Hot Mix Asphalt (HMA), placed in two stages of 160 mm in 2012 to be topped with another 80 mm in 2013. The HMA mixture properties retrieved from the batch plant are provided in Table 1. The HMA layer was placed on 450 mm of granular base course (GBC) on one metre of compacted Clayey-Sand (SC) subgrade soil.

Table 1. Binder type and HMA mixture properties.

Parameter	Value
Binder type	PG 58-28
Effective air content (%)	3.5
Effective binder content (%)	9.1
Aggregate gradation:	
Passing 3/4" sieve (%)	93
Passing 3/8" sieve (%)	68
Passing on #4 sieve (%)	49
Passing #200 sieve (%)	6.8

As illustrated schematically in Figure 1, the test road includes three main test sections. The three test sections include: 1) TDA fill embankment; 2) pavement monitoring; and 3) insulated sections. The TDA fill embankment test section starts at Stationing 130 + 80 and ends at Stationing 130 + 140 and comprises three 20-m test sections: 1) PLTT is the southern section, stretching from 130 + 80 to +100; 2) OTR is the second section, from Stationing 130 + 100 to + 120; and 3) PLTT-Soil mixture is the last section, from Stationing 130 + 120 to + 140.

The second main test section is the pavement performance monitoring section, which includes two 20-m test sections, 100 m apart from each other, stretching from Stationing 130 + 140 to + 160 and also from 130 + 240 to + 260 (Figure 1).

The third test section is the insulated pavement sections, located at the northern section of the test road from Stationing 130 + 260 to + 350. This test section includes three sections of insulation placed directly below the GBC layer: 1) from Stationing 130 + 260 to + 300, 250-mm thick TDA layer is placed as an insulation layer; 2) one metre thick bottom ash layer is placed; and 3) one layer of rigid board polystyrene (Styrofoam) board is placed.

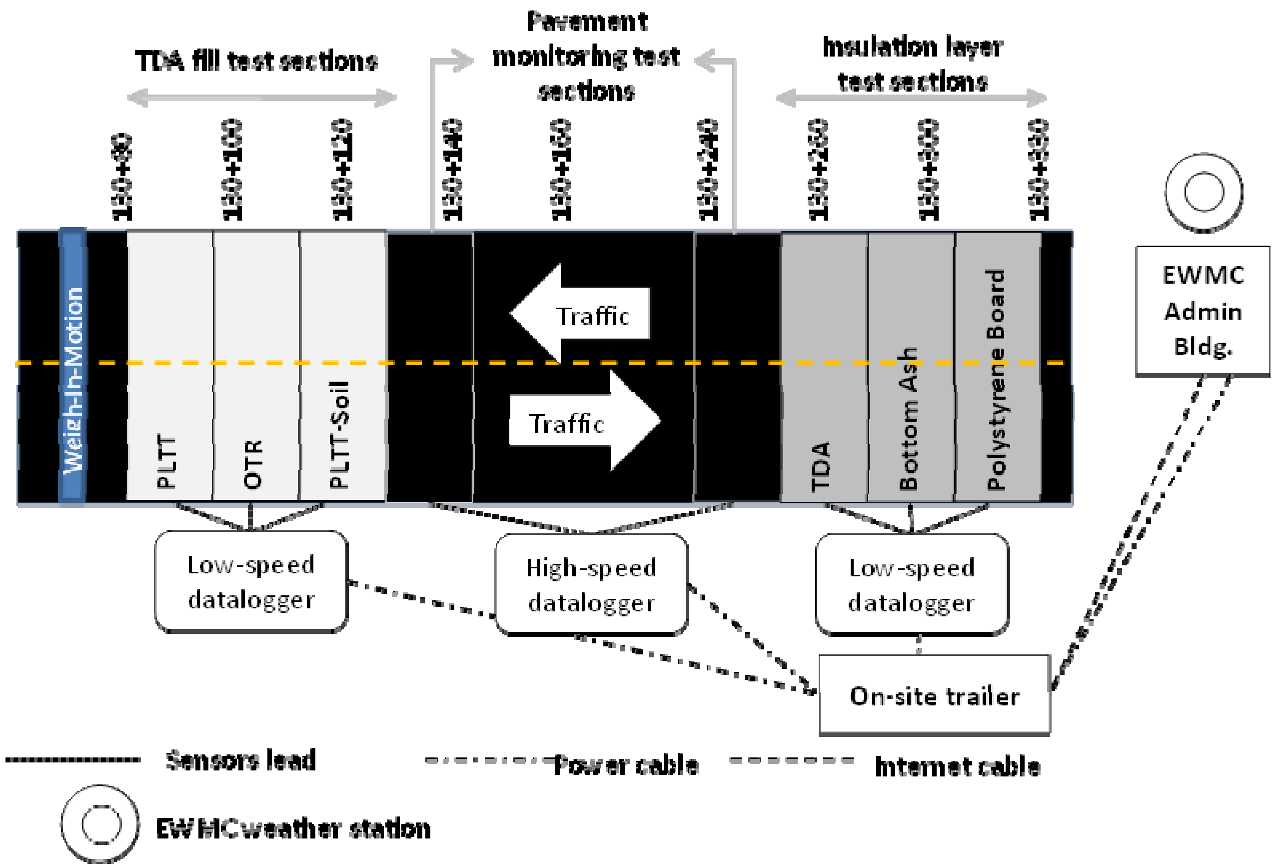

Figure 1. Schematic layout of the test road including the three test sections: 1) TDA fill embankment, 2) pavement monitoring and 3) insulated sections.

All three main test sections were instrumented with a variety of environmental, geotechnical and pavement sensors. The TDA fill embankment test sections were instrumented during construction with environmental and geotechincal instrumentation. As demonstrated in Figure 1, all the sensors within the TDA embankment fill were wired to low-speed datalogger No. 1, located approximately at Stationing 130 + 110. This datalogger is a CR1000 from Campbell Scientific Corp. (CSC), programmed to collect the data from all the sensors at 15 minute intervals.

The northbound of the two pavement monitoring test sections were instrumented with high-frequency instrumentation to capture the effect of traffic loading on the pavement structure. A high-speed CR9000 datalogger from CSC was programmed to be triggered by the pass of a truck and continue to collect the data until the truck passes the northern pavement test section. Environmental sensors were also installed in the pavement monitoring sections, which were connected to the low-speed datalogger No. 1 for the southern test section and datalogger No. 2 for the northern pavement test section. The environmental sensors are used to monitor moisture flow and frost penetration across the pavement system. After the final stage of paving in summer 2013, a Weigh-In-Motion (WIM) system, as well as a traffic video camera, will be installed at the southern section of the road, as shown in Figure 1, to continuously monitor and characterize the traffic. The EWMC's weather station, located approximately one kilometre from the test road is used to monitor climatic indices.

The insulation layer sections were instrumented with environmental sensors across the pavement structure's depth. Datalogger No. 2 (another CR1000 datalogger) was used to continuously collect the data for the insulation test section. A trailer was provided by the EWMC and was positioned at the side of the test road in the northern section (Figure 1) to facilitate the data collection process and supply power to the three dataloggers. Power and fiber optic internet cables were conveyed to the trailer from the EWMC Administration Building through underground directional drilling. Individual power cables were carried to each datalogger from the trailer through cables as presented schematically in Figure 1.

The data collection and data transfer system from the IRRF's test road to the University of Alberta is presented schematically in Figure 2. An antenna Model L14221 from Campbell Scientific was installed on top of the on-site trailer. Each of the three dataloggers is equipped with a spread spectrum Model RF401 radio to communicate with the antenna on the trailer. The antenna is connected to a desktop computer in the trailer, which is programmed to automatically collect the data from each datalogger every day. The data from the on-site computer is then retrieved at the University of Alberta through remote desktop access.

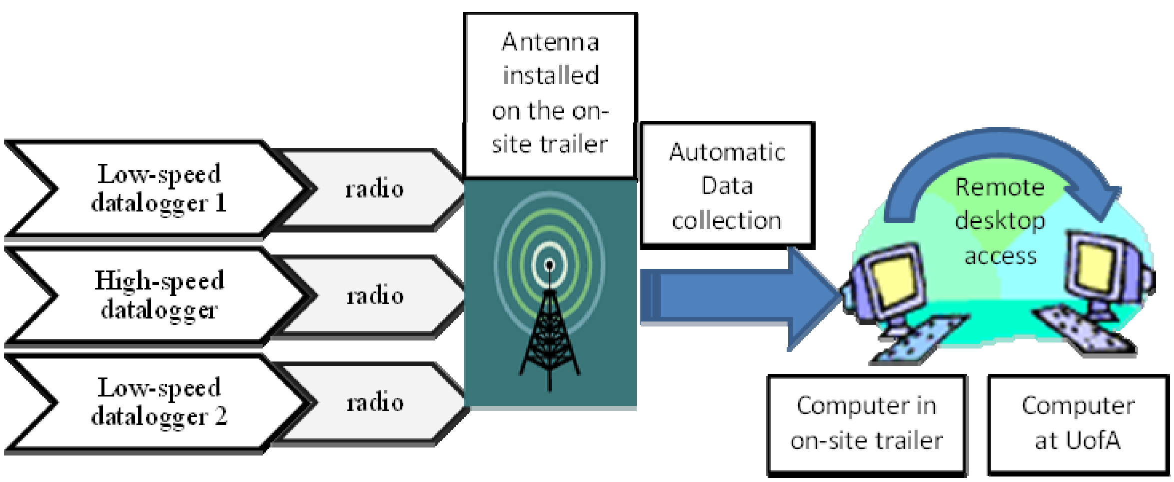

Figure 2. Schematic presentation of remote-access data collection.

3- Tire Fill Embankment Test Section

The vertical alignment of the EWMC access road was in cut through the designated TDA fill section. To accommodate vertical profile for the road the PLTT, OTR and PLTT-soil mixture test sections were place below existing grade. An approximately 8 m deep and 60 m long pit, with 17- and 40-m bottom and top widths, respectively was excavated. A nonwoven geotextile was laid on all sides of the pit. Filling of the pit started on May 15th 2012 by placing the TDA material in 300-mm loose lifts, which were compacted by six passes of a smooth drum vibratory compactor.

Figure 3 shows a schematic longitudinal cross-section of the three successive TDA fill sections. Each test section includes two upper and lower 3-m thick TDA layers, which are separated with an intermediate 0.5-m mineral soil layer. The intermediate soil cap prevents internal heating and potential combustion of the TDA according to ASTM D 6270-08 *(3)*. Each of the upper and lower TDA layers was wrapped in geotextile to avoid mixing with natural soil (Figure 4).

The TDA embankment was capped with one metre of compacted soil on which the pavement structure was built. More details regarding the drainage and geometry design and compaction process for the test sections can be found in another reference *(4)*.

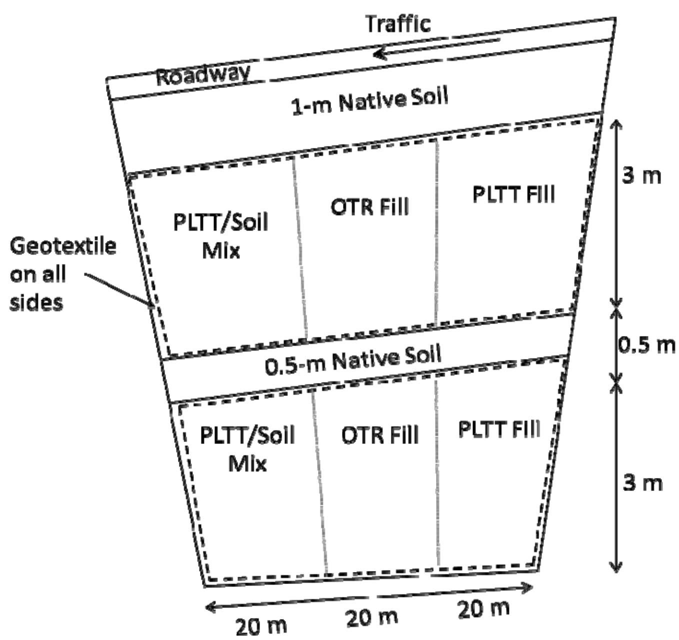

Figure 3. Longitudinal cross section of the three successive TDA fill embankment test sections.

Figure 4. The embankment pit, half filled with PLTT, OTR and PLTT-soil mixture.

Figure 5 shows a schematic transverse cross section of the PLTT section, which is replicated in the other two sections. A total of 60 environmental and geotechnical sensors were installed in the three successive test embankments at various depths and locations (Figure 5). The environmental sensors are used to evaluate the fill's drainage characteristics and potential for internal heating. The geotechnical sensors are used for monitoring the fill's short and long-term compressibility and settlement under the upper layers' weight. A total of 25 Vibrating Wire (VW) Liquid Settlement Systems (Model SSVW105), supplied and calibrated by RST Instruments, were used to monitor the settlement of the embankment. Of the 25 settlement plates, seven were installed in each of the PLTT and OTR sections and six were installed in the TDA-soil mixture section. Further, two settlement plates were installed in the adjacent pavement monitoring test section, which also serves as the control section for the tire fill sections. Settlement plates 1 to 4 were installed on top of the lower TDA layer to monitor the settlement of this layer and settlement plates 5 to 7 were installed on top of the upper TDA layer. For the control section two settlement plates were installed 1.9 m below the top of asphalt (Figure 8). Each test section has one reference settlement plate, installed on stable ground outside the influence of the embankment section (Figure 5). The reference settlement plates are used to correct the measurements from the embankment settlement plates for daily changes in the atmospheric pressure.

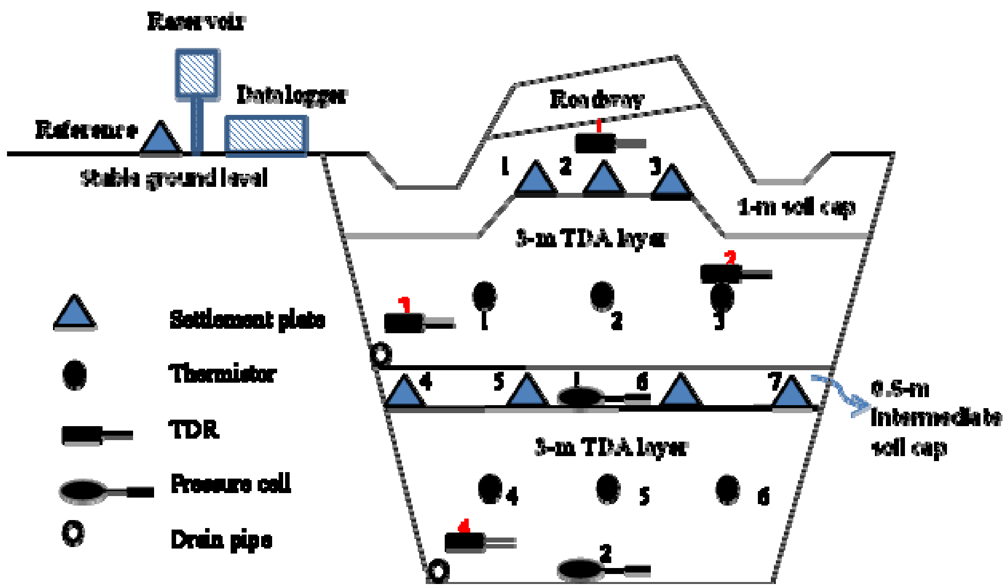

Figure 5. Transverse cross section and instrumentation layout of the TDA fill embankment sections (the schematic is not to scale).

An encapsulation of fine sand was used to protect the settlement plates from the steel wires of the TDA. Each settlement plate has a lead-out wire connected to datalogger No. 1 and a liquid-filled tube. The liquid-filled tube was connected to a reservoir filled with glycol and installed outside the embankment on stable ground. The right picture in Figure 6 shows a reservoir installation. All the settlement plates in one test section, together with that section's reference plate, were connected to one reservoir. The hydraulic head between the sensor and the reservoir produces a frequency change in the VW transducer. The tube and the wire from each settlement plate were carefully conveyed to the datalogger and corresponding reservoir, respectively through separate flexible conduits. The conduits protected the instrumentation leads from the steel wires protruding from the TDA. Figure 7 shows the complexity of the instrumentation wires and tubes to be connected to the datalogger and reservoirs on ground level.

Figure 6. Left: picture of a settlement plate installation and Right: picture of a reservoir for settlement plates in one section.

Figure 7. Installation of settlement plates in the three TDA fill embankment test sections.

Twelve-inch diameter VW Total Earth Pressure Cells (Model LPTPC-V), supplied and calibrated by RST Instruments, were installed to measure the total stress from the fill material. A total of six earth pressure cells, two at each section, were installed. Pressure Cell 1 was installed on the lower TDA layer and Pressure Cell 2 was installed at the very bottom of the pit prior to placing the fill material (Figure 5). The installation process for the pressure cells was similar to that for the settlement plates as described previously.

Internal heating and even fires have occurred in several past TDA fill embankment projects. To monitor for this condition thermistors were installed at mid-depth in each TDA layer.. Model 109AM-L thermistors from Campbell Scientific were used to monitor the temperature changes at various depths of the embankment. A total of 18 thermistors, six in each section, excluding the control section, were utilized in the two layers (Figure 5). Four Time Domain Reflectometers (TDR) Model CS650 from CSC were also installed at different depths of the embankment, as seen in Figure 5, to capture the flow of moisture throughout the embankment. Similar to the installation procedure followed for the settlement plates, the thermistors and TDRs were placed within fine sand. Special care was taken while covering the TDRs in sand to make sure the metal arm of the TDR did not come in contact with the wires embedded in the TDA. Such contact would affect the resistivity measurements by the sensors.

4- Pavement Monitoring Test Section

Two sections of the test road (from 130 + 140 to 160 and also from 130 + 240 to + 260) were selected for instrumentation and long-term pavement performance monitoring. The two pavement sections also serve as control sections for the tire fill embankment and insulation layer sections. A (three-dimensional) schematic cross section of one instrumented pavement section is provided in Figure 8. Note that the layout and nature of instrumentation is the same for both pavement monitoring sections. As seen in Figure 8, the HMA layer, GBC and subgrade soil were instrumented with a variety of low-speed environmental and high-speed pavement sensors.

The environmental sensors include a total of 10 TDRs, installed in two columns of five to capture the transverse as well as vertical distribution of moisture within the system. TDR 1 through 5 were installed on the outer wheel path, while TDR 6 through 10 were installed on the inner wheelpath of the northbound lane. TDR 1, 6, 2 and 7 were installed at the top and mid-depth of GBC and TDR 3 and 8 were installed at the top of the subgrade, TDR 4 and 9 were installed at depth 1-m in the subgrade and TDR 5 and 10 were installed at depth 2-m in the natural soil to monitor moisture flow and frost penetration through the pavement structure. All 10 TDRs in the pavement monitoring section at Stationing 130 + 150 were connected to datalogger No. 1 (Figure 1) and the TDRs in the northern test section at Stationing 130 + 250 were wired to datalogger No. 2.

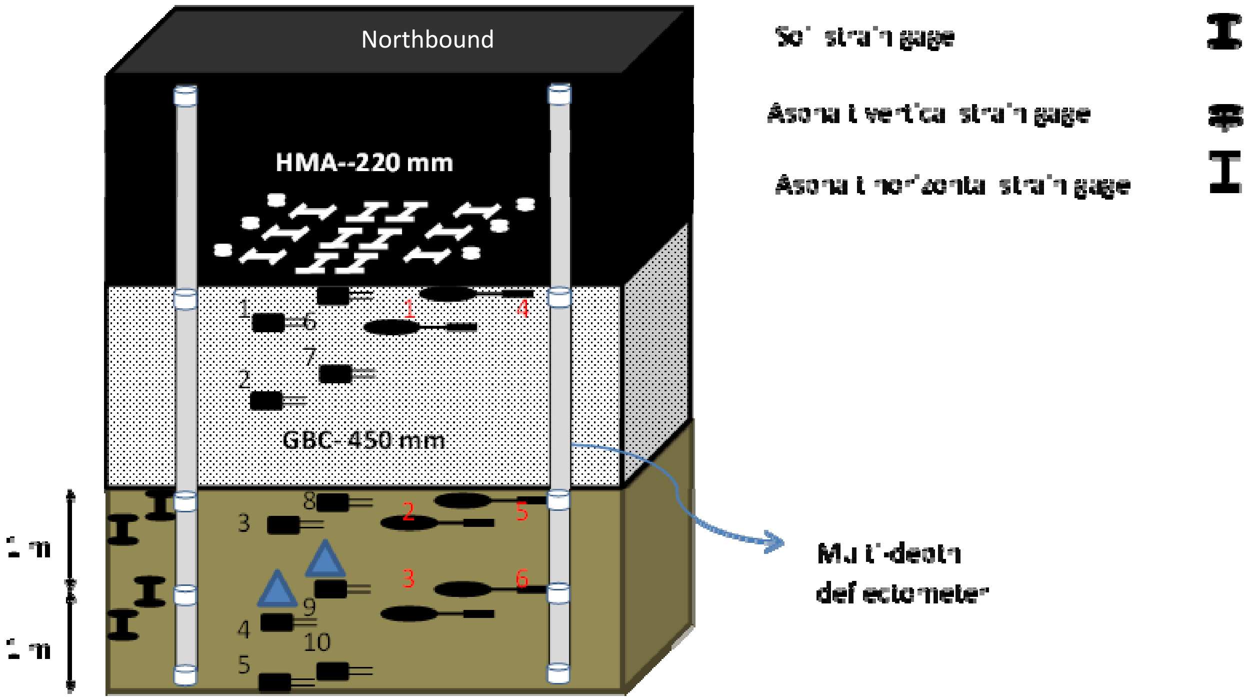

Figure 8. Schematic cross section of the instrumented pavement monitoring test sections (not to scale).

Six twelve-inch diameter strain gage Total Earth Pressure Cells (Model LPTPC-S), manufactured and calibrated by RST Instruments were installed throughout the GBC and subgrade to monitor the distribution of traffic loads within the pavement structure. As shown in Pressure Cells 1 and 4 were installed at depth 100-mm from the top of the GBC, on the inner and outer wheel paths, respectively. The 100-mm cover had to be considered to protect the sensors and their wiring from the high-temperature HMA. Cells 2 and 5 were installed on top of finished subgrade and Cells 3 and 6 were installed at depth 1-m within the subgrade. All the pressure cells in both pavement monitoring sections are wired to the high speed datalogger.

At each of the two pavement monitoring sections, 12 high-speed asphalt horizontal strain gages (ASG-152) were installed in the transverse and longitudinal directions, plus another six vertical asphalt strain gages (ASG-VS). The horizontal asphalt strain gages will capture the strains that result in bottom-up alligator cracking in the wheelpath. The vertical asphalt strain gages are used to monitor vertical strains leading to rutting. The matrix of strain gages, as seen in Figure 8, were installed on top of the GBC in such a way that the inner and outer gages laid on the inner and outer wheelpaths of the northbound lane, respectively. All asphalt gages were manufactured and calibrated by the CTL Group and included 10 metre high-temperature resistant wires.

The instrumentation was installed one day before paving. Each gage was located through surveying and was identified by wood sticks. The GBC surface was covered with prime coat and gages were placed on the prime coat. When installation was complete, the sensors were covered with another layer of prime coat to secure the instrumentation in place. The gages' wires were laid on the shoulder and down the side slope and connected to the high-speed datalogger to take the initial reading (Figure 9). To protect the sensors and their wires from the paver track and the asphalt truck wheels 50 mm of the HMA mixture was placed over the gages and lightly packed by foot. To provide further protection another 50-mm layer of HMA was placed on top of the gages right before paving.

Figure 9. Asphalt strain gage installation process.

5- Insulation Layer Test Sections

Frost heave and thaw weakening during the spring are two challenges associated with frost penetration below the pavement in regions with extreme cold climate, such as Canada. To limit the effects of frost, it is common practice to provide a sufficiently thick non-frost susceptible layer such as gravel beneath the pavement structure. This can exhaust the natural resources of gravel and be very costly in regions where quarries or gravel sources are not easily accessible. Alternative treatments are occasionally used, including the use of rigid polystyrene boards placed underneath the base course as insulation layers. Polystyrene boards however, can be costly, thus recycled materials such as TDA and bottom ash are being evaluated as sustainable alternatives in this project.

As presented schematically in Figure 10, the insulation layer test sections start at Stationing 130 + 280 and include: 1) the TDA insulation section: a 250-mm TDA layer underneath the GBC; 2) a bottom ash section: a 1000-mm of bottom ash layer under the GBC; and 3) the polystyrene insulation section: one layer of 100-mm polystyrene boards for insulation. To improve the transition from insulation layers to untreated ground and to avoid deferential icing, a 20-m section was constructed from 130 + 340 to +360, where a 50-mm layer of polystyrene board was placed under the GBC.

To monitor frost penetration and compare the effectiveness of each material, all four sections were instrumented with thermistors and TDRs at various depths as presented in Figure 10. All the sensors are connected to low-speed datalogger No. 2, located approximately at Stationing 130 + 310. The pavement monitoring test section at Stationing 130 + 250 is used as the control section with no insulation layers.

Multi-Depth Deflectometers (MDDs) from the CTL Group will be installed in each test section as well as the control sections after the final stage of paving in summer 2013. As shown schematically in Figure 10 the MDDs will include transducers at each layer interface to monitor potential frost heave of each layer. Two MDDs are also considered in the two pavement monitoring sections as presented in Figure 8 to monitor potential frost heave in the control sections.

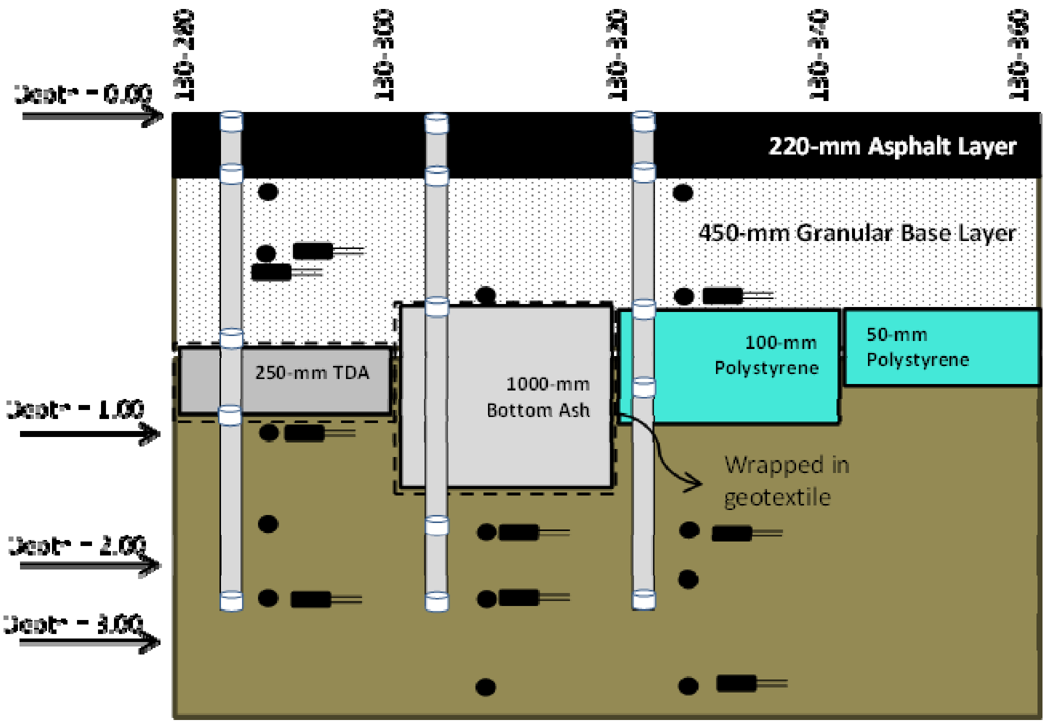

Figure 10. Schematic cross section of the instrumented insulation layer sections, including the TDA, bottom ash and polystyrene board test sections.

6- Field Performance Tests

Periodic Falling-Weight Deflectometer (FWD) tests are scheduled to be performed on the test road to monitor seasonal changes in the pavement layers' moduli. Regular automated profile measurements and distress surveys of the roadway will also be carried out every year to closely monitor the road performance. A series of FWD tests were performed on three occasions during construction: 1) on top of the finished subgrade on July 11th 2012; 2) on top of the finished base on July 27th 2012; and 3) on the newly placed asphalt layer on August 15th 2012.

FWD tests were carried out in the northbound from Stationing 130 + 35 to 130 + 255 (just before the insulation sections). Dynatest FWD device was used to apply four drops, resulting in target load magnitudes of 5.8, 8.1, 10.0 and 12.4 kN at approximately 5-m intervals along the centerline and the outer wheelpath, using a 300-mm diameter load plate. Surface deflections were measured using seven geophones located at 1200, 900, 600, 450, 300, 200 and zero mm from the center of the load plate. The subgrade modulus was backcalculated based on the elastic half-space (Boussinesq's) theory as presented in Equation 1:

$$Mr = \frac{\pi(1-\nu^2)qa}{2d_1} \qquad \text{Equation 1}$$

Where,

Mr = subgrade resilient modulus (Mpa),

q = applied pressure (Mpa),

a = radius of the loading plate (mm),

d_1 = the deflection under the plate center (mm) and

ν = the Poisson ratio of the subgrade material (defined as 0.35 for SC soil type *(5)*).

The backcalculated modulus for the four FWD drops at each location along the centerline and the outer wheelpath are presented in Figure 11 (a) & (b), respectively. According to Figure 11 (a), the subgrade Mr along the outer wheelpath is relatively consistent with average values of 60, 53, 49 and 47 for Drops 1 through 4, respectively. Subgrade Mr shows an abrupt increase to 86 Mpa at Stationing 130 + 145. This point is the end of the TDA fill test sections and the start of the normal existing ground. Beyond the transition point at Stationing 130 + 150, the modulus tapers gradually to a minimum value of 47 Mpa at Stationing 130 + 190. Another sudden increase is evident at Stationing 130 + 220. A possible explanation for the variation is the change in the natural soil profile at this station.

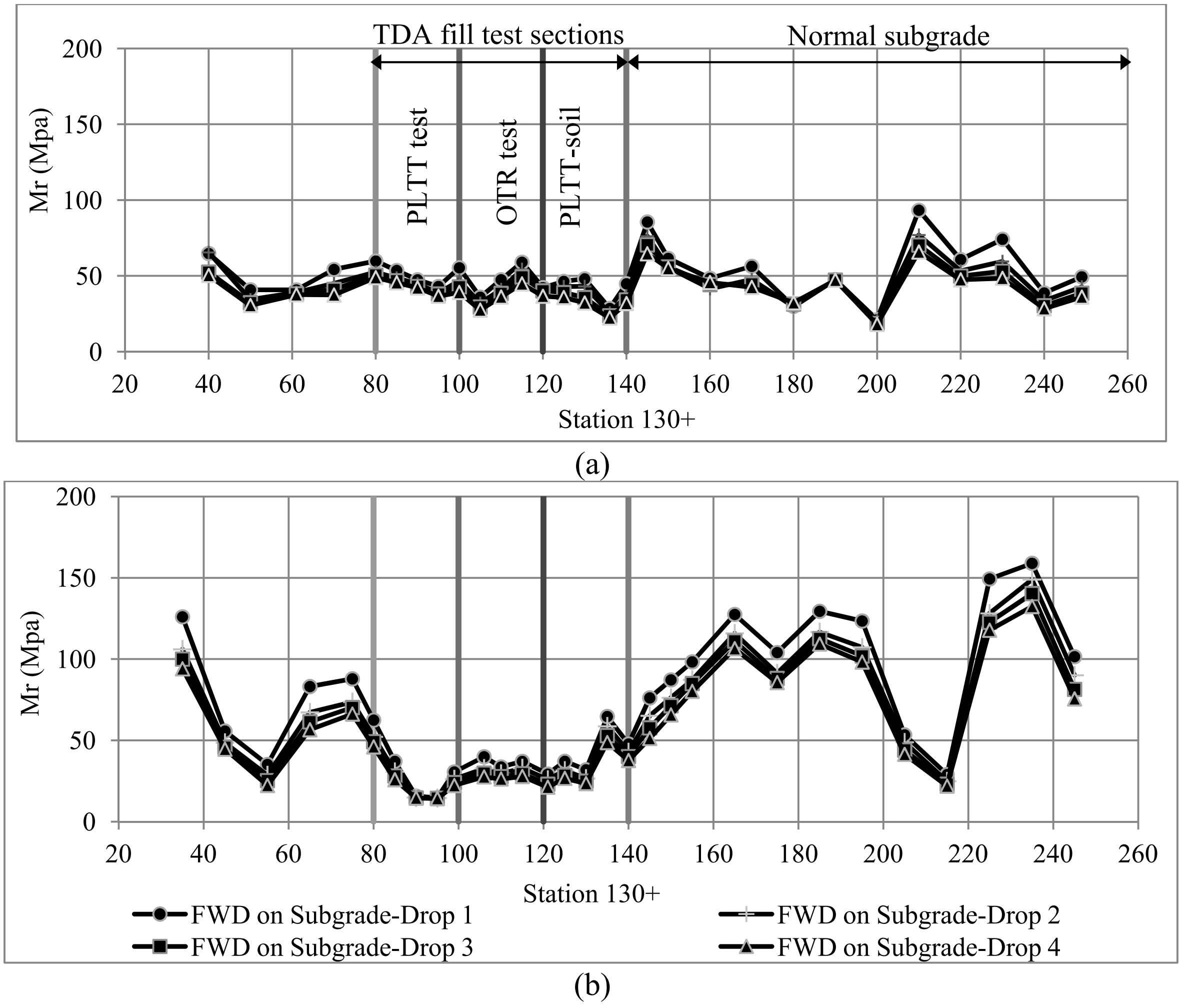

Figure 11. Subgrade Mr, backcalculated from FWD tests performed directly on the subgrade, along the (a) wheelpath and (b) centerline.

Figure 11 (b) presents the FWD backcalculated subgrade Mr along the centerline. The average Mr along the centerline is 70, 61, 58 and 54 Mpa for Drops 1 through 4, respectively. These average values are consistently higher than those obtained for the tests performed in the outer wheelpath, as discussed previously. The backcalculated Mr at the start point (Stationing 130 + 40) drops from a maximum of 107 Mpa to a minimum of 28 Mpa at Stationing 130 + 55 and then picks up to a maximum value of 74 Mpa. This variation may be due to localized moisture, note that no variation is evident in Figure 11 (a) for the same section. The modulus significantly drops at the edge of the tire fill embankment (Stationing 130 + 80) and remains as low as 32 Mpa over the fill sections. Backcalculated modulus starts to increase at the end of the fill sections at Stationing 130 + 140 and continues to ascend until Stationing 130 + 170. A sudden drop is seen at Stationing 175, which may be due to such reasons as localized moisture. A sudden drop is noted at Stationing 130 + 190, where the terrain changes. Significant variability existed in the uniformity and quality of compaction of the subgrade along the centerline. It is evident that special care is required during compaction, especially at the transition zones from fill or cut sections to normal ground.

7- Summary

The Integrated Road Research facility (IRRF) is a new research initiative in western Canada, established based upon a unique collaboration amongst the University of Alberta, Alberta Transportation, the City of Edmonton, Alberta Tire Recycling and Canada Foundation for Innovation (CFI). As part of the IRRF, a new test road was constructed and heavily instrumented in summer 2012. The extensive financial and in-kind support from the partners made the construction and instrumentation of the multi-million dollar test road possible. The test road includes three main test sections: 1) Tire-Derived Aggregate (TDA) fill embankment sections, including three successive test sections made of Passenger-Light-Truck-Tire (PLTT), Off-the-Road (OTR) tires and PLTT-soil mixture; 2) pavement performance monitoring test sections; and 3) pavement insulation layers test sections, comprising polystyrene boards, bottom ash and TDA. Design, planning, construction and instrumentation of the road became possible through close collaboration amongst different parties and weekly on-site meetings during construction. With continued support the University of Alberta will access valuable field monitoring data for the performance monitoring and evaluation of the test sections over the years to come. Seasonal FWD tests, automated profile measurements and distress surveys are scheduled to be performed on the test road every year.

FWD tests were performed on the finished subgrade to evaluate the quality of compaction along the road. The results of the tests were presented and discussed in this paper. FWD test performed on the subgrade showed great sensitivity to change in the terrain slope, fill versus normal ground or cut, and moist versus dry zones. The results showed that special care needs to be taken during compaction at transition zones between cut and fill sections and also where the ground topography varies.

Acknowledgements

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