The Effect of Insulation Layers on Subgrade Strength during Thaw Season

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ABSTRACT

A well-known strategy for minimizing the negative effects of prolonged low temperatures on frost-susceptible subgrade is using insulation layers. It helps to mitigate the formation of ice lenses and frost heave in the subgrade and subsequently reduce the associated damage despite the presence of a shallow water table. Using insulation layers aids with the drainage of the excess water formed from melted ice lenses during thaw season, which reduces subgrade strength before it discharges out of the system.

This paper evaluates the effect of using a recently introduced by-product of power generation, bottom ash, as an insulation layer, and the commonly used Polystyrene boards on subgrade resilient modulus variations during thaw season at the IRRF test road facility of University of Alberta, Edmonton, Canada. Using temperature data received from Time Domain Reflectometers (TDR) installed across the pavement depth over the course of two successive springs (2014 and 2015), the onset of thaw season was established. Timeline for the recovering period was based on Me-PDG recommendation. To evaluate the subgrade strength, Falling-Weight Deflectometer (FWD) testing was conducted at 10-m intervals along the test road during thaw season and the average condition. The back-calculated moduli from deflection basins were used to determine the resilient modulus of the insulated sections and the control section.

The study results revealed that using polystyrene boards as insulation layers protected subgrade soil from freezing and thawing effect since the resilient moduli were almost constant during thaw season and had greater values compared to control section. Although bottom ash layer had been affected by freeze and/or thaw, the section exhibited less variation in subgrade modulus than that of the control section during recovering period, particularly in the month of May.

Key words: Insulation Layer, Thaw Season, Resilient Modulus, Subgrade

INTRODUCTION

In regions with prolonged winters, the temperature usually remains at below 0° for a few months. If the subgrade soil is frost-susceptible and water is present in the pavement, it may produce frost-heave. Differential frost-heave can negatively affect the riding quality of the road and may cause formation of ponds of water on the road. In spring, when thawing starts in different layers of pavement, the subgrade layer would store significant amounts of water for a short period of time. It creates excess pore water pressure and decreases the effective stress, or the resilient modulus, since there is not enough time for its drainage out of the system. As the load bearing capacity of the road is affected by the low resilient modulus of the subgrade, traffic loading causes higher deflection which leads to deterioration and accumulation of fatigue in the pavement upper layers [1].

The seasonal variation of subgrade modulus has been investigated by different researches and agencies. A wide range of ratios has been reported based on the subgrade characteristic, severity of winter and frost depth. For example, Alberta Transportation and Utilities' "Pavement Design Manual" Guide focuses on Alberta as a province with a prolonged severe winter and suggests a ratio of 0.625 and 0.875 for adjusting the resilient modulus of subgrade in April and May compared to the normal condition [2]. An approximate 70 to 79 percent loss in resilient modulus of subgrade is reported for three districts in Nevada over a five-year monitoring period [3]. A study conducted in Ontario, where the pavement undergoes several freeze-thaw cycles, showed the approximate ratio of 20 to 80 percent for the clay and silty-clay subgrades in early spring compared to fall [4]. Minnesota Road Research Project reported a 25 to 32 percent decrease in subgrade modulus during spring and summer compared to fall when the subgrade is fully recovered from freeze-thaw effect [5]. Another study, conducted in the University of Waterloo, at the Centre for Pavement and Transportation Technology (CPATT) test track, reported a 27 percent decrease in subgrade modulus during the month of May and a 30 and 49 percent loss in April, compared to subgrade effective modulus [6].

Alleviating the frost-heave and thaw weakening damage and minimizing the seasonal variation of subgrade modulus is possible by eliminating one of the contributing factors. Using insulation layers is one of the strategies for protecting frost susceptible subgrade from frost penetration. If insulation layers minimize the variation in resilient modulus of the subgrade and provide an acceptable load bearing capacity, thicknesses of the base/subbase layer may be reduced.

Since the 1990s, several materials were introduced and evaluated as insulation layers, including sawdust, tire chips and plastic. [7]. Polystyrene boards are one of the most well-known insulation materials that has a long history of application. Plastic foam boards are verified to be effective in both decreasing the frost depth and extenuating the induced heave. The study conducted at Wolf Creek Pass in Colorado showed that using polystyrene as an insulation layer led to a formation of 14 cm less frost heave than that of the conventional section [8]. The study undertaken at the test road in Alaska used polystyrene of two different thicknesses of 5 and 10 cm illustrated 20 and 10 cm thaw depth, respectively, compared to the conventional section, which had 61 cm thaw depth. The settlement was also restrained as the insulated sections showed 9 cm less deflection compared to the conventional section [9]. Recent research at the two insulated test roads in Edmonton, Alberta, Canada, showed that a 5 cm and 10 cm thick extruded Polystyrene boards can reduce the frost depth by at least 40 percent [10], [11].

The struggle to use waste and recycled materials as an economical insulation layer is an on-going trial-and-error process. Previous research attempts include using saw-dust, marginal material and tire-derived-aggregate in different projects [7], [12]. Bottom ash, which is a by-product of burnt coal used in power plants, was recently introduced as an insulation layer. Currently, it is classified as a waste material which does not have any specific usage. Researchers in the City of Helsinki, Finland, illustrated that using bottom ash decreased the frost depth for about 40 to 60 percent of that in the normal section [13]. This

study also revealed that carefully compacted bottom ash has lower permeability and can be thus categorized as a non-frost-susceptible layer. Two different studies in Edmonton, Alberta, Canada, comprising of a 110 and 100 cm bottom ash layer, displayed frost depth of about 1.5 and 1.45 cm and prevented the frost from reaching the frost-susceptible subgrade [14], [11].

Using insulation layers is one of the approaches to preventing the frost related damages in Edmonton with freezing index as high as 1,365°C.days [15]. The objective of the current study is to investigate the effect of using insulation layers on the subgrade modulus variation during the critical thaw period over the course of two successive springs (2014 and 2015). The data was gathered at the University of Alberta's Integrated Road Research Facility (IRRF)'s test road located in Edmonton, Alberta, Canada. The road is comprised of a bottom ash layer and two polystyrene boards of different thicknesses. The embedded instrumentation at different depth of the pavement identified the start of the thaw season for different sections. The results are compared with the adjacent conventional section which performed as the control section. Using Mechanistic-Empirical Pavement Design Guide (Me-PDG) [16], the required time for subgrade to recover from thaw effect was calculated. To evaluate the subgrade strength, Falling-Weight Deflectometer (FWD) testing was conducted on each section during recovering period and the normal condition. The back-calculated moduli from deflection basins were used to determine resilient modulus of subgrade and then compared with the control section.

DESCRIPTION OF THE TEST ROAD FACILITY

The construction of IRRF's test road facility, located in east Edmonton, started in May 2012. The first and second stages of the paving were accomplished in August 2012 and August 2013, respectively. The road is tentatively scheduled to open to traffic in 2016. It will be subjected to up to 500 trucks per lane per day and serve as the access road to the Edmonton Waste Management Center (EWMC). The two lane test road is about 500 m long and is comprised of 25 cm hot mixed asphalt (HMA) located on top of 45 cm Granular Base Course (GBC). All the sections are located in cut section, so the natural soil was used as the subgrade soil. Figure 1 illustrates a schematic plan view of the test sections. The normal section which is located at stationing 130+240 to +260, served as a control section (CS), followed by bottom ash section (B.Ash) and Polystyrene section with 10 and 5 cm thicknesses (Poly-10 and Poly-5).
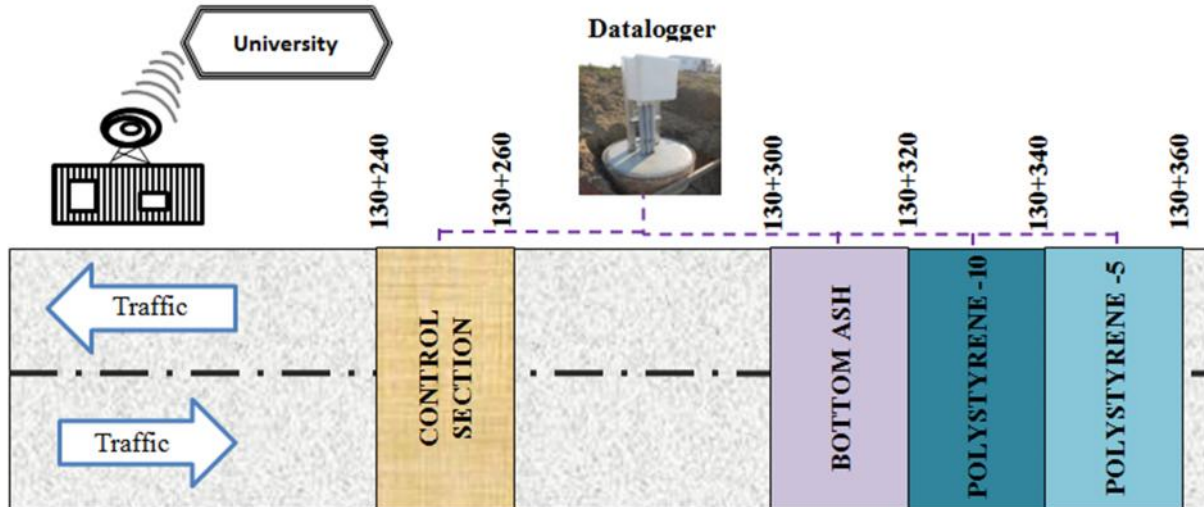

Figure 1: Plan view of the test sections

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MATERIALS

In accordance with the City of Edmonton's specifications for Designation-1 asphalt concrete mix, two HMA mixes were prepared using Marshall Mix design [17]. The first and second mixtures consisted of granular aggregates with the maximum nominal size of 12.5 mm and 25 mm respectively. The 25 cm asphalt layer was constructed in the following way: 9 cm of the first mixture (in two upper layers) and 16 cm of the second mixture (in two lower layers). The GBC layer, classified as Well-Graded Gravel (GW) based on the Unified Soil Classification System (USCS), was comprised of crushed aggregates [18]. Sieve analysis of the subgrade soil classified it as Clayey Sand (SC). Subgrade soil had liquid limit of 25 and plastic index (PI) of 9 percent, respectively. Figure 2 shows the aggregate size distribution of all pavement layers.

The bottom ash is composed primarily of silica, alumina, iron and less than five percent non-combusted coal particles. It was free of large lump and impurities. During compaction, the moisture level in the bottom ash layer was maintained as low as 35 percent. The layer was wrapped in geotextile to avoid mixing with natural soil. The particle size distribution is illustrated in Figure 2.
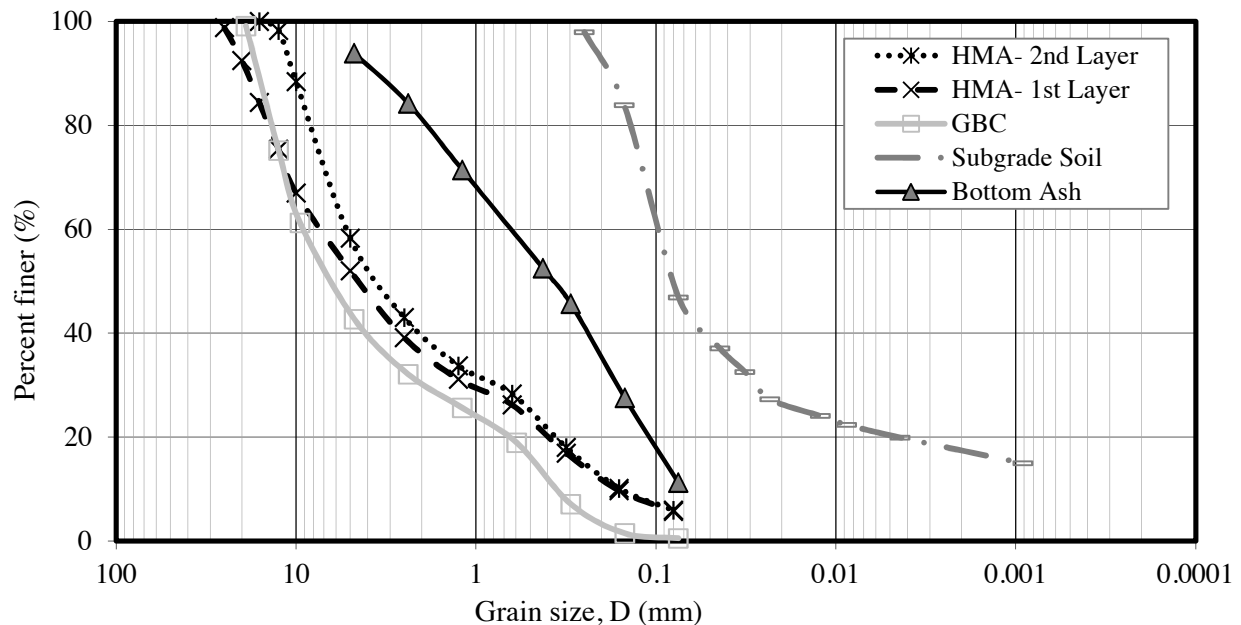

Figure 2: Grain size distribution of different material used in the pavement

Closed cell Styrofoam Highload 100 extruded Polystyrene foam boards produced by Dow Chemical Company were used in this project. Based on the manufacturer's data sheet, the boards have a compressive strength of 690 kPa and a compressive strength of 690 kPa and a minimum flexural strength of 585 kPa.

INSTRUMENTATION AND DATA COLLECTION

Except for the Poly-5 section, all the IRRF sections except for the Poly-5 section, are fully instrumented with the 109AM-L thermistors and CS650 Time Domain Reflectometres (TDRs) to record the pavement moisture and temperature variation across the depth. Figure 3 illustrates the cross sections and the as-built depth of sensors. The TDRs of CS and thermistors of the sections Poly-10 and B.Ash are located at a 0.5-

m distance from the inner edge of the road's shoulder. Only the temperature data recorded by TDRs are used in this investigation.
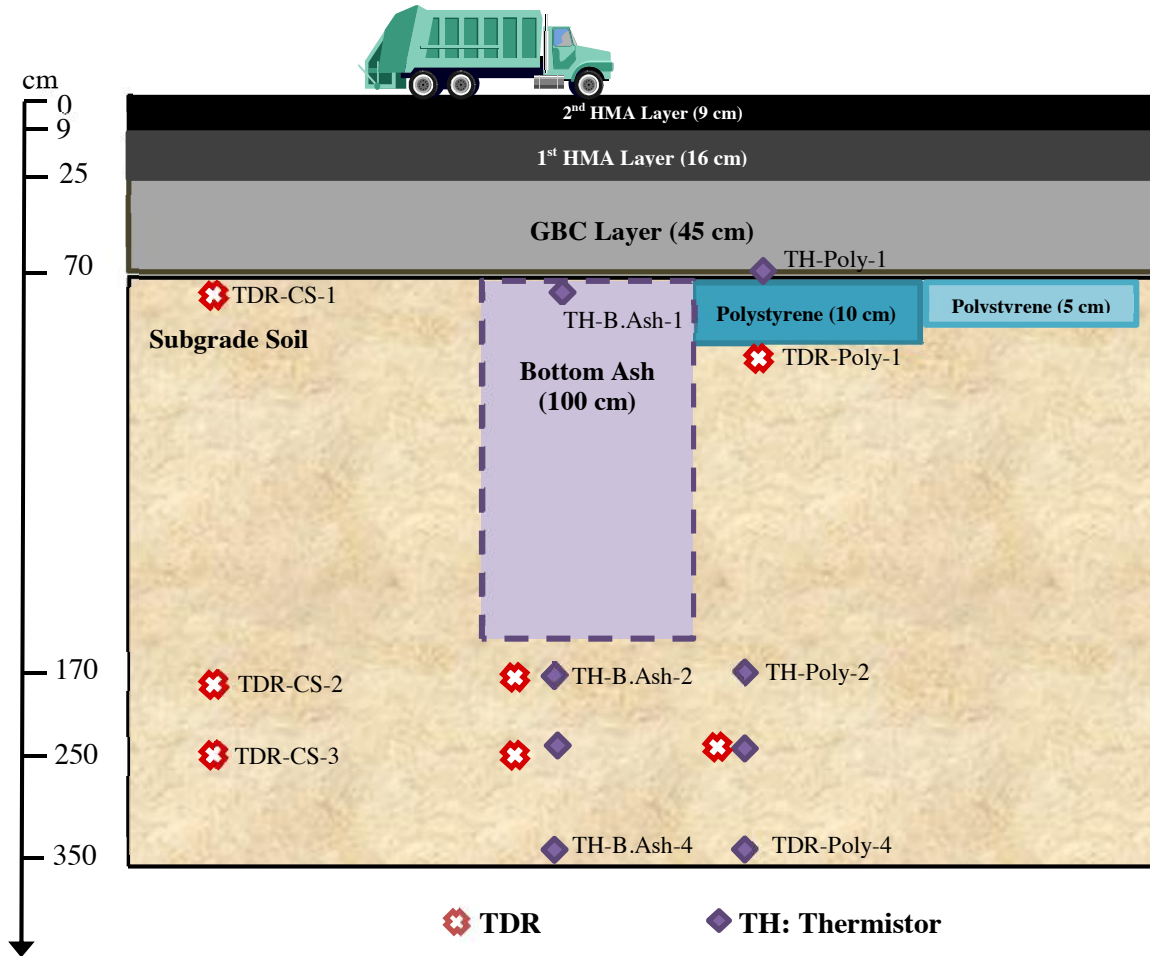

Figure 3 : Cross sections and as-built depth of thermistors and moisture probes.

The data from the sensors are collected using a CR1000 Datalogger equipped with a spread spectrum antenna to frequently transmit data to the on-site computer. Using a remote desktop access, the data is further transmitted to the University of Alberta.

RECOVERING PERIOD: ONSET AND DURATION

With the gradual increase in ambient temperature, the pavement's temperature rises in the beginning of spring. When it reaches above 0°C, the top layers of the pavement begin to thaw, while the lower layers remain frozen. Until the excess water drains out of the system and the subgrade re-obtains its strength, the top layers are soaked in water. The Mechanistic-Empirical Pavement Design Guide (Me-PDG) defines the recovering period as the portion of time from the beginning of thawing until the time the subgrade layer is fully recovered from the drainage of the excess melted water and reaches a stable or normal condition [16]. As previously mentioned, one of the objectives of this study is to establish the onset and duration of the recovering period based on field data.

Figure 4 shows the temperature distribution on top of the subgrade and bottom ash layer in CS and B.Ash sections, and underneath the polystyrene layer in Poly-10 section. The data indicates that CS and B.Ash sections follow the same trend of temperature variation within the monitoring period, while the Poly-10 section showed a completely different range of variation. Figure 4 reveals that the temperature right underneath the polystyrene layer never decreases below 0°C. Thus, the subgrade layer of the section insulated with a 10 cm polystyrene board is fully protected from the freeze and thaw effect. The CS and B.Ash sections showed that the temperature reached 0°C on the same day in March 2014 and March 2015, indicating the simultaneous start of thawing for both of the sections. However, as illustrated in Figure 5, the temperature at deeper layers of the B.Ash section never decreases below 0°C, while the CS remained frozen for about three months. This phenomenon indicates that, although the CS and B.Ash sections started thawing at the same time, the freeze and thaw depth and the recovering period duration in CS is and B.Ash section are different.
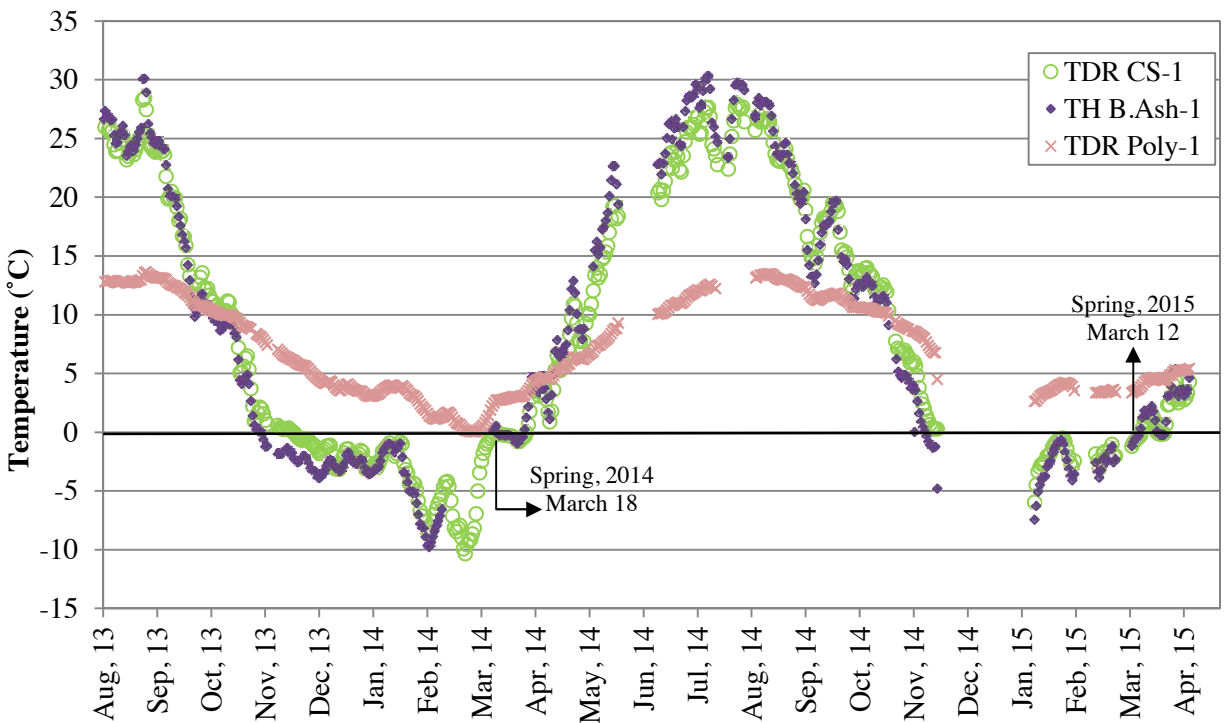

Figure 4: Temperature distribution in different sections on top of the subgrade layer during the monitoring period

Despite the fact that temperature indicates the onset of recovering period, its duration is more dependent on material (subgrade) properties, rather than on the temperature change. The Me-PDG design guide proposes a recovering period of approximately 120 days for the subgrade material used in this project. Based on the laboratory testing, the clayey sand (CS) subgrade of this project has PI=9% and P-200=46.9%. Hence, the recovering period started in mid-March in CS section; the section can be considered as the normal one from mid-July [16].
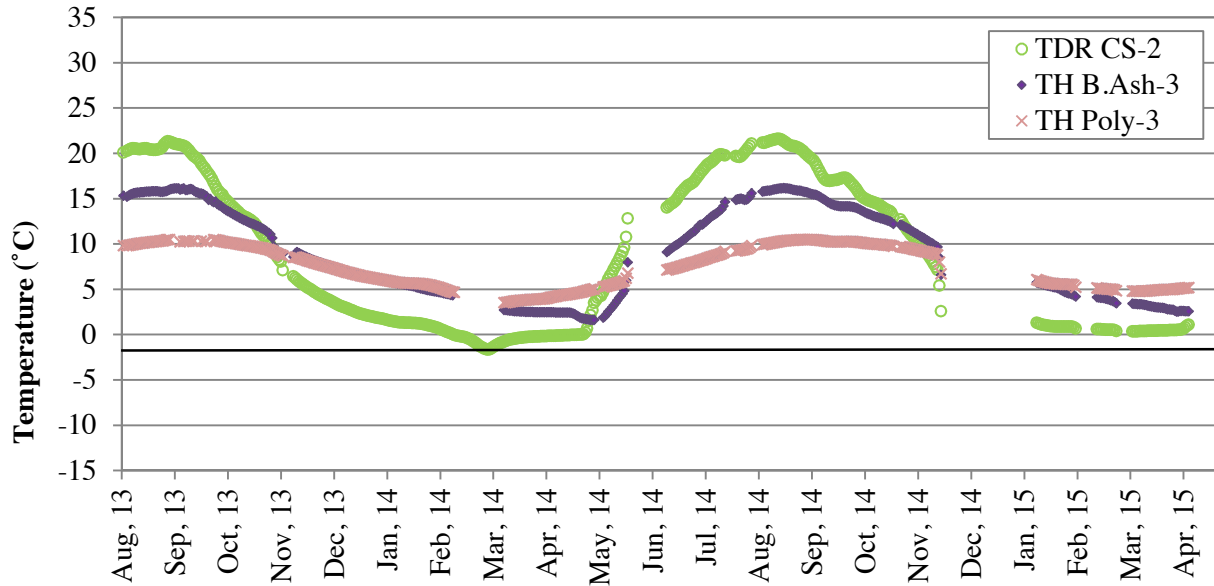
Figure 5: Temperature distribution in different sections at depth 1.7 m from top of HMA during the monitoring period

FALLING WEIGHT DEFLECTOMETER (FWD) TESTING

For monitoring the subgrade modulus variations during the recovering period and establishing related reducing factor of subgrade modulus in comparison to fully recovered (unfrozen condition), FWD testing was conducted in different sections of the IRRF's test road. A Dynatest 8000 with a nine-sensor configuration at 0, 200, 300, 450, 600, 900, 1200, 1500, and 1800 mm from the centre of the load plate was used. As mentioned in the previous section, recovering period is considered to last from mid-March to mid-July. For this reason, the results of FWD testing conducted on 8th April 2015, 23th April 2015, 29th April 2014, and 30th May 2014 are used as representative of the recovering period. Also, the FWD testing conducted on 17th October 2014 is used for back-calculating the resilient modulus of a normal section. The load was applied in the middle of each section to prevent interference between the different insulated sections. The stress levels of 40.0 KN is applied for investigation purpose.

As there may be some inaccuracy in the applied load, the deflection should be corrected based on the exact FWD standard target load level before commencing the analysis. Therefore, the deflection data were normalized based on 40KN load. The acceptable tests were selected based on the "Long-Term Pavement Performance Program" Manual for FWD Testing which recommends not to exceed the range of 36.0 to 44.0 KN for the applied load [19]. The resulting normalized deflections were also examined to uncover possible irregularities in the deflection basin based on the method proposed by Xu et al. [20].

The temperature of the HMA layer at 20 mm from the surface for each test is reported in Table 1, which plays a vital role in illustrating the deflection of the pavement. Particularly, higher temperature tends to soften the HMA layer, while low temperature causes increasing of the HMA modulus. Considering the fact that HMA has the most important influence on the load bearing capacity of the pavement, changes in the HMA modulus should be monitored to enable an accurate comparison between the FWD testing results.

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Table 1: The HMA layer's temperature at 20 mm from the surface

Test ID	FWD 1	FWD 2	FWD 3	FWD 4	FWD 5
Test Date	8th Apr. 2015	22th Apr. 2015	29th Apr. 2014	30th May 2014	17th Oct. 2014
Temperature (˚C)	10	15	18	20	7

Figure 6 illustrates the temperature distribution data in the depth of different sections, collected exactly on the day of FWD testing. Using this graph, the state of freezing or thawing through the pavement depth can be investigated. Figure 6 (a) shows that although CS and B.Ash sections are both partially frozen in April 2014, the CS is frozen at a deeper level than the B.Ash section. During the FWD testing, performed in April 2015, (Figure 6 (c)), the B.Ash section was partially frozen at the depth similar to that of April 2014. However, as the temperature distribution data show, the CS was completely thawed. The temperature distribution in other graphs indicates that during FWD 2, FWD 4 and FWD 5, none of the sections were frozen (Figure 6 (b, d and e)).
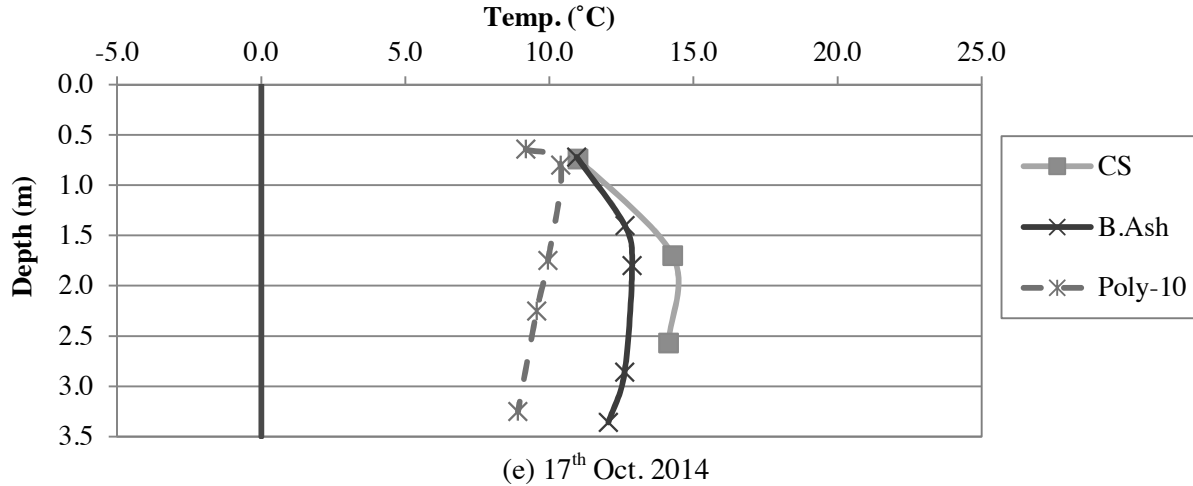

(a) 8th Apr. 2015

(b) 22th Apr. 2015

(c) 29th Apr. 2014

(d) 30th May 2014

(e) 17th Oct. 2014
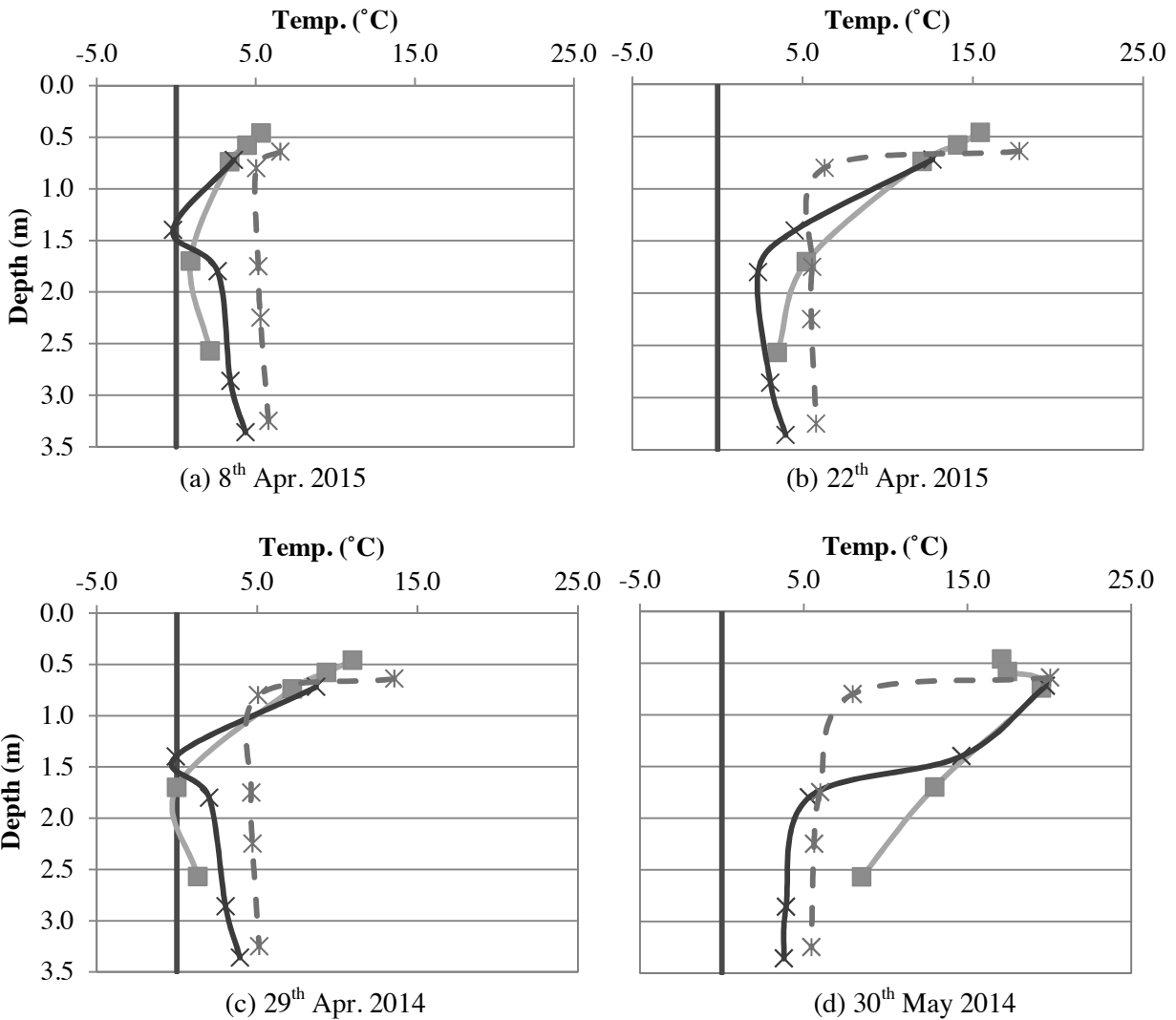
Figure 6: Temperature distribution in depth of different sections in (a) April 2014, (b) May 2014, (C) April 2015 and (d) Oct. 2014

FWD Testing Result

Figure 7 presents the deflection basins of all sections when the tests were performed during the recovering period and normal condition. As expected, the results indicated that the maximum deflections followed the same trend of the HMA temperature. While the temperature is increasing from FWD 1 to FWD 4 (Table 1), the maximum deflections also increase. The maximum deflection during October 2014 which had the lowest temperature is considerably lower than that of other FWD tests. Apart from the date of testing, Poly-10 always exhibited larger maximum deflection (D0) followed by the Poly-5 section, except for FWD 1, when the CS had a larger D0 than the Poly-5 section.

For ease of comparison, the maximum deflections of all sections underneath the loading plate from different tests are shown in Table 2. As mentioned above, the maximum deflection is gradually increasing from FWD 1 to FWD 4, as a reason of increasing HMA temperature and lower subgrade modulus resulted from higher moisture content in spring. Comparing maximum deflections of different tests with the value of that in October reveals that the average D0 of all sections in May 2014 is about 69 percent higher of that in October 2014. During the test FWD 3 when the temperature is similar to the test conducted in May 2014, the average maximum deflections was about 39 percent higher than of that in October. Thus, May is the most critical month in evaluating the resilient modus variation during the recovering period.

Table 2: Maximum deflections (D_0) during thaw season and their ratio to the deflection projected in October 2014

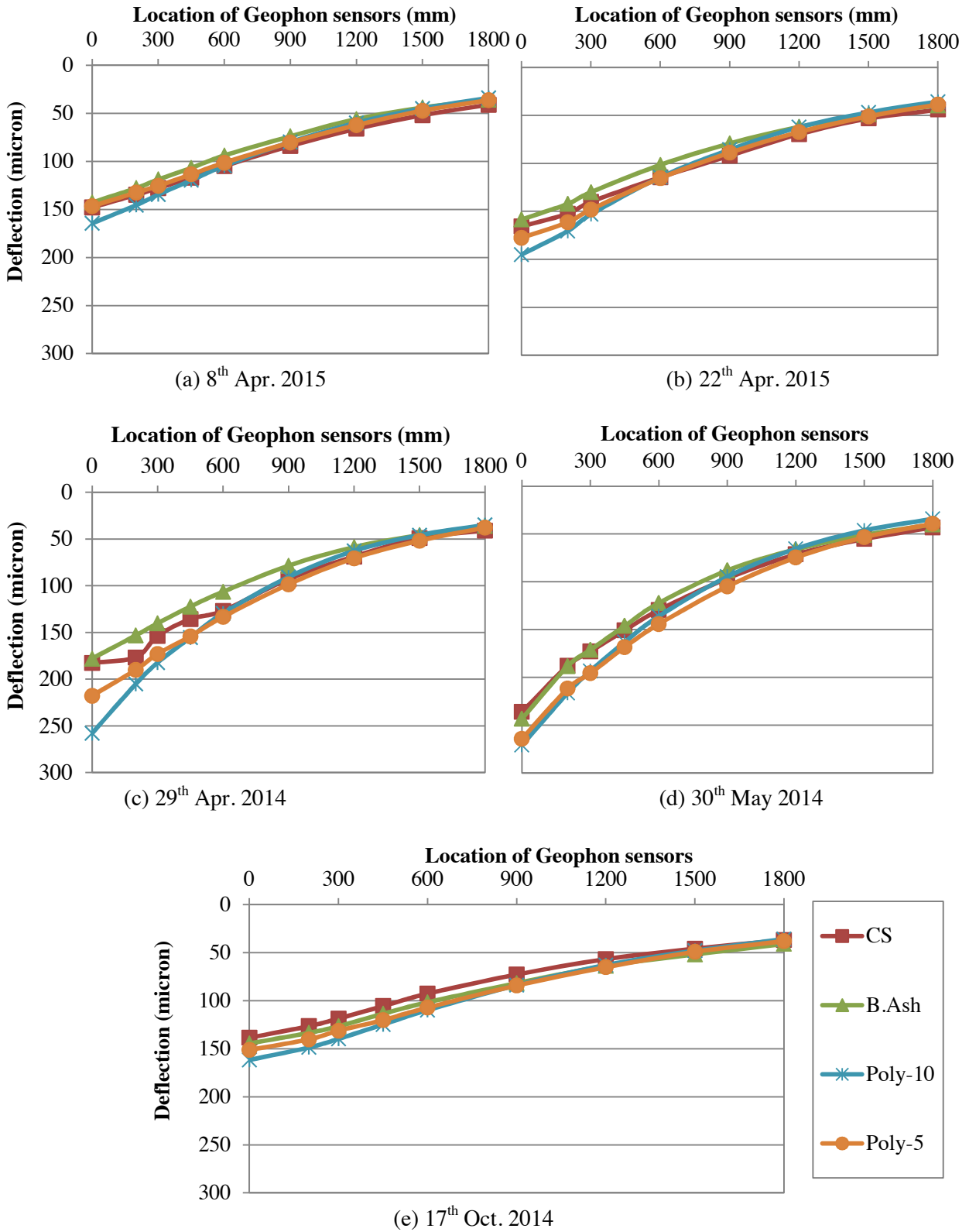|	**Do (maximum deflection, micorn)**					**Compared deflection with FWD 5**			
	8-Apr-15	22-Apr-15	29-Apr-14	30-May-14	17-Oct-14	8-Apr-15	22-Apr-15	29-Apr-14	30-May-14
Test ID	FWD 1	FWD 2	FWD 3	FWD 4	FWD 5	FWD 1	FWD 2	FWD 3	FWD 4
CS	147.7	165.8	182.6	236.2	138.5	107%	120%	132%	171%
B.Ash	142.7	158.5	178.0	243.4	150.0	95%	106%	119%	162%
Poly-10	164.4	195.1	258.0	270.9	161.7	102%	121%	160%	168%
Poly-5	146.5	177.7	217.8	264.3	151.2	97%	118%	144%	175%
COV	6.39%	9.18%	17.76%	6.51%	6.32%				

Figure 7: Deflection basin of FWD testing on top of the HMA in (a) April 2014, (b) May 2014, (C) April 2015 and (d) Oct. 2014

The result of the FWD 1 test, which had a temperature similar to October, showed an equally higher average maximum deflection compared to October. The ratio of average maximum deflection to the maximum deflection in October reveals that the Poly-10, having the ratio of 1.37, had the maximum variation, followed by the Poly-5 and the CS with ratio of 1.33 and 1.32. The B.Ash section with ratio of 1.20 had the minimum variation within all sections.

The FWD 3 with the COV of about 18 percent exhibited the maximum variation in maximum deflection, which may have resulted from the combination of high moisture content and high HMA temperature compared to other tests. The FWD 1, FWD 4 and FWD 5 had approximately the same COV as high as about 6.5 percent.

Modulus of Subgrade

To investigate the effect of using insulation layers on subgrade modulus changes during the recovering period, equation proposed in the AASHTO method was used for back-calculating the subgrade modulus based on FWD data AASHTO [21] method suggested the modulus of subgrade is calculated using Equation 1:

$$M_r = \frac{0.24 \times P}{D_r \times r}$$

Equation 1

where M_r is the resilient modulus of the subgrade, P is the target load, D_r is the normalized deflection under load P at distance r, and r is the distance of the selected geophone from the load plate. In this method, the selected deflection for back-calculation should be far enough from the centre of load plate to avoid the effect of structural capacity of other layers. For satisfying this criterion, the selected deflection location is compared to $0.7 \times a_e$, which can be calculated for all the sections using Equation 2:

$$a_e = \sqrt{\left[a^2 + \left(D \sqrt[3]{\frac{E_p}{M_r}}\right)^2\right]}$$

Equation 2

where a_e is the radius of stress bulb at the subgrade-pavement interface, a is the load plate radius, and D is the total thickness of pavement layers above the subgrade, comprising the total thickness of HMA and GBC. The deflection observed at the farthest geophone D9 (located at 1800 mm from the load plate) meets the abovementioned requirement for all the sections in different months.

The overview of the deflection data collected from the geophone at 1800 mm from the center of the load plate (D9) is presented in Figure 8. The deflection data reveals that the CS always experienced the highest deflections compared to insulated sections during the recovering period, which indicates lower load bearing capacity of subgrade compared to the normal condition. As expected, the B.Ash section showed lower deflection in FWD 1 and FWD 3, when the section was partially frozen (Figure 6). When the B.Ash section is fully thawed in FWD 2 and FWD 4, the difference between the deflections of these two tests and the deflection in October is not substantial. It is worth mentioning that during the critical month of May, the deflection data of B.Ash section is notably lower than of that in the CS. Both of the Poly-5 and Poly-10 sections had less or equal deflections during the recovering period compared to their normal condition. Less fluctuation in deflection signifies that subgrade has been protected by insulation layers from freeze and/or thaw effect.
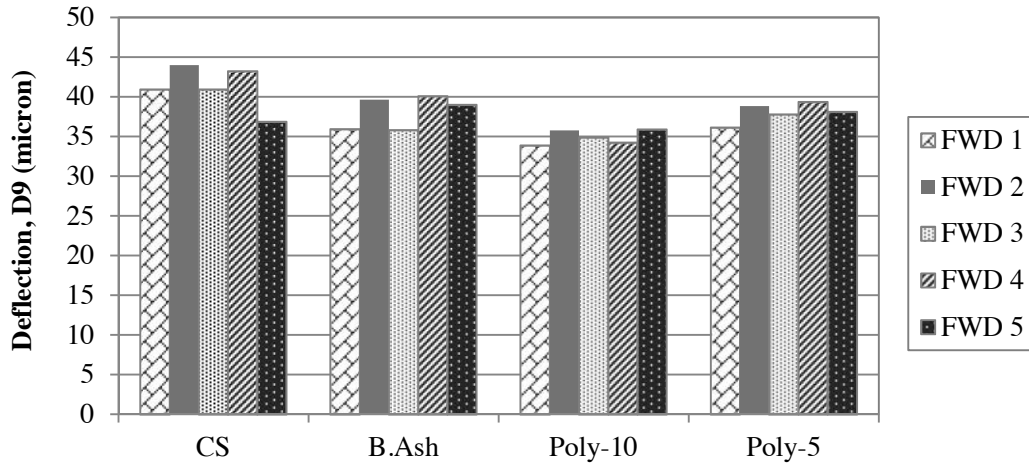
Figure 8: Deflections of the geophone at 1800 mm from the center of load plate (D9)

The back-calculated modulus of subgrade using the reported deflection data is presented in Table 3. The result shows that, apart from the date of testing, the Poly-10 section always had the highest subgrade modulus. Comparing the average subgrade modulus during the recovering period with the normal condition resulted in a ratio as high as 1.04. This section had the lowest COV of the subgrade modulus, 2.6 percent, which indicates that this section has the least variation in subgrade modulus compared to other sections. Both of the B.Ash and Poly-5 sections had the second strong subgrade modulus during the recovering period with the average Mr value as high as approximately 143 MPa. The average Mr value of the Poly-5 section during the recovering period was equal to its value under normal conditions, meaning that the recovering period ratio is equal to 1.00. This section had the second least COV of subgrade modulus as high as 3.3 percent. Although the B.Ash section had the ratio of 1.03 when the average subgrade modulus in recovering period compared to its normal condition, the higher COV for Mr, 5.5 percent, within the recovering period, is an indicator that the section is affected by the changes in temperature and moisture in different months. The CS was the only section that had a recovering period ratio of smaller than one. The section had the average ratio as low as 0.87, which is higher than the previously reported values for Alberta. This section exhibited the widest range of variation of Mr Values by having a COV equal to 7.1 percent for Mr values during the monitoring period.

Table 3: Subgrade modulus of different sections during the monitoring recovering period and the normal condition

Test ID	Mr (MPa)					Compared Mr with FWD 5				Avr.
	FWD 1	FWD 2	FWD 3	FWD 4	FWD 5	FWD 1	FWD 2	FWD 3	FWD 4	
	8-Apr-15	22-Apr-15	29-Apr-14	30-May-14	1-Oct-14	8-Apr-15	22-Apr-15	29-Apr-14	30-May-14	
CS	132.3	123.1	132.3	125.3	146.9	0.90	0.84	0.90	0.85	0.87
B.Ash	150.7	136.7	151.2	135.2	138.9	1.09	0.98	1.09	0.97	1.03
Poly-10	159.9	151.5	155.3	158.2	150.8	1.06	1.00	1.03	1.05	1.04
Poly-5	149.9	139.5	143.3	137.6	142.1	1.05	0.98	1.01	0.97	1.00

SUMMARY AND CONCLUSIONS

The paper investigated the effects of using insulation layers on subgrade modulus variation during thaw season compared to the normal condition in IRRF's test road, Edmonton, Alberta, Canada. The road is comprised of three insulated sections using bottom ash and two different thicknesses of polystyrene boards. The nearby normal section served as control section. For identifying the onset of recovering period, all the sections, except for the Poly-5 section, were instrumented using TDRs and thermistors. The temperature data read by TDRs are used in this investigation. Laboratory testing was conducted to identify characteristics of the different layers. FWD testing deflection results were applied to evaluate the subgrade modulus of insulated sections in comparison to a conventional section. Study observations are summarized as follows:

1- Evaluating the temperature data right underneath the GBC layer of the CS and B.Ash sections indicated that thawing started at the same time for these two sections.
2- The temperature data underneath the polystyrene with 10 cm thickness revealed that the subgrade of this section is fully protected from any freeze and/or thaw effect.
3- The temperature data at the depth of 1.7 m below the surface revealed that the temperature at subgrade of the B.Ash section never decreases below $0°C$. Thus, this insulated layer protected the subgrade from any freeze and/or thaw effect.
4- Based on the ME-PDG recommendation, the recovering period is assumed to be 120 days; it started in mid-March and lasted until mid-July.
5- Apart from the date of testing, the Poly-10 section always exhibited larger maximum deflection followed by the Poly-5 section.
6- The highest COV of maximum deflections during the month of May showed that it is the most critical month within the recovering period.
7- The ratio of the average back-calculated resilient modulus of the CS subgrade during the recovering period compared to the normal condition is as high as 0.87. This section also exhibited the widest range of Mr values within the monitoring period, as high as 7.1 percent.
8- The back-calculated Mr value of the subgrade showed that apart from the date of testing, the Poly-10 section always had the highest values during the monitoring period. This section also exhibited the highest recovering period ratio of subgrade modulus as high as 1.04. Both of the B.Ash and Poly-5 sections demonstrated the ratio of 1.03 and 1.00 followed the Poly-10 section, respectively.

Based on the above observations, it was concluded that control section exhibited the lowest average subgrade modulus during the recovering period, which makes the section vulnerable to traffic loading during spring thaw season. Also, the CS was the only section with an average modulus ratio of smaller than one during the recovering period. Both thicknesses of polystyrene boards restrained the subgrade modulus variation during spring. Although the B.Ash section showed some signs of freeze and thaw effect, it outperformed the CS by showing smaller ratio of D0 and D9 compared to its normal condition, during the recovering period and the critical month of May, when the sections are thawed and the ambient temperature is high.

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