DEVELOPMENT AND CALIBRATION OF FROST DEPTH AND THAW DURATION PREDICTORS BASED ON THE WEATHER INFORMATION

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ABSTRACT

To minimize pavements damage of seasonal freezing and thawing in Northern Ontario, the Ontario Ministry of Transportation and other Departments of Transportation place Seasonal Load Restrictions (SLR) every year during spring-thaw period. This paper examines how to predict the frost depth and thaw duration, and details the freezing/thawing indices calculation based on field data captured from innovative sensors and data collection systems in 2 pilot sites in Northern Ontario. Comparisons are made to historical dates for SLR in Northern Ontario.

KEYWORDS

FROST DEPTH / THAW DURATION / FREEZING-THAWING INDICES / INNOVATIVE SENSORS / SEASONAL LOAD RESTRICTION

1. INRTODUCTION

A flexible road normally transfers traffic loading vertically from one structural layer down to another in such a way that the whole pavement structure deflects without rutting or cracking. During winter, the pavement structure, mainly in Northern Ontario freezes from the surface to the subgrade layer. Typically frost depth varies from 1.0 metres to as high as 2.0 metres in northern Ontario. The available moisture in the pavement structure upon freezing behaves anomalously and the pavement structure experiences a volumetric expansion called frost heave. Provided the frozen condition remains stable, the road exhibits increased strength that can even justify the allowance of overloaded commercial vehicles. On the other hand, warmer winters and/or the arrival of spring cause temperatures in the soil to oscillate around the freezing point with more or less amplitude and frequency. As a result, the pavement reaches a critical state where the upper layers are thawed while the lower layers remain frozen. This phenomenon is called the freeze-thaw cycle.

Water trapped between the underlying pavement layers saturates the structure and renders it unable to transfer traffic loading properly, and pavement deformation occurs. The deterioration is most dramatic when the freezing front penetrates into a fine grained, frost susceptible soil, as frost heave is amplified, and the damaging effects of pumping due to partial thawing and saturation are aggravated [1]. Hence, the most effective and easy action to prevent the pavement from any damage during this freeze-thaw cycle is to impose loads on the axles and is known as the Seasonal Load Restriction (SLR) regulation.

1.1 SEASONAL LOAD RESTRICTIONS IN ONTARIO

Seasonal load restrictions are imposed each year on low volume routes designated as "Schedule 2 Highways", usually throughout March, April and May. Although the SLR periods are commonly called "half load periods", section 122 of the Highway Traffic Act [2] specifies the load restriction limit to be 5,000 kg per single axle. Vehicles exceeding this limit have to take alternative routes or be subject to the penalties described in the Act. Also, oversized load permits, often called Winter Weight Premiums (WWPs), that are usually allowed as long as the pavement structure is frozen and thus assumed to withstand these higher loads, are not available during an SLR period. SLRs have been typically imposed on or around March 15, usually in response to a three-day warning trend (i.e. a forecast of at least three consecutive days with an average daily temperature above 00 C). The ban is then lifted in response to recommendations by MTO maintenance coordinators who conduct field inspections of the roads to look for signs of strength recovery [3,4]. Indicators include dry road surface cracks, ditches clear of snow and flowing well, and, no residual wetness on the road shoulders after they have been graded. Thus, this makes it an SLR period spanning from eight to ten weeks.

1.2 SEASONAL LOAD RESTRICTIONS IN CANADA

A market scan for Transport Canada in 2005 summarized the various methods used in Canada for determining start and stop dates for load restrictions [1]. The imposition of WWP is most typically done by using fixed dates across Canada, except in Alberta where frost depth and the number of days with temperatures less than 00 Deg C are used. Pavement structures that should receive an SLR schedule are normally identified using design and strength criteria, such as whether or not the frost penetrates down to a frost susceptible subgrade soil. Quantitative methods have progressively been introduced to complement and address limitations of the traditional expert judgment and historical records used in the decision-making process. Calendar-based imposition systems use fixed start dates derived through analysis of historical thaw data and do not take into consideration annual fluctuations. Used alone, visual observations and engineering judgment often fail to prevent the pavement damage that has been initiated in the lower layers to propagate up to the surface. In an effort to address these concerns, some agencies are moving to adopted more quantitative approaches based on the monitoring of deflection and the use of threshold values (suspected to be associated to strength shifts) to trigger and lift SLR. Other analytical approaches include the use of measured and predicted temperatures as inputs for empirical-mechanistic indicators of the road's strength, such as the thaw index used in Minnesota and in Manitoba. More recently, British Columbia's truckers have shortened SLR periods through the use of Tire Pressure Control System (TPCS) to abide by "reduced tire-pressure" periods. The ban period once again falls between eight to ten weeks.

2. OBJECTIVES AND APPROACH

The benefits of implementing SLR on low-volume roads have been investigated by many agencies. However, there is also a need to better identify the key factors of pavement deterioration to develop practical indicators for the bearing capacity of low-volume pavements throughout the seasons. A preliminary study based on frost data collected in Northern Ontario showed good correlation between frost thickness in the pavement structure and ambient air temperatures provided by Road Weather Information Systems (RWIS). Canadian jurisdictions such as Quebec and Manitoba and Minnesota in the United States have developed models [5]. In Ontario, in order to modify and validate the model, MTO and CPATT demonstrated in two pilot sites. These roads are Highway 601 in Dryden-Ontario, starting 1.6 km north of Highway 17, and Highway 651 west of Chapleau-Ontario, starting at the Highway 101 junction and extending about 29 km north. They are typical Schedule Two Low Volume surface treated road and used as an access road to forestry resources. Highway 601 and 651 are instrumented with sensors like a thermistor string to monitor pavement temperature, soil moisture content, relative humidity and air temperature to obtain the comprehensive knowledge of freeze-thaw phenomenon.

3. USE OF INNOVATIVE SENSORS, DATA COLLECTION, AND INTERPRETATION

3.1 INSTRUMENTATION

As noted, the study also involved the design and placement of instrumentation during the fall of 2007 on Hwy 651 and Hwy 601 to monitor the freezing and thawing progression in the pavement structure. This was proposed and executed to further validate the usage of RWIS by conforming with the in-situ conditions. To achieve this, the thermistor strings, relative humidity (RH) sensors, air temperature sensors, and water content gauges were installed at the two locations. These monitor in-service pavement real time conditions compared to the surrounding environmental conditions. The use of innovative sensors and data collection techniques are proving to be very informative and are advancing pavement engineering knowledge. The following sections provide installation details including the types of sensors; as well as describe the working principles of the sensors installed at the two locations [6].

3.2 THERMISTOR STRINGS (W0E 404)

The CPATT team worked with Campbell Scientific Inc.'s to purchase the thermistor strings and install them within the pavement structure at various depths as follows: 15 cm, 30 cm, 40 cm, 50 cm, 75 cm, 100 cm, and 150 cm. These heights were selected to best represent in-situ performance. The thermistor readings are very important for tracking thaw depth and freezing depth.

3.3 RELATIVE HUMIDITY AND AIR TEMPERATURE PROBE

The HC-S3 XT Temperature and Relative Humidity Probe was selected as it is a rugged, accurate probe, and are ideal for long-term, unattended applications. The probe uses Hygro Clip technology to measure RH and a Pt100RTD to measure temperature and is suitable for a temperature range of -50 °C to +50 °C. The probe connects directly to Campbell Scientific dataloggers. The CR1000 was selected for this research. Each Hygro Clip probe is 100% interchangeable and can be swapped in seconds without any loss of accuracy, eliminating the downtime typically required for the recalibration process. A radiation shield (Model 41003-X) is being used since the HC-S3 is exposed to sunlight. When exposed to sunlight, the HC-S3 must be housed in a 41003-X 10-plate radiation shield. The specifications of the Relative Humidity and Air Temperature probe HC-S3-XT could be found respectively in the reference [6].

3.4 WATER CONTENT REFLECTOMETER

The CS616 Water Content Reflectometer was selected in this research measuring the volumetric water content of porous media, the CS616 uses time domain measurement methods that are sensitive to dielectric permittivity. The probe consists of two 30 cm long stainless steel rods connected to a printed circuit board. The circuit board is encapsulated in epoxy, and is shielded by a four-conductor cable which is connected to the circuit board to supply power, enable probe, and monitor the output. The probe rods can be inserted from the surface or it can be buried at any orientation to the surface. The CS-616 has the following features and is installed on both the sites at subgrade level to monitor the long term water content. It measures the volumetric water content using time-domain reflectometer methods. It is designed for long-term unattended water content monitoring and has an accuracy ±2.5% VWC (Volumetric Water Content) using standard calibration with a resolution better than 0.1% VWC and measurement time is <500 microseconds.

3.5 DATA LOGGER PROGRAM AND DATA ACQUISITION

The data logger CR 1000 is programmed to scan sensor readings after every 5 seconds and the data is stored at five second intervals. The data is collected data manually from each data logger on a biweekly basis by MTO personnel and sent to the CPATT, University of Waterloo. The data is then uploaded to the MTO's data portal.

3.6 DATA ACQUISITION

The CR-1000 data logger has a module that measures sensors, drives direct communications and telecommunications, reduces data, controls external devices, and stores data and programs in an on-board, non-volatile storage. The module can simultaneously provide measurement and communication functions. The on-board, BASIC-like programming language supports data processing and analysis routines.

The CR1000 can communicate with a PC using landlines, cellular CDMA, or cellular GPRS/EDGE transceivers. A voice synthesized modem enables anyone to call the CR1000 via phone and receive a verbal report of real-time site conditions. Although this data logger is designed to provide an easy means of data acquisition. Although modem based data download could be achieved, the manual method was agreed upon given there are field staff at both locations and remote nature of the site made it more desirable to have regular checking of the equipment during manual downloads. A CF100 module attached to the CR1000 that can store data on a Compact Flash (CFM 100) card is used to retrieve record data. In addition to this, a PC or a laptop can also be connected to the data logger via DV3 cable and is able to read the CF card. The data file, after retrieval, can be sent electronically for further analysis or stored in a database. Figure 1 shows the VIEW screen where data can be seen and also transported to other destinations.

C:\Campbellsci\PC400\CR1000-1_Table1.dat

File View Help

All arrays

TIMESTAMP	RECORD	Batt_Vol	Temp_1	Temp_2	Temp_3	Temp_4	Temp_5	Temp_6	Temp_7	AirTC	RH	VW	PA_uS
"2008-04-23 05:00:00"	4068	12.63	7.474	7.435	6.511	5.13	4.639	1.191	-0.055	4.797	96.9	0.379	30.12
"2008-04-23 06:00:00"	4069	12.62	7.037	7.144	6.357	5.073	4.698	1.231	-0.053	4.508	97.2	0.379	30.12
"2008-04-23 07:00:00"	4070	12.61	6.659	6.863	6.184	5.007	4.747	1.27	-0.052	3.661	95.5	0.379	30.11
"2008-04-23 08:00:00"	4071	12.72	6.334	6.663	6.092	4.992	4.79	1.303	-0.049	4.457	91.9	0.379	30.11
"2008-04-23 09:00:00"	4072	13.57	6.067	6.503	6.019	4.996	4.823	1.336	-0.063	8.54	70.98	0.379	30.11
"2008-04-23 10:00:00"	4073	13.6	6.263	6.244	5.819	4.884	4.846	1.359	-0.069	10.27	51.08	0.379	30.12
"2008-04-23 11:00:00"	4074	13.51	7.446	6.135	5.662	4.786	4.853	1.396	-0.07	11.85	42.38	0.379	30.11
"2008-04-23 12:00:00"	4075	13.44	9.03	6.241	5.546	4.689	4.853	1.406	-0.079	14.4	32.09	0.378	30.1
"2008-04-23 13:00:00"	4076	13.39	10.84	6.58	5.545	4.612	4.852	1.425	-0.089	15.23	31.6	0.378	30.1
"2008-04-23 14:00:00"	4077	13.36	12.59	7.113	5.651	4.593	4.843	1.453	-0.089	16.78	27.11	0.379	30.11
"2008-04-23 15:00:00"	4078	13.34	14.16	7.783	5.86	4.609	4.83	1.469	-0.092	17.06	24.97	0.379	30.11
"2008-04-23 16:00:00"	4079	13.34	15.39	8.5	6.161	4.706	4.821	1.499	-0.091	16.16	25.38	0.379	30.11
"2008-04-23 17:00:00"	4080	13.38	16.19	9.21	6.531	4.833	4.824	1.52	-0.089	14.57	29.12	0.378	30.1
"2008-04-23 18:00:00"	4081	13.41	16.1	9.81	6.91	5.006	4.833	1.539	-0.089	13.54	25.36	0.379	30.11
"2008-04-23 19:00:00"	4082	13.17	15.14	10.16	7.24	5.169	4.862	1.576	-0.071	12.33	28.55	0.379	30.11
"2008-04-23 20:00:00"	4083	12.89	13.94	10.27	7.527	5.356	4.894	1.598	-0.069	9.91	41.6	0.379	30.11
"2008-04-23 21:00:00"	4084	12.78	12.75	10.19	7.712	5.539	4.932	1.617	-0.059	4.054	65.46	0.378	30.1
"2008-04-23 22:00:00"	4085	12.73	11.55	9.97	7.819	5.712	4.998	1.654	-0.052	0.593	75.07	0.378	30.1
"2008-04-23 23:00:00"	4086	12.68	10.43	9.64	7.824	5.812	5.07	1.667	-0.058	-1.106	80.8	0.379	30.11
"2008-04-24 00:00:00"	4087	12.64	9.38	9.23	7.755	5.88	5.147	1.705	-0.058	-1.77	84.3	0.379	30.11
"2008-04-24 01:00:00"	4088	12.61	8.46	8.8	7.602	5.903	5.208	1.728	-0.055	-1.957	86	0.379	30.11
"2008-04-24 02:00:00"	4089	12.58	7.625	8.36	7.43	5.886	5.288	1.749	-0.043	-2.211	87.6	0.378	30.1
"2008-04-24 03:00:00"	4090	12.56	6.885	7.9	7.206	5.819	5.356	1.788	-0.052	-2.415	89.2	0.378	30.1
"2008-04-24 04:00:00"	4091	12.54	6.208	7.452	6.965	5.744	5.406	1.809	-0.051	-2.838	90.7	0.378	30.1
"2008-04-24 05:00:00"	4092	12.53	5.591	7.025	6.705	5.64	5.466	1.849	-0.049	-2.957	91.5	0.378	30.1
"2008-04-24 06:00:00"	4093	12.52	5.033	6.618	6.453	5.515	5.505	1.868	-0.048	-3.127	92.8	0.378	30.1
"2008-04-24 07:00:00"	4094	12.52	4.534	6.221	6.183	5.391	5.545	1.908	-0.038	-2.754	91.2	0.378	30.1
"2008-04-24 08:00:00"	4095	12.71	4.263	5.939	6.007	5.321	5.553	1.945	-0.049	0.059	84	0.378	30.08
"2008-04-24 09:00:00"	4096	13.74	4.254	5.707	5.852	5.263	5.552	1.955	-0.048	8.31	49.62	0.378	30.08
"2008-04-24 10:00:00"	4097	13.66	4.779	5.414	5.569	5.068	5.53	1.972	-0.058	11.32	39.69	0.378	30.08
"2008-04-24 11:00:00"	4098	13.52	6.13	5.32	5.349	4.896	5.503	1.984	-0.065	14.6	33.04	0.377	30.07
"2008-04-24 12:00:00"	4099	13.42	7.972	5.468	5.208	4.747	5.478	1.998	-0.07	17.28	28	0.377	30.07
"2008-04-24 13:00:00"	4100	13.35	10.01	5.889	5.195	4.627	5.435	2.004	-0.083	20.41	22.94	0.377	30.06
"2008-04-24 14:00:00"	4101	13.3	11.91	6.486	5.298	4.577	5.404	2.021	-0.085	21.4	22.01	0.377	30.06
"2008-04-24 15:00:00"	4102	13.28	13.25	7.204	5.52	4.587	5.347	2.031	-0.094	21.07	20.57	0.376	30.04
"2008-04-24 16:00:00"	4103	13.29	13.87	7.917	5.838	4.654	5.308	2.04	-0.085	20.6	20.79	0.377	30.06
"2008-04-24 17:00:00"	4104	13.29	14.29	8.52	6.196	4.779	5.279	2.05	-0.094	20.28	20.96	0.376	30.04
"2008-04-24 18:00:00"	4105	13.3	14.43	9	6.545	4.943	5.261	2.06	-0.093	19.92	23.62	0.376	30.04
"2008-04-24 19:00:00"	4106	13.3	14.08	9.35	6.856	5.098	5.252	2.07	-0.093	18.21	26.25	0.376	30.04
"2008-04-24 20:00:00"	4107	13.01	13.42	9.52	7.094	5.237	5.247	2.075	-0.079	16.5	28.94	0.376	30.04
"2008-04-24 21:00:00"	4108	12.87	12.69	9.58	7.299	5.401	5.266	2.084	-0.079	15.2	28.26	0.376	30.04
"2008-04-24 22:00:00"	4109	12.83	11.94	9.52	7.436	5.546	5.296	2.085	-0.078	13.98	27.73	0.376	30.04
"2008-04-24 23:00:00"	4110	12.81	11.31	9.39	7.518	5.666	5.338	2.098	-0.076	13.43	28.89	0.376	30.03
"2008-04-25 00:00:00"	4111	12.79	10.75	9.21	7.53	5.764	5.388	2.109	-0.074	12.69	30.82	0.376	30.03

Figure 1: PC 400 screen demonstrating Highway 601 pavement and air data

4. FREEZE THAW PHENOMENON AND REAL TIME DATA

It is necessary when considering SLR to identify and understand the freeze thaw cycles. The freeze-thaw areas have been observed to be a function of the precipitation, temperature, soil, and pavement type. In areas where the frost depth penetrates and remains in the subgrade until the spring thaw with relatively few freeze-thaw cycles, is termed as a high freeze area. On the other hand, an area where the frost depth does not penetrate deep into the subgrade and has a high number of freeze-thaw cycles is termed as a low freeze area [7].

The cyclic freezing and thawing introduces fatigue damage to the pavement structure and can weaken it over prolonged exposure. Capillary forces and lack of drainage through the pavement structure due to top down thawing are factors that contribute to freeze-thaw damage [8, 9]. During thaw progression in the pavement structure the vehicle loading is not distributed and transferred as designed. This results in the deformation of the pavement structure. Moreover, in the event of thaw penetrating into the subgrade, pavement strength conditions become worse, resulting in a need for spring load restrictions in order to mitigate damage. In addition to this, the situation is even worse when the accrued moisture in the pavement structure is not allowed to drain. Lower temperatures during melting ice lenses within the pavement structure make the pavement structure very weak and incapable of carrying full legal loads. Hence, one of the ways to mitigate damage to the pavement structure is to reduce the axle load which is a common practice in the study area. Another possibility to mitigate pavement damage during this pavement unfriendly spring thaw period is to allow full axle loads with reduced tire pressures [3]. The hypothesis behind this possibility is that a greater tire contact area to the pavement results in the distribution of the load over a larger area, reducing the active damage caused by heavy vehicles.

4.1 FREEZING/THAWING INDICES, FROST DEPTH, AND THAW DURATION

To validate the true SLR duration, the real time pavement and weather data from the data logger is compared with the analytical thaw duration measurement from Equation (1) used in a study at the Minnesota Department of Transportation-Cold Weather Road Research facility [10].

$$D = 0.018(FI) + 25 \qquad (1)$$

Where FI = Freezing Index, Degree-Days
D = Thaw Duration, Days

The effects from winter temperatures can be estimated by knowing the local Freezing Index (FI) and the Thawing Index (TI). The FI is calculated from the product of the mean daily air temperature below freezing multiplied by the number of days at that temperature. The sum of all these "degree C-days" is the Freezing Index.

The Freezing Index (FI) can also be calculated from Equation (2) [7] given below:

$$FI = \sum (0^0 C - T_{MEANi}) \qquad (2)$$

Where T_{MEANi}= Mean Air Temperature

This site specific equation was adopted because it was developed during an earlier study in Ontario based in Northern Ontario. The results from the above equations, data logger record, and the pavement’s in-situ strength during the thaw-weakened period are very similar and conforms the use of either the individual method, combination of two, or all for identification of the SLR.

Mabood summarized the FI and TI values calculated from the on-site measured sensor readings [6]. Although both the test sites are located in different areas, both sites have similar cumulative freezing/thawing indices, predicted frost depth and thaw durations. The calculation indicates that both the highways are behaving in a similar manner despite the fact they are located in different areas of Northern Ontario.

The use of innovative sensors on these access roads to resources has insight into in-service weather impacts. The data will provide the opportunity to relate Portable Falling Weight Deflectometer (PFWD) measurements to in-situ performance. In addition it will quantify how the freeze thaw cycle impacts strength and performance during SLR.

4.2 HISTORICAL DATES FOR SLR IN NORTHERN ONTARIO

As discussed above, SLRs have been traditionally imposed on or around March 15, usually in response to a three-day warming trend (i.e. a forecast of at least three consecutive days with an average daily temperature above 0^0 C). The ban is then lifted based on visual field inspections by MTO maintenance coordinators. Table 1 summarizes ten years of historical date for impositions and lifting of SLR in Ontario's north western region. The test sites located on Highway 601 and 651 lie within the locations presented in the table. The historical record indicates that the past SLR period is from eight to ten weeks. Further to this, the thaw-durations for both the regions, as calculated from the sensor readings, equal eight weeks. This is an indication of the critical thaw period. In addition, the pavement starts thawing and loses its strength in the first or the second week of April and starts recovering in mid May. In any case, it further emphasis the need to evaluate and monitor in-service predictions.

Table 1: Implementation and Termination Dates for Reduced Loading - Northwestern Region [MTO's Regional Office Record]

Year	Thunder Bay (Dryden-Hwy 601 location)			Saulte Ste. Marie (Chapleau-Highway 651 location)		
	Start	End	Duration (weeks)	Start	End	Duration (weeks)
1993	Mar 22	May 20	8	Mar 5	May 17	10
1994	Mar 15	May 24	9	Mar 18	May 24	9
1995	Mar 15	May 23	9	Mar 14	May 12	8
1996	Mar 18	May 27	9	April 1	May 21 & 27	8
1997	Mar 14	May 20	9	Mar 21 & 27	May 26 & June 2	9
1998	Mar 2	May 5	9	Mar 2	May 4	8
1999	Mar 15	May 14	9	Mar 17	May 18	8
2000	Mar 1	May 8 & 13	9-10	Mar 1	May 1 & 8	9
2001	Mar 18-20	May 18-22	9	Mar 18	May18	8
2002	Mar 19-28	May 21-31	10	Mar 18	May 27	9
2003	Mar 18-20	May 20-23	9	Mar 20	May 20	8

5. COMPREHENSIVE DATA CACLULATION AND VALIDATION

In April of 2009, the data of Highway 651 from November 2007 to October 2008 and the data during March 19, 2009 to April 16, 2009 were received from MTO, which includes the pavement or subgrade temperature below pavement surface at 15, 30, 40, 50, 75, 100 and 150 cm, Air temperature, Relative Humidity, and Volumetric Water Content. According to the data, the Freezing and Thawing Indices were calculated as the following Table 2. The predict frost depth is 108 cm and the thaw duration is 58 days.

Table 2: Freezing and Thawing Indices on Hwy 651 as worked out from on-site sensor readings (2007 November to 2008 October)

Month	Freezing			Thawing		
	Mean Air Temperature T_{mean}, *0^o C*	**Number of Days Temperature Falling Below 0^o C**	**Freezing Index (FI) [T_{mean} x No. of Days below 0^o C], *Deg C-days***	**Mean Air Temperature T_{mean}, *0^o C***	**Number of Days Temperature Falling Above 0^o C**	**Thawing Index (TI) [T_{mean} x No. of Days Above 0^o C], *Deg C-days***
November	-8	21	166	3	9	26
December	-11	30	345	0	1	0
January	-15	27	398	1	4	6
February	-16	29	455			0
March	-12	31	365			0
April	-4	14	56	4	16	66
May	-1	5	6	4	26	116
June			0	12	30	362
July			0	13	31	406
August			0	12	31	358
September			0	9	30	261
October	-3	11	32	5	20	110
ΣFI			1821	ΣTI		1821
Frost Depth FD, √FI – 42.7 inches, 108 cm				Thaw Duration D= 0.018 x FI + 25; 58 Days ~08 weeks		

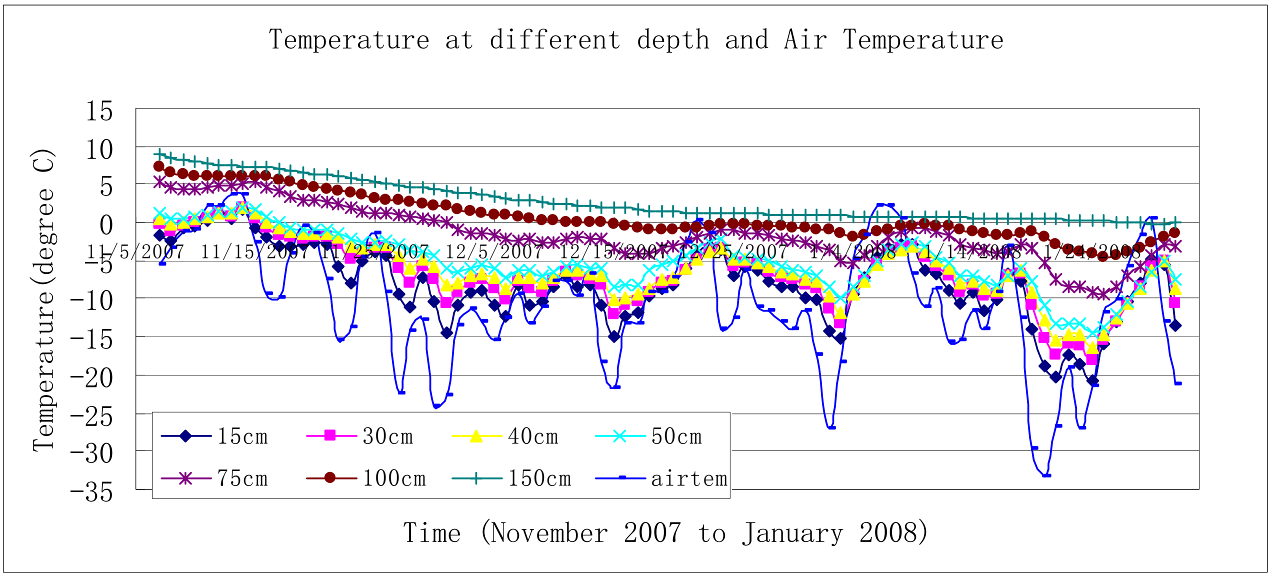
The mean daily temperatures of Highway 651 below surface at different depth 15, 30, 40, 50, 75, 100 and 150 cm, and mean daily air temperatures during the November 2007 to October 2008 are shown in the following Figure 2. It is observed that the pavement temperature 15 cm beneath the surface was influenced significantly by the air temperature。And the influence of air temperature on the highway structure temperature became weak as the depth of the highway structure beneath the pavement surface increases.

It is presumed that the pavement or subgrabe becomes frozen when the measure mean temperature is zero degree Celsius or below zero degree Celsius. From Figure 2, it is observed that the pavement below surface at 15cm started freezing around November 15,

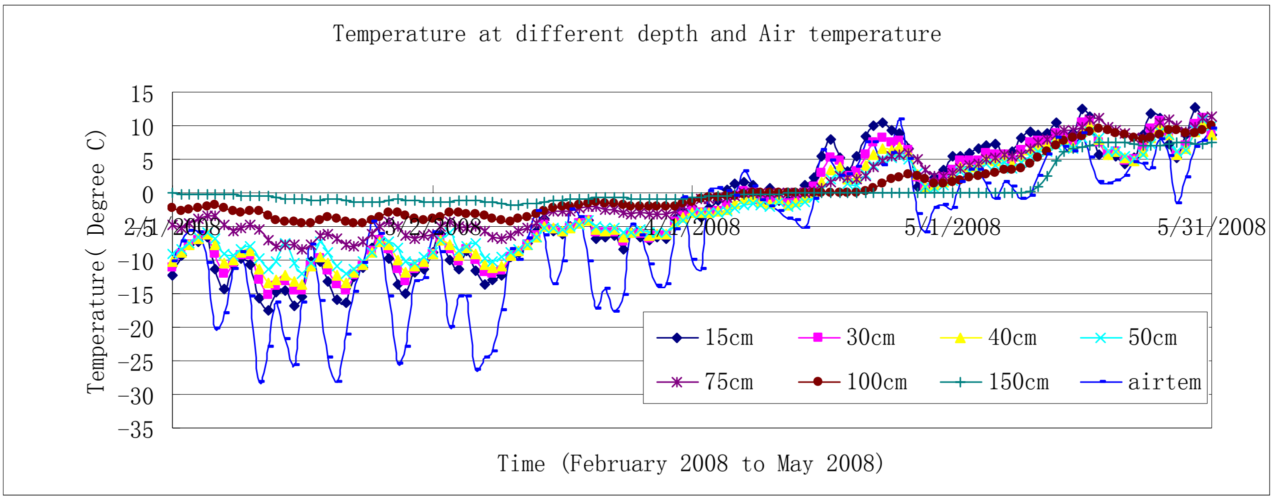
2007, and the subgrade below surface at 150 cm became completely frozen around January 27, 2008, which took more than two months (around 74 days). That means the actual frost depth in 2008 is deeper than the estimated frost depth.
It is assumed that the pavement or subgrade becomes thawed when the mean measure temperature recovers to zero degree Celsius or above zero degree Celsius. From Figure 3, on April 5, 2008, the pavement temperature at various depths remains below zero degree Celsius more than 2 months. And the pavement started thawing around April 5, 2008, and the subgrade below the surface at 150 cm became completely thawed around May 15, 2008, which took 40 days.

The changes of Volumetric Water Content (VWC) of subgrade are shown in Figure 4, which occurred the sudden obvious increase around April 5, 2008, and kept at a higher level for two months until the end of May. It is observed that the SLR should be kept for 8 or 9 weeks from the beginning of April to the end of May, which is consistent with the predict results based on the daily mean air temperature shown in Table 4 and was actually conducted in 2008 according to the SLR record in the Northwestern Region of Ontario, which was from the middle of March 13 or 17 to the end of May 26. The VWC's sudden increase also could be noted from the data of 2009 shown in Figure 4, the SLR in 2009 is suggested to lift until the end of May.

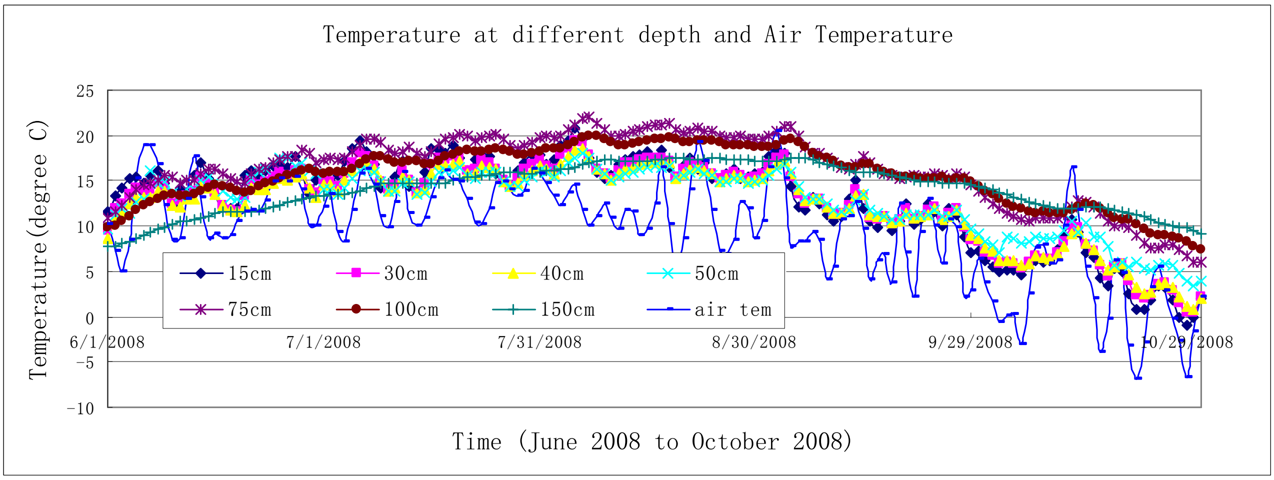
From the Figure 3, the VWC exhibited fluctuation from the middle of December in 2007 to mid January in 2008, which means the water moving, ice deforming and the frost progress penetrating. It is a complex function of climate, soil characteristic and water content of subgrade soil. The long term monitor of temperature and water content of highway will be useful to predict the frost depth and SLR duration exactly.



(a)



(b)



(c)

Figure 2: Pavement Temperature and Air Temperature during November 2007 to October 2008

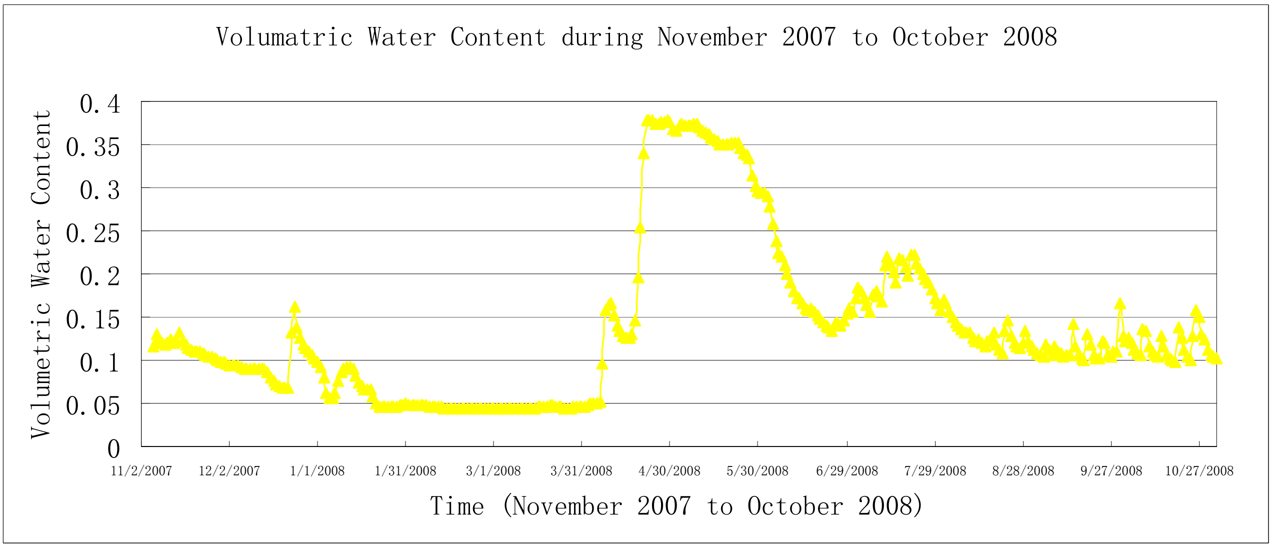


Figure 3: VWC in Subgrade during November 2007 to October 2008

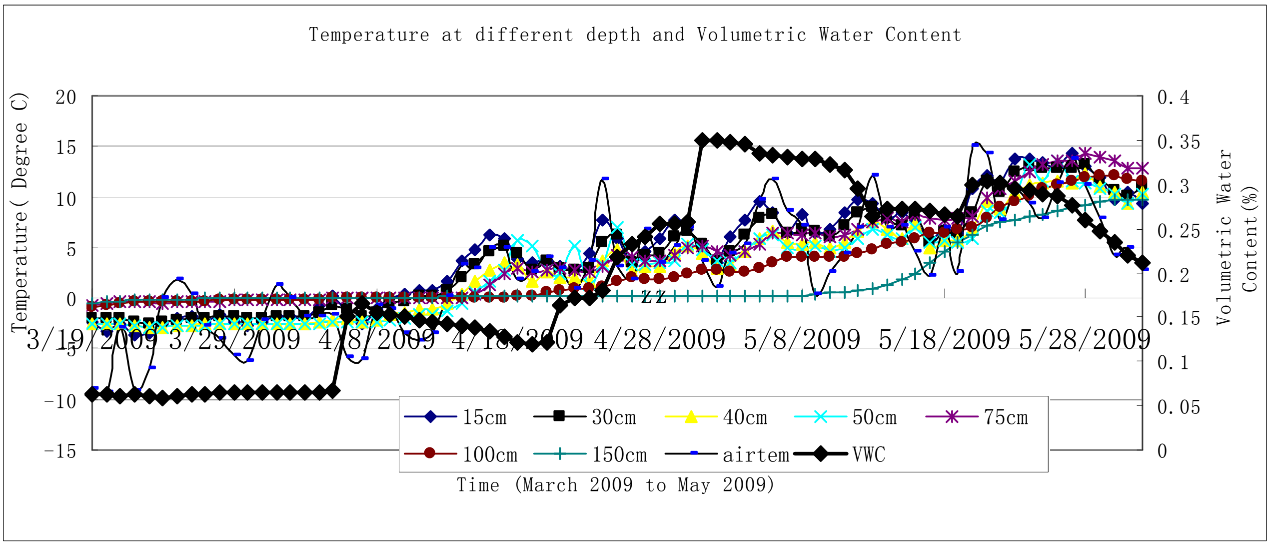


Figure 4: Pavement Temperature, Air Temperature and the Volumetric Water Content in Subgrade during March 19 2009 to May 28 2009

6. CONCLUSIONS AND RECOMMENDATIONS

The predicted frost depth of Highway 651 and 601 were determined to be 106cm and 103cm based on the mean daily air temperature. The temperature sensor data of the highway structure at different depths reveal the Highway 651 structure of frost depth is 150cm in 2008. The actual frost depth is deeper thus than the estimated result. Continued monitor will be underway, the predicted frost depth will be adjusted on long term data.

The predicted thaw duration of Highway 651 and 601 with the results of 8 to 9 weeks, 56 days of highway 601, 55 days and 58 days in 2008 of highway, were calculated based on the mean daily air temperature. The temperature sensor data of highway 651 at different depth together with the volumetric water content of highway subgrade, the spring thaw duration was during April 5 to May 26 in 2008, which is consistent with the estimated results.

The predicted thaw duration were also compared with the history record of Northwestern Region of Ontario. It is suggested that the spring thaw duration should start from the end of March or the beginning of the April, which may delay 2 weeks.

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REFERENCES

[1] Bullock, M.(2005), Intelligent Transportation Systems (ITS) for Variable Load Restrictions, prepared for Transport Canada by IBI Group.

[2] Reduced Load Periods. Highway Traffic Act, R.S.O. 1990, Chapter H.8, Section 122 (1990) , http://www.elaws.gov.on.ca/html/statutes/english/elaws_statutes_90h08_e.htm#BK83/, site accessed 04/20/2008.

[3] Bradley Allan H.(2006), Hauling with Full Axle Weights and Reduced Tire Pressures on Weight-Restricted Roads in British Columbia, Transportation research record,1967, pp.20-26, TRB 85th annual meeting, January 2006, National Research Council, Washington D.C.

[4] Bradley Allan (2006), Mercier Steve, Forest Engineering Research Institute of Canada, IR-2006-12-22

[5] Baiz S.(2007), Using Road Weather Information Systems(RWIS) to optimize the Scheduling of Load Restrictions on Northern Ontario's Low-volume Highways, Master thesis, University of Waterloo

[6] Mabood F.(2008), Evaluating Tire Pressure Control System to Improve Productivity and Mitigate Pavement Damage, Master thesis, University of Waterloo

[7] Tighe, S., Huen, K., Mills, B., Perchanok, M.(2006), Development of Tools for Improved Spring Load Restriction Policies in Ontario, University of Waterloo, Civil Engineering, 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island.

[8] Tighe, S.L.(2004), Innovation Through Partnership Intelligent Transportation Systems Research and Development for Canada, Parameter Definition-IBI Group.

[9] Tighe, S.L.(2000), Ontario Spring Load Restriction, Presentation to the Transportation Association of Canada Pavements Standing Committee, Ottawa.

[10] Worel, B. (1999), Improved Spring Load Restriction Guidelines for Minnesota, Mn/ROAD Operations.