Capital Cost Comparison of Pavements Comprised of Insulation Layers: Case Study in Edmonton, Canada

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Abstract: Using insulation layers is the go-to strategy for alleviating winter frost heave and subgrade weakening during spring thaw, but the cost effectiveness of using insulation layers compared to conventional methods needs to be evaluated. This study quantifies (in Canadian dollars) the capital cost for construction of roads comprised of insulation layers (bottom ash and polystyrene boards), along with substituting the subgrade material with high-quality granular base course (GBC) material based on a test road in Edmonton, Alberta, Canada. **DOI: 10.1061/(ASCE)CO.1943-7862.0001660.**

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Introduction

Seasonal variation in solar radiation, ambient temperature, and precipitation, and a shallow water table causes pavement performance variation throughout the year (ARA, Inc. 2004). The performance alteration is more pronounced for pavements that undergo severe freeze-thaw cycles during winter and spring, especially in cold regions. Frost penetration in susceptible subgrade soils leads to heave during winter, which negatively influences the riding quality of roads. In early spring, the ice lenses formed during winter start melting and the available water in subgrade soil decreases the subgrade strength and weakens the pavement support (Doré and Zubeck 2009). This weakening leads to pavement damages, including cracks and fatigue (Doré and Zubeck 2009). In a study conducted in Quebec by St-Laurent and Roy (1995), it was revealed that the relative damage that occurred during the recovering and thawing season might be 1.5–3 times more than the average annual load-induced damages. The construction costs of pavement to withstand such a high range of temperature fluctuation, and the resultant damages, is more than the construction cost of conventional pavements, and the cost is proportional to the temperature fluctuation (Sakulich 2011). All expenses are presented in this paper in Canadian dollars.

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Using insulation layers to protect the frost-susceptible subgrade from frost penetration and subsequent thaw weakening is one of the strategies for diminishing the aforementioned problems. The insulation layer provides a heat barrier between the ambient layer and underlying layer, which controls the heat transfer and delays thawing or freezing (Zhi et al. 2005). Polystyrene (poly-5) is one of the insulation materials with a long history of application in cold climates. In a project constructed at the University of Alberta's test road, the use of 10 cm of Styrofoam decreased the frost depth by at least 40% compared to a conventional roadway (Tavafzadeh et al. 2014). In another roadway near Chitina, Alaska, settlement observed in a section constructed with a 10-cm polystyrene layer was 11 times lower compared to the normal section (Esch 1972). However, using polystyrene is not a cost-effective solution. For instance, a runway rehabilitation performed at Churchill Falls Airport in Labrador under harsh conditions revealed that using polystyrene is the most costly solution (Uzarowski et al. 2013). The cost of rehabilitation using polystyrene injection in Wyoming was reported to be $\$210/m^2$, which is an expensive solution when comparing reconstruction using polystyrene panels of $\$206/m^2$; however, both the time saved and safety of this method are the advantages of using polystyrene injection (Edgar et al. 2015).

In recent years, researchers have moved toward using more sustainable materials as insulation, including waste materials. Using disposable and recycled materials in pavement construction has a low environmental impact and is becoming a more accepted practice. Bottom ash (B.Ash), which is a waste material from the incineration of coal in power plants, is being introduced and used as an insulation layer in pavement construction. Alberta produces a large quantity of its electricity through coal power stations and, consequently, bottom ash is easily available. Bottom ash is mainly composed of silica, alumina, and iron. A study conducted in Helsinki, Finland, revealed that frost depth in bottom ash sections was 40%–60% of that in conventional sections (Field et al. 2011). Furthermore, two different studies conducted in Edmonton, Alberta (2001 and 2014) illustrated that bottom ash was able to keep frost from penetrating into the subgrade, and frost depth was contained to the bottom ash layer (Havukanen 1987; Edgar et al. 2015). Application of this material was also economically investigated at Delhi Technological University, where researchers introduced pond ash as a new type of industrial waste subbase material, which can replace conventional subbase material in pavement construction. The saving in the total cost of construction was 11.5%–12.4% when the subbase layer was made of pond ash with no additions. It has been revealed that using pond ash mixed with fiber and lime would save 5.2%–13.0% of construction costs (Sarkar and Dawson 2015).

Preventing frost from penetrating frost-susceptible subgrade soil leads to limiting the seasonal variation in pavement (ARA, Inc. 2004). However, waste and recycled material applications need to meet specific property requirements for the intended usage. Accordingly, this would be a process of recycling and improving relevant specifications and performance. Using waste materials in road construction would be cost effective for transporting and processing the material (Huang et al. 2007). Hence, conducting a cost-benefit analysis to compare the initial and long-term cost of incorporating an insulation layer in pavement must be investigated.

The main objective of the following study is to provide a capital cost comparison for the construction of roads, which are comprised of different insulation materials, along with replacing the frost-susceptible subgrade with high-quality base material. Granular base course (GBC) material is an ideal substitution for frost-susceptible subgrade because the material is strong and minimally affected by freeze-thaw cycles. For the purposes of this study, it was assumed that GBC material was used instead of an insulation layer alternative. Using GBC material increases the life expectancy of the pavement, but it is important to know the minimum required thickness and how much the insulation extends the predicted lifetime of the road.

For this reason, the Integrated Road Research Facility's (IRRF's) test road, which is a unique road located in Edmonton, Alberta, was investigated. The road was equipped to measure temperature and moisture at different pavement depths using thermistors and time-domain reflectometers (TDRs), while falling weight deflectometer (FWD) tests were regularly conducted along the road and weather data were collected from an on-site weather station. During construction, the data were collected for cost calculation.

The comparison was initially started by calculating the minimum required thickness of the substitute material. Two criteria were used for estimating the minimum required thickness: complete prevention of frost from reaching the frost-susceptible subgrade, and ability to decrease the heave occurrence to zero despite frost occurring in the subgrade. Using the calculated and available thicknesses for different materials in the test road, the effective modulus of pavement of different sections was calculated and compared to provide a platform of the structural performance of different sections. Next, the number of loads each section can carry during the pavements' lifetime was calculated and compared. To estimate the initial cost of each section, the data collected during the construction of the IRRF's test road were utilized. Comparing the life-cycle cost will be another important indicative for selecting the insulation material used for road construction; however, that goal is out of the scope of this study.

Test Road Design and Instrumentation

The construction of the IRRF test road facility started in May 2012 and was completed in August 2013. Based on the data collected from weight-in-motion (WIM) systems at the Edmonton Waste Management Centre during the spring of 2016, the road carries about 2,000 vehicles per lane each day. Approximately 38% of this traffic is composed of Class 5 trucks and higher according to the Federal Highway Administration (FHWA 2014) 13 vehicle classification.

Road pavement consists of 25-cm dense-graded hot mix asphalt (HMA) on top of 45-cm GBC. In this test road, bottom ash and polystyrene were used as insulation layers and were located between the subgrade and the GBC layer. The adjacent conventional section served as a control section (CS). Fig. 1 shows the location and thickness of different layers.

In accordance with the City of Edmonton's specifications for Designation 1 asphalt concrete mix, this study used two types of dense-graded HMA mixes with a maximum nominal aggregate size of 12.5 and 25 mm, based on Marshall mix design (ASTM 2015). The GBC layer was classified as well-graded gravel according to the Unified Soil Classification System [ASTM C136 (ASTM 2006)]. Sieve analysis of the subgrade soil resulted in a classification of clayey sand. Subgrade soil has a liquid limit of 25 and a plastic index (PI) of 9%.

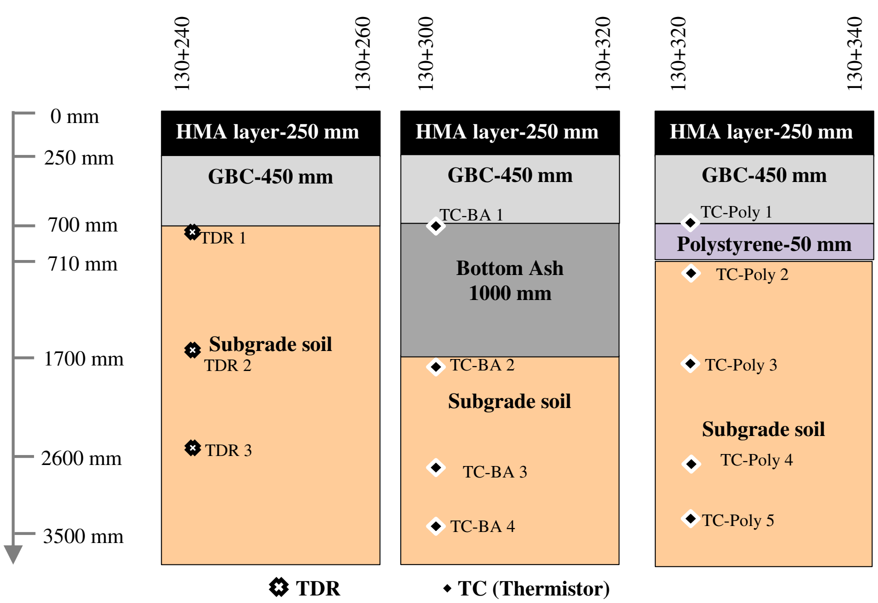

Fig. 1. Cross section of the IRRF test sections.

Table 1. Material properties used at IRRF test road

Material	K (kJ/day/m/°C)	Density (t/m^3)	VWC (m^3/m^3)	References
HMA	205	2.35	0.001	Measured in lab
GBC	300	2.10	0.16	Côté and Konrad (2005)
Subgrade	189	1.85	0.32	Measured in lab
B.Ash	50	0.950	0.34	Measured in lab
Polystyrene	0.6	—	—	Dow Building Solutions (2016)

The bottom ash was free of large lumps and impurities. The amount of noncombusted coal particles was less than 5% of the material by weight, and the optimum moisture content of bottom ash was about 35%. The bottom ash layer was wrapped in geotextile to avoid mixing with natural soil. Table 1 shows the volumetric water content (VWC) and dry density, as well as the thermal conductivity of the material.

This project used closed-cell StyrofoamStyrofoam Highload 100 (Dow Chemical Company, Midland, Michigan) extruded polystyrene boards, which have a compressive strength of 690 kPa and a minimum flexural strength of 585 kPa based on the manufacturer's data.

All the sections were instrumented using CS650 TDRs and thermistors from Campbell Scientific, Edmonton, Canada, at a depth of 0.7 m below the GBC layer, and depths of 1.7 and 2.5 m in the subgrade layer (Fig. 1). The TDR probes were able to collect both unfrozen volumetric water content and temperature data.

A CR1000 data logger (Campbell Scientific, Edmonton, Canada) was programmed to collect data from the sensors at 15-min intervals from all of the sections. The data logger was equipped with a spread-spectrum Model RF401 radio (Campbell Scientific, Edmonton, Canada) with a Model L14221 antenna (Campbell Scientific, Edmonton, Canada) installed at an on-site trailer, where a computer transmitted the data regularly to the University of Alberta.

Performance Evaluation

Thermal Performance

The main objective of applying insulation layers in pavement is to protect the frost-susceptible subgrade from freeze and thaw damages. When a thick layer of material, such as bottom ash, is used as an insulation layer, the intention is both to protect the underlying subgrade and to substitute the top portion of the frost-susceptible subgrade with a nonvulnerable material. Subgrade soil has a liquid limit of 25 and a PI of 9%. Based on recommendations by Rieke et al. (1983), the segregation potential of the subgrade soil is calculated to be more than $200 \times 10^{-5}\ \mathrm{mm}^2/(\mathrm{S} \cdot {}^\circ\mathrm{C}) 200 \times 10^{-5}\ \mathrm{mm}^2/(\mathrm{S} \cdot {}^\circ\mathrm{C})$, which is considered a moderate frost-susceptible subgrade according to Saarelainen's (1996) categorization, where mm^2, S, and °C are the units for surface area, time, and temperature.

It has been previously proven, at the IRRF test road, that 1 m of bottom ash could effectively prevent frost from penetrating into the subgrade layer (Zhi et al. 2005). The minimum required thickness of the polystyrene layer can also be computed using the equivalent thermal resistivity R-value concept (Doré and Zubeck 2009), where it is calculated using the following equation:

$$R\text{-value} = D/k \tag{1}$$

where D = layer thickness; and k = thermal conductivity; therefore, the required thickness of polystyrene material is equal to $D_{\mathrm{Poly}} = D_{\mathrm{B \cdot Ash}}/k_{\mathrm{B \cdot Ash}} \times k_{\mathrm{Poly}}$. The thermal conductivity of bottom ash and polystyrene material is shown in Table 1. Assuming 1 m of thickness of bottom ash, the minimum required thickness of the polystyrene is 1.2 cm. However, the polystyrene boards are typically produced in a minimum thickness of 5 cm, which was used in the IRRF road (Fig. 1).

Minimum Required Thickness of GBC

One of the solutions considered to rectify the frost-heave occurrence in pavement is to substitute the subgrade material with quality GBC. In this study, apart from using the GBC as the structural component of the pavement, it was assumed that GBC material was substituted for the frost-susceptible subgrade. The first criterion for obtaining the minimum required thickness of GBC is determining its thermal performance. The thickness can be calculated based on the same concept explained in the previous section for the polystyrene layer. According to Côté and Konrad's (2005) investigation, the thermal conductivity of the GBC layer, with an optimum moisture content of 7.5% and more than 60% quartz (based on the X-ray chemical composition conducted at the University of Alberta), is assumed to be as high as 300 kJ/day/m/°C (Table 1). Hence, the required thickness of the GBC layer to prevent frost penetration to the subgrade soil was calculated to be equal to 6 m.

The second criterion for estimating the GBC thickness is evaluating the risk of heaving. Based on the modified method proposed by Rajaei and Baladi (2015), the heave rate is calculated using the following formula:

$$V_H = \frac{v_i^2}{g \cdot v_w} K_{ff} \left[\frac{-T_l \cdot L}{v_m \cdot T_a} - P_{OB} + P_{wf} \right] \tag{2}$$

where V_H = frost-heave rate (m/s); v_i = specific volumes of ice (0.00109 m^3/kg); K_{ff} = hydraulic conductivity of frozen fringe (m/s); T_l = temperature at the base of the active ice lens (°C); L = latent heat of fusion of water (J/kg); v_m = specific volumes of water (0.001 m^3/kg); T_a = bulk freezing temperature; P_{OB} = overburden pressure (Pa); and P_{wf} = water pressure at the edge of the frozen fringe (Pa). The value of P_{wf} can be calculated using Eq. (3) (Rajaei and Baladi 2015)

$$P_{wf} = -g \frac{z}{v_w} \left(1 + \frac{v_w \left(V_H + \rho_{si} \Delta v \frac{dz}{dt} \right)}{v_i \cdot K_{uf}} \right) \tag{3}$$

where z = distance between bottom of soil column and position of ice penetration (m); ρ_{si} = mass of ice per unit volume of soil (kg/m^3); Δv = specific volume difference of ice; water $= v_i-$; $v_w = 0.00009\ \mathrm{m}^3/\mathrm{kg}$; dz/dt = frost depth propagation rate, which is equal to 3.24×10^{-6} m/s based on the temperature data collected at depth 1.7 m below the surface of the CS; k_{uf} = thermal conductivity of the unfrozen zone (W/°C · m); and the other parameters are previously defined. The value of z was assumed 6 m below the surface because soil temperature becomes constant through the year at this depth (Rieger 1983). For calculating the mass of ice per unit volume of soil, it was assumed that all water in the subgrade soil was frozen. Hence

$$\rho_{si} = \frac{m_{\mathrm{ice}}}{V_s} = \mathrm{VWC} \times 1.09 \times \rho_{\mathrm{ice}}$$
$$= 0.32 \times 1.09 \times 916.7 = 320\ \mathrm{kg/m^3}$$

where VWC was measured and shown in Table 1. It was assumed that the GBC layer is thick enough that no heaving occurs in the pavement, and the heave rate should be zero and no ice lenses should form in the system. Thus

$$\text{If } V_H = 0 \rightarrow P_{wf} - P_{OB} = \frac{T_l \cdot L}{v_m \cdot T_a} \tag{4}$$

where T_l, the temperature at the base of the active ice lens, was calculated using the following formula (Rajaei and Baladi 2015):

$$T_l = T_{ff} - \frac{a}{K_p} \times \left(\rho_{si} L \frac{dz}{dt} + \frac{k_{uf}(T_{Bot} - T_{ff})}{z} \right) \tag{5}$$

where T_{ff} = temperature at the base of the frozen fringe (°C) (Gilpin 1980); a = thickness of the frozen fringe (m); K_p = thermal conductivity of the partially frozen zone (W/°C · m); T_{Bot} = temperatures at the bottom of the soil column (°C); and the other parameters are previously defined. Since no ice lenses will be formed in the system, the following equations will be used:

$$a = 0 \rightarrow T_l = T_{ff} \tag{6}$$

$$T_{ff} = -\frac{8\sigma_{iw} v_w T_a}{D_{10} \cdot L} \tag{7}$$

where σ_{iw} = surface tension between ice and water, which was assumed to be 0.4 (N/m); D_{10} = soil diameter at 10% passing, which was equal to 0.001 m (based on the laboratory test); and the other parameters are previously defined. Using the preceding equations, P_{OB} was calculated as high as 55,660 Pa. The extra GBC required to impose the same overburden pressure on the subgrade layer is equal to 1.85 m.

By comparing the thicknesses obtained from the two criteria, the extra GBC layer thickness was selected to be 1.85 m to avoid frost-heave damage. Even if the frost reaches the subgrade layer of this section, heave will not occur in the system due to the high overburden pressure on the subgrade layer, making the smaller GBC value an acceptable choice.

Structural Performance

In the previous section, the thicknesses of different materials were recalculated in such a way to provide the same or almost equivalent thermal performance up until the subgrade layer. Although all the sections of road satisfied the minimum thickness criteria, it is also important to compare their structural performances. The structural performance of the CS, B.Ash, and poly-5 sections was previously investigated, and the data summarized in Tables 2 and 3 (Tavafzadeh et al. 2016). In these tables, the year is divided into three main periods: non-freeze-thaw season (when the subgrade is not affected by frost action and has recovered from extra water of thaw occurrence); freezing (when the subgrade is frozen); and recovering period (when the thaw started in the system until the water content has reached its stable value). Following those periods, the annual average values were calculated accordingly. For the section of the road constructed using the extra GBC material, the subgrade strength (M_r value) was estimated based on the subgrade modulus of CS during the non-freeze-thaw season, which is equal to 139.6 MPa.

The structural numbers (SNs) of the sections were calculated using the following formula (AASHTO 1993) and are presented in Table 4:

$$\text{SN} = 0.0045 D \sqrt[3]{E_p} \tag{8}$$

Table 2. Effective modulus of pavement (E_p) of different sections of IRRF

Section	Average E_p (MPa): Non-freeze-thaw period	Freezing period	Recovering period	Average E_p (MPa)
CS	1,284	6,590	1,466	3,113
B.Ash	1,211	6,867	1,484	3,187
Poly-5	957	6,655	1,079	2,503

Source: Data from Tavafzadeh et al. (2016).

Table 3. Resilient modulus (M_r) of different sections of IRRF

Section	Average M_r (MPa): Non-freeze-thaw period	Freezing period	Recovering period	Average M_r (MPa)
CS	140	305	129	191
B.Ash	135	320	136	197
Poly-5	139	164	143	149

Source: Data from Tavafzadeh et al. (2016).

Table 4. Predicted traffic for each section

Section	SN	M_r (MPa)	w_{18} ($\times 10^6$)	Traffic comparison (%)	Pavement life (years)
CS	9.5	63	3,405	—	20
B.Ash	9.6	65	3,886	14	22
Poly-5	9.3	50	1,548	−55	11
Extra GBC	17.7	49	362,570	10,547	124

where D = total thickness of pavement layers above the subgrade (in.); and E_p = effective modulus of the pavement (psi).

The SN number of the extra GBC section was calculated using the AASHTO (1993) formula

$$\text{SN} = a_1 D_1 + m_2 a_2 D_2 \tag{9}$$

where a_1 and a_2 = layer coefficient; D_1 and D_2 = layer thicknesses; and m_2 = coefficient for considering drainage for the unbound layer (GBC). Based on the developed master curve, the 3,100-MPa (450,000-psi) elastic modulus of the HMA layer results in $a_1 = 0.45$, and its thickness is 0.25 m. The GBC layer, by having a modulus as high as 210 MPa (30,000 psi) based on the laboratory data, expressed $a_2 = 0.14$, $m_2 = 1.05$, and thickness = 1.85 m of extra GBC. Taking into account the usual 0.45-m GBC layer, which creates 2.3-m total thickness of GBC, the SN of the extra GBC section will be as high as 17.74.

For comparing the structural capacity of the sections, the accumulated expected 80 kN (18-kip) equivalent single-axle load (ESAL) (w_{18}) was estimated for different sections using the following AASHTO (1993) formula:

$$\log w_{18} = Z_R \times S_0 + 9.36 \log(\text{SN} + 1) - 0.20 + \frac{\log\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1{,}094}{(\text{SN}+1)^{5.19}}} + 2.32 \log M_R - 8.07 \tag{10}$$

where, considering the reliability of 90%, $Z_R = -1.28$; $S_0 = 0.45$ is the standard deviation; ΔPSI = present serviceability index, which is assumed to be 1.9; and the other parameters are previously defined.

Based on the AASHTO method, the M_r values obtained from back-calculating FWD tests have to be adjusted to the values representative of the AASHO road test subgrade in the development of the flexible design equation. The correction factor for flexible pavement is $C = 0.33$ (Alberta Transportation and Utilities 1997). Hence, the M_r values back-calculated in Table 3 are multiplied by 0.33 and can be used in the design procedure. Using Eq. (9), the future traffic is estimated and presented in Table 4. The calculated future traffic indicates that the sections constructed using bottom ash can carry 14% more traffic compared to the CS during the life-expectancy period. The extra GBC section can carry more than 10,000 traffic units, and the polystyrene sections can carry less than half the traffic that the CS can carry during the lifetime of the pavement.

In another approach for comparing the performance of the different sections, the pavement life (PL) is calculated by assuming the traffic of 9 million ESAL for the first year and a growth rate of 4%. The PL of different sections are calculated and presented in Table 4. This table shows that B.Ash and CS have approximately the same life expectancy, while the poly-5 section life is almost half the value of that of the CS and B.Ash sections. As expected, the PL of the extra GBC section is almost 6 times the value of that of the CS, which resulted from substituting the subgrade material with the higher-quality GBC material.

Cost Estimation

Pavement selection is one of the most challenging engineering decisions facing roadway administrators. Many municipalities are seeking ways to manage their budgets more efficiently while improving roadway performance (Hendrickson and Au 1989). It is important for professional designers and construction managers to have an estimation of the construction costs. From the owner's perspective, it is equally important to estimate the corresponding construction cost of each alternative for a proposed facility (Hendrickson and Au 1989). The unit costs of various construction tasks are required to estimate total costs. These unit costs are then multiplied by the expected quantities required by different projects.

Using the reports gathered during the IRRF construction and recent RSMeans online construction cost database, which is valid in North America for both hourly and daily cost estimations of labor and machinery, unit initial costs of different structural and insulation materials were estimated. The cost estimates for GBC, bottom ash, and polystyrene layers above subgrade are shown in Tables 5–7. The subgrade was assumed to be finished and ready for construction of the upper layers. The cost analysis consisted of the layers above the subgrade. Because the section length in the IRRF project was about 20 m, the details of construction were first estimated for 20 m of the road and then the cost of a cubic meter was estimated based on the applied volume. The cost estimation for each material consists of four main parts: (1) labor; (2) machinery; (3) material; and (4) contractor's profit and overhead charges. For all road sections, the construction volume was calculated considering a width of 14.1 m and a length of 20 m. All the sections of the road (Fig. 1) were excavated up to the desired depth with a slope of 2:1, and then filled with proper material.

The cost analysis per cubic meter of GBC layer construction is shown in Table 5. The GBC material was provided by a local supplier at an approximate distance of 25 km from the IRRF construction site. The material was transported to the site using 12 trucks. A Caterpillar (Peoria, Illinois) D7R XR Series II bulldozer was used for spreading the material and a tandem roller and grader were used for fine grading and compaction of the GBC layer. Lifts of 150 mm were used to spread the GBC.

Table 5. Cost analysis of layer constructed by GBC

Item	Unit	Quantity	Rate ($)	Amount ($)
Labor component				
Labor	Days	1.25	303.2	379
Equipment operator	Days	1.87	408.8	764
Truck driver	Days	1.75	345.6	605
Water tanker driver	Days	0.25	292.8	73
Machinery component				
Bulldozer	h	5	174.62	873
Truck, 12 CY	h	14	86.35	1,209
Grader, 30,000 lb	h	5	89.3	446
Tandem roller, 10 t	h	5	29.92	150
Water tanker	h	2	510	1,020
Material component				
GBC	t	302.4	22	6,653

Note: Construction volume = 144 m^3. If A = total labor component amount = \$1,821; B = total machinery amount = \$3,698; C = total material amount = \$6,653; then the grand total per cubic meter = $[1 + \mathrm{CP\,\&\,OC}(12.5\%)] \times (A + B + C)/144 = \$95.1$; and CP & OC = contractor's profit and overhead charges.

Table 6. Cost analysis of layer constructed by bottom ash

Item	Unit	Quantity	Rate ($)	Amount ($)
Labor component				
Labor	Days	2	303.2	606
Equipment operator	Days	2	817.6	1,635
Truck driver	Days	4.5	345.6	1,555
Water tanker driver	Days	0.5	292.8	146
Machinery component				
Bulldozer	h	5	174.62	873
Vibratory roller	h	14	86.35	1,209
Truck, 20 CY	h	5	89.3	446
Water tanker	h	5	29.92	150
Material component				
Bottom ash (30% extra)	m^3	387.4	0	0
Geotextile	m^2	654.88	2.65	1,735

Note: Construction volume = 298 m^3. If A = total labor component amount = \$3,943; B = total machinery amount = \$7,333; C = total material amount = \$1,735; then the grand total per cubic meter = $[1 + \mathrm{CP\,\&\,OC}(12.5\%)] \times (A + B + C)/298 = \$49.1$; and CP & OC = contractor's profit and overhead charges.

Table 7. Cost analysis of layer insulated by polystyrene

Item	Unit	Quantity	Rate ($)	Amount ($)
Labor component				
Labor	Days	0.5	303.2	152
Truck driver	Days	0.12	345.6	41
Machinery component				
Truck, 20 CY	h	1	86.35	86
Material component				
Bottom ash (30% extra)	m^2	338	69.17	23,379

Note: Construction surface = 338 m^2. If A = total labor component amount = \$193; B = total machinery amount = \$86; C = total material amount = \$233,379; then the grand total per square meter = $[1 + \mathrm{CP\,\&\,OC}(12.5\%)] \times (A + B + C)/338 = \$78.9$; and CP & OC = contractor's profit and overhead charges.

The cost analysis per cubic meter of constructing the bottom ash layer is shown in Table 6. During construction, when the excavation was complete, a woven geotextile with an apparent open size of 0.212 mm was used to wrap the bottom ash material. A minimum overlap of 0.6 m was maintained at every seam. The geotextile was

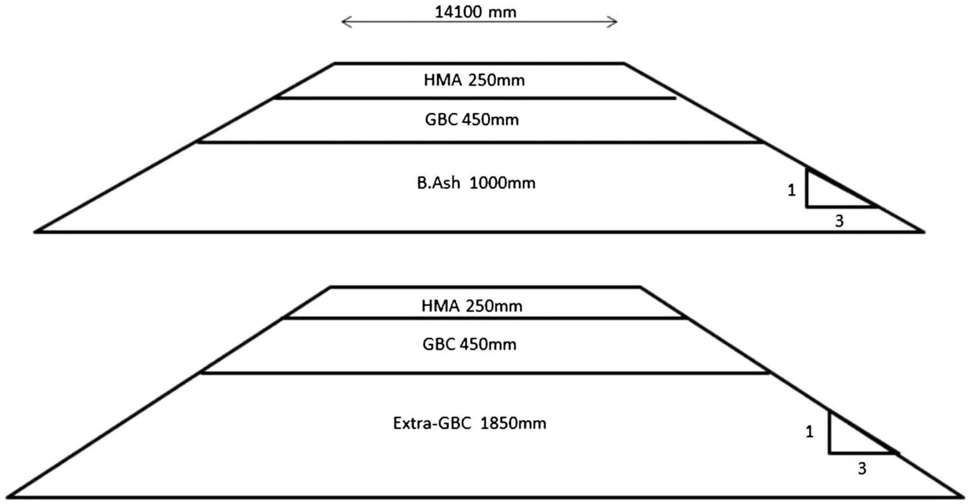

Fig. 2. Pavement structure with different insulation layers.

in rolls of 3.66×91 m. There are different sources of bottom ash material in Alberta, including Transalta Sundance Generating Station, located in Parkland County; Keephills Generating Station at Range Road 40 Kapasiwin; and Genesee Generating Station near Warburg. All the stations are located at an approximate distance of 95 km from the IRRF construction site. Because bottom ash is a waste material in these generating stations, there was no cost considered for material procurement. The bottom ash was transported to the site by 20 CY trucks and a Caterpillar D7R XR Series II bulldozer spread it over the subgrade. A water tanker and vibratory roller were used for mixing water with bottom ash and compacting the layer. A combination of 500-, 300-, and 200-mm layers were used to spread bottom ash in this section. A 500-mm layer was used whenever the bottom ash was placed on top of geotechnical instrumentation to avoid damaging the sensors with the construction equipment.

The cost analysis per square meter of section covered by one 5-cm board of polystyrene is shown in Table 7. The polystyrene boards were provided by a local supplier at 0.6×2.4 m, and a thickness of 5 cm. The calculation is based on the surface coverage.

It can be concluded from Tables 5–7 that the cost of construction per cubic meter of the GBC and the bottom ash layers is $95.00 and $49.00, respectively. The construction cost for each square meter of road using polystyrene boards as an insulation layer on top of the subgrade was estimated to be as high as $79.00. As expected, the cost per cubic meter of bottom ash material is lower than the GBC because there is no surcharge for procuring the waste material. The price of a cubic meter of bottom ash is approximately half the value of GBC.

In the following section, the authors aim to calculate the construction cost for 1 m of the road of different sections. It was assumed that the subgrade surface was ready for executing different layers of material (Fig. 2). The necessary thickness was calculated in the previous section based on the possibility of heave accumulation and thermal performance of materials. Hence, the construction cost of 1 m of road using bottom ash, poly-5, and extra GBC sections was calculated to be as high as $977.00, $1,334.00, and $3,946.00, respectively. By comparing the capital cost of construction of these sections, it can be concluded that the cost of construction of 1 m of the road using GBC is about four times that of the bottom ash section, and about three times the poly-5 section.

In the case of an approximately equal shipping distance for different sites, it is possible to estimate the construction cost when affected by different frost depths. Table 8 presents the estimated required thicknesses of different material when using GBC, bottom ash, and polystyrene layers. The frost depth was calculated based on the approximate total frost that penetrates into the subgrade layer. The minimum required thickness of each section followed the same method of calculation explained in the previous section for the GBC. It can be seen that in all cases, 5 cm of polystyrene boards (the minimum applicable thickness) satisfied the thermal condition, while for the GBC layer the second criterion (minimizing the heave occurrence in subgrade) is the governing factor.

Table 8. Required thickness of insulation layers (m) for different frost depths

Total frost depth (m)	Material		
	Extra GBC	Bottom ash	Polystyrene
1.3	0.4	0.5	0.006
2	1.15	0.75	0.009
2.6	1.85	1	0.012
3.3	2.6	1.25	0.015
3.9	3.3	1.5	0.018

Using the information provided in Table 8, the construction costs for different insulation material were compared based on the required thickness of each material for frost depths of 1.3, 2, 2.6, 3.3, 3.9, and 4.6 m, as represented in Fig. 3. Considering the construction site location and the availability of material, the proper method of insulation can be selected. For instance, for a frost depth of 1.3 m, the construction cost of 1 m of roadway, if considering equivalent depth for different material, is $688.00 for GBC, $452.00 for bottom ash, and $1,334.00 for polystyrene.

Fig. 3 also indicates that for sites where the availability of each material and the distance of the source to the project location are the same as the IRRF test road and the frost depth is less than 1.6 m, using bottom ash and GBC will be more cost effective than polystyrene boards. For frost depths between 1.6 and 3.5 m, using bottom ash as insulation will be the most cost-effective way to insulate the subgrade. When the frost depth is higher than 3.5 m, polystyrene boards can outperform the other two materials to prevent frost ingress through deeper layers. In addition, it can be concluded that the construction cost of bottom ash has less sensitivity to change in thickness than the GBC material. This stems from the availability of inexpensive bottom ash as opposed to the costly GBC material.

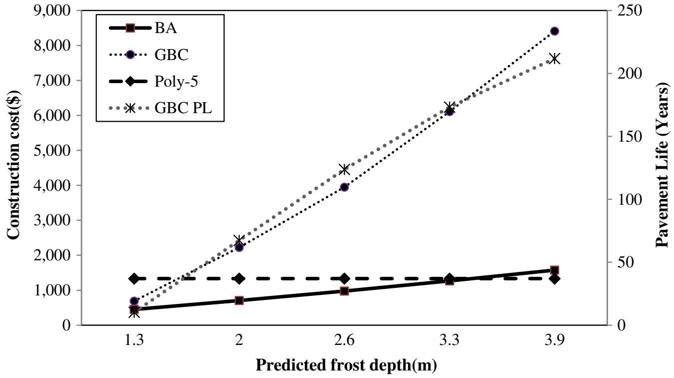

Fig. 3. Comparison of construction cost of different insulation layers.

This cost comparison is based on the IRRF's construction site costs and would be valid for construction sites with similar access to material sources.

As shown in Table 4, the life expectancy of pavements constructed using the 5-cm-thick polystyrene is almost half the life expectancy of the conventional section. In addition, the bottom ash will not affect the life expectancy of the pavement. The considerably high cost of construction of roads using GBC material in high freezing zones (for instance, frost depth of 3.3 m) can be justified by their higher PL because the life expectancy will considerably increase by using GBC (almost 170 years compared to 20 years or less for CS).

Summary and Conclusions

This study provides a performance and cost comparison of the utilization of different insulation materials in pavement constructions, along with substituting the high-quality base material with frost-susceptible subgrade. The study focused on cost estimations of GBC, bottom ash, and polystyrene layers. The estimated unit cost values were considered to be reasonable at the time of this study, but may vary significantly from project to project depending on conditions, specific project requirements, equipment availability, and location of the project. Observations resulting from this study are summarized as follows:

1. The main criterion that contributed to the selection of GBC thickness was overburden pressure, while for bottom ash and polystyrene boards the criterion was thermal performance of the layer to prevent the frost from penetrating into the subgrade.
2. The selected thicknesses of bottom ash, polystyrene, and GBC material to conduct the comparison are 1.00, 0.05, and 1.85 m, respectively.
3. The total traffic that the B.Ash section could carry was estimated to be 14% of the value of that of CS. While the poly-5 section can carry half of the traffic of the CS section, the extra GBC section can tolerate more than 10,000 times the traffic of the CS.
4. The construction cost per cubic meter of the GBC and the bottom ash layers was $95.00 and $49.00, respectively. In addition, the insulation cost for each square meter of road with polystyrene boards was $79.00.
5. The total cost of construction of insulation layers for 1 m of bottom ash was $977.00, for 5 cm of polystyrene the cost was $1,334.00, and for 1.85 m of extra GBC the cost was $3,964.00.
6. At locations with similar material availability and source distance from the site, and with a frost depth less than 1.6 m, bottom ash and GBC material will be more cost effective than polystyrene boards; however, this implication depends on the availability of each material and the distance of the source to the project location.
7. For frost depths between 1.6 and 3.5 m, using a bottom ash layer as insulation will be the most cost-effective way to insulate the subgrade. At locations where the frost depth is higher than 3.5 m, polystyrene boards can outperform the other two materials to prevent frost ingress through deeper layers.
8. The high capital construction cost of pavement using granular base material can be justified by the high life expectancy of these pavements.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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