Behavior of flexible pavement containing foam glass aggregates as thermal insulation layer

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RÉSUMÉ
Au Canada, deux techniques sont d'usage pour protéger les chaussées des risques de dommages et de vieillissements prématurés en lien avec la pénétration du gel dans les structures : le surdimensionnement des infrastructures en installant des matériaux non gélifs ou l'intégration d'une couche de polystyrène qui joue le rôle d'isolant. Pour le moment, seul le polystyrène a un usage normalisé au Canada comme matériau isolant en génie routier. Les granulats de verre cellulaire (GVC) issus du recyclage des résidus de verre représentent une technologie prometteuse encore inédite au Canada qui fait l'objet d'un programme de recherche du CRSNG à l'Université Laval. Quatre sites d'essai en milieux municipaux ont été mis en place au Québec en intégrant des GVC comme matériau isolant associé avec des sections témoins incluant du polystyrène ou sans isolant. Un bilan comparatif sur plusieurs années du suivi du comportement thermique et des gonflements mesurés sera détaillé ici.

ABSTRACT
To protect pavements from the risks of damage and premature deterioration associated with frost penetration, two techniques are used in Canada: oversizing the infrastructure by using non-frost sensitive materials or by incorporating polystyrene panels as insulation layer. To date, polystyrene is the only material with a standardized design procedure recommended by the Canadian road authorities as an insulating or lightweight material. Foam Glass Aggregates (FGAs) made from the recycling of glass waste represent a promising technology that is still new in Canada and is the subject of an NSERC research program at Université Laval. Four road test sites in municipal environments were built in Quebec using FGAs as insulation material associated with control sections including polystyrene or without insulation. A comparative assessment of the thermal behaviour and frost heaving measured over several years will be detailed.

1 INTRODUCTION

In cold climates, to ensure adequate frost protection of flexible pavement structures, infrastructure constructed only with natural granular materials may require increased layer thicknesses reaching a total pavement thickness up to 1 m or more (Doré and Zubeck, 2009). To limit construction costs where severe frost related issues are expected (excavation depth and quantity of granular materials), the use of insulating materials represents an economic and technical solution (Bilodeau et al., 2016). Therefore, in northern regions, insulation layers are increasingly used as an effective design solution for flexible pavements. Indeed, in presence of frost sensitive soils, coupled with severe climatic conditions (high yearly precipitation, freezing and thawing cycles, global warming), are challenging and complex conditions for road network managers. This type of material acts as a thermal protection layer for the structure against nocuous frost penetration. In seasonal freezing conditions, a layer of insulating material retains heat in pavement structures and limits the frost penetration in frost sensitive subgrade soils. Frost penetration reduction decreases the associated damages, such as differential frost heave, surface profile deterioration, and consequently decreases rehabilitation and maintenance costs.

Several types of insulated and light materials are used around the world. But in Canada and in the province of Québec, extruded (XPS) and expanded (EPS) polystyrene panels, are the most widely used for pavement insulation. This technology however has a few technical downsides, like the polystyrene susceptibility to fuel spillage, which can lead to the partial or total loss of the protective layer. In Canada, this material benefits from extensive knowledge and feedback from several decades of experience (Saint-Laurent 2012). This has enabled the development of design charts and calculation methods incorporated into design softwares to support the adequate and optimized use of the technology.

An additional challenge is the supply of good quality insulation materials especially away from large urban centres. This last challenge favours the use of residual materials (industrial origin or deconstruction materials). However, nowadays alternative insulation materials are available like Foam Glass Aggregates (FGAs) made from recycled glass of various origins. FGAs production present a double advantage. It can help resolve recycled glass management issues, and it can respond to the increasing demand for light, insulating and draining materials for various civil engineering applications. FGAs have the potential to increase the pavement durability. Firstly, in winter, its low thermal conductivity limits the frost penetration in the sub-base layer and the subgrade, providing a high level of protection against the frost action. Secondly, during the critical thaw period, where pavement damage rate typically increases, granular nature of FGAs contributes to the improvement of the drainage in the system and thus helps to limit the temporary reduction in bearing capacity, as well as to limit the associated damages. FGAs, as lightweight aggregates, can also be used when building thick embankments on soft soils in order to avoid overloading and excessive consolidation. In many European countries, FGAs are used successfully to protect roads and building foundations, for pipe insulations and design of light embankments (Emersleben and Meyer, 2012).

In this paper, the thermal behavior and frost heave results measured in FGAs insulated road section will be compared to structures insulated with EP or without insulation where possible. These field observations will be compared to the laboratory characterization including a temperature-controlled laboratory pit test.

2 FGA

2.1 Origins

Foam glass is a lightweight insulating material, the first documented mention of foam glass is almost 100 years old during the cork shortage, with a first patent filed by the company Saint-Gobain in France in the 1930's (Bernardo et al, 2007; Emersleben et Meyer, 2012; Attila et al., 2013).

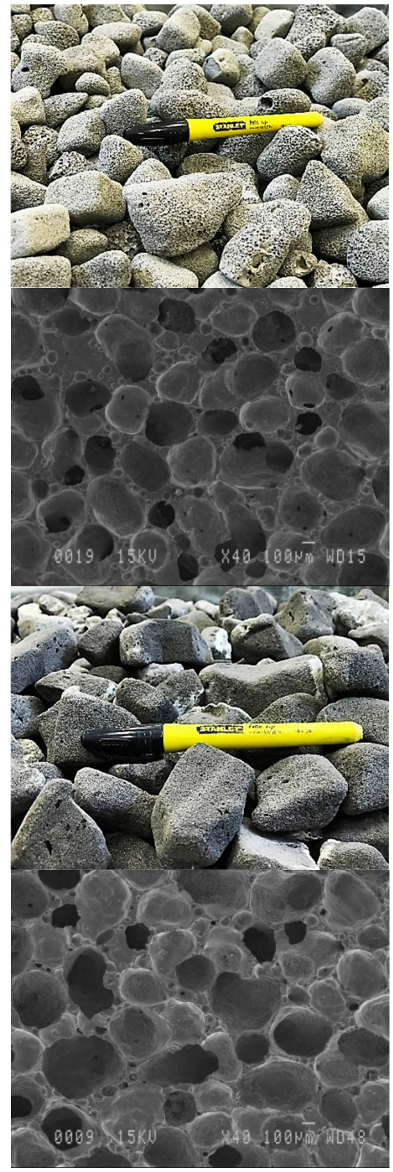
The production requires a foaming agent and the same primary materials needed to make glass, like quartz sand and melting addition or glass residues (cullet). In the case of foam glass aggregate (FGAs) production, many alternative materials from various origins can potentially be used as cullet, like industrial fly ash, cathode ray tubes or car windshields for example (Volland et al., 2012; Attila et al., 2013; Binhussain et al., 2014; Marangoni et al., 2014).

The mix is baked at high temperatures (around 800-900°C) to obtain the viscoelastic state of glass while provoking the gaseous decomposition of the activator, i.e. a foaming agent. This process causes the mixture to foam and the high viscosity keeps the bubbles in the matrix. At the exit of the fluidized bed furnace, quenching generated at ambient temperature leads to the fragmentation into aggregates (Shutov et al., 2007; Ritola et Vares, 2008).

2.2 Samples description

Two batches were imported from Europe for the purposes of the research project to assess properties and performance using Quebec standards and in the specific environment and climate of the Province. FGAs have a variable color matrix characterized by unconnected millimetric and micrometric alveoli obtained by the foaming process. It is this specific structure that gives FGAs their lightweight and insulating properties.

Figure 1 shows centimetre and micrometre scale photographs of the FGA sample. The scanning electron microscope (SEM) observations (Figure 1.b and 1.d) are performed under a vacuum of $1x10^{-3}$ Pa on samples by Au-Pd sputter coating.



1.a.
1.b.
1.c.
1.d.

Figure 1 : FGAs appearance on centimetric scale and micrometric scale observed with a scanning electron micrograph.

- Grey sample bulk (1.a) and micrograph observation (1.b)
- Black sample bulk (1.c) and micrograph observation (1.d)

The main physical characteristics of the studied FGAs are summarized in **Error! Reference source not found.**. The main characteristics are very similar for both samples and are consistent with the values found in the literature (Segui et al, 2016).

Table 1. Characteristics of tested FGAs

FGAs samples		Grey	Black
Characteristics	Unit		
Granular size[1]	mm	0 – 60	0 – 60
Density[2]	-	0.29	0.28
Density - bulk [3]	kg/m3	150	130
Density – compacted[3]	kg/m3	175	152
Void Ratio[3]	%	40	40
Absorptivity[2]	%	38	29
Thermal conductivity[4]	W/(m.K))	0.06 / 0.09	0.05 / 0.085

[1]CAN/BNQ 2560-040
[2]LC 21-067
[3]LC 21-060
[4]ASTM-D5334-14, on dry / wet particle

3 EXPERIMENTAL SITE

This section presents the experimental pavement structures insulated with FGAs, which are part of an ongoing research program. Four test sections are considered for this paper. The pavement structures stratigraphy is presented in the figure 2, 6 to 8 temperature sensors are installed in each section and monitoring the thermal conditions on an hourly basis. The locations of the experimental sites are shown on the map of annual mean temperature in Quebec (figure 3). The summary of weather conditions off each site is presented in table 2.

Table 2. Summary of climatic conditions of each experimental site (Transports Québec. 2003)

Site	FGAs	Tm[1] (°C)	Precip.[2] (mm)	Fi_{max}[3] (°C.d)	Ratio
Lab. pit test	Grey	-10	-	305	-
Kingsey Falls	Grey	5	1000	963	1:3
Québec City	Grey	4	1275	1431	1:3
Rouyn-Noranda	Black	1	975	1353	1:2.4

[1]annual mean temperatures
[2]annual mean cumulative precipitation (water equivalent)
[3]maximum Ig reached during monitoring period
[4]EPS : FGAs

For each urban experimental sites, a 15 to 20 meters length FGA section was built. The design of the FGAs insulation layer thickness is based on the typical practices of the municipality with EPS and on the recommendation of the FGAs producers to multiply the EPS thickness by 3. In the province of Québec, the allowable maximum frost heave is about 60 mm and the thickness of the insulating layer is optimized to prevent the frost front from reaching the subgrade. Usually, a minimum granular layer of 450 mm is required on top of the insulating layer to prevent the risk of icing in the fall before the onset of snowfall and winter road maintenance (Transports Québec, 2003). Each site has at least a 2nd test section insulated with EPS, and sometimes a third reference test section built without insulation. Stratigraphy's of FGAs sections are detailed in figure 2.

On the four experimental sites, three were built with the grey FGAs, and the fourth with the black FGAs. The first one, with the grey FGAs, is the large size test pit (2 m width × 6 m length × 2 m height) of the Civil and Water Engineering Laboratory at Université Laval. The test pit has a temperature control system at the bottom and is coupled with a climate and load simulator heating/cooling system that can maintain the pavement surface temperature between -15°C and +40°C. The water table level is also precisely controlled. During the testing phase, the pavement structure system was maintained in static temperature gradient condition: around -12°C at the top and 2°C at the bottom, with the water table maintained at – 1600 mm. The FGAs insulation layer was placed high in the laboratory structure without paying attention to icing protection to promote accelerated mechanical damage from the simulator moving wheel (figure 2.1., mechanical response and performance are not analyzed in this paper). These climatic conditions are identical to those set during previous tests on a reference structure without insulation

The second experimental pavement structure was built at the end of fall 2015 in Kingsey Falls, with the grey FGAs, Québec in a street subjected to heavy vehicle traffic. The structure is detailed in figure 2.2.

The third experimental pavement structure was built with the grey FGAs in fall 2017 in Québec city on a residential street with few heavy loads traffic (figure 2.3). The 2nd asphalt layer was placed the following spring.

The fourth experimental pavement structure was built with the black FGAs sample in 2019 in Rouyn-Noranda, on a bypass road serving a residential area with a moderate heavy loads traffic. In comparison with the required EPS thickness, the thickness of the FGAs layer has a thickness ratio 2.4 times the EPS layer, which is lower than the ratio recommended by the European manufacturer (3 times) (figure 2.4.) The first and second asphalt layer were placed successively the summers of 2020 and 2021.

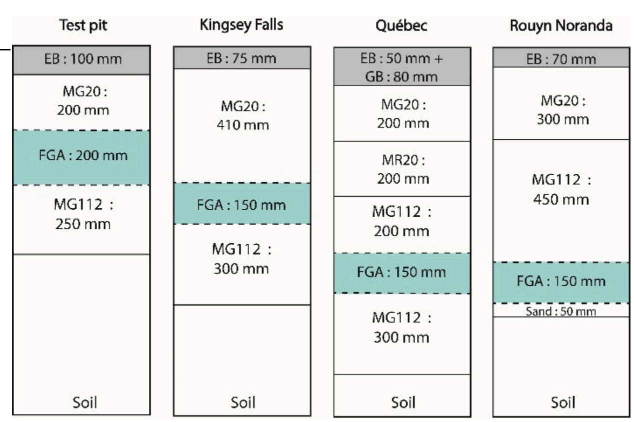


Figure 2. Stratigraphy of experimental roads sections insulated with FGAs. MG20 and MG112 aggregates used as base and subbase materials comply with the size and quality requirements defined in the local standard NQ 2560-114/2002

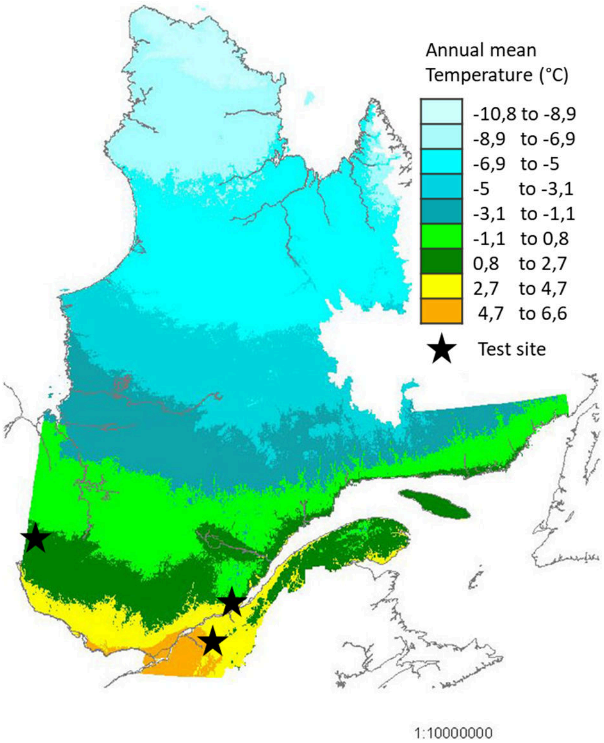


Figure 3. Map of annual mean temperature in Quebec and locations of the experimental sites are indicated by the stars (Gerardin and McKenney, 2001)

4 RESULTS

The results and observations of ongoing field monitoring are summarized in this section.

Figure 4 shows the evolution of the frost front penetration measured as a function of the cumulative Freezing Index (Fi) inferred from temperature measurements at 50 mm depth in asphalt concrete for two laboratory test sections. The reference structure has a standard stratigraphy built according to Québec's standard. The FGAs structure is insulated with a 200 mm thick layer of the grey FGAs. The FGAs layer replace the upper part of the subbase layer off the structure. The black line represents the result obtained for the reference structure with no insulation, while the solid blue line represents the results for the FGA insulated structure. For an equivalent Fi, the frost front is maintained at the level of the insulating layer while it reached a depth of 1500 mm in the reference structure.

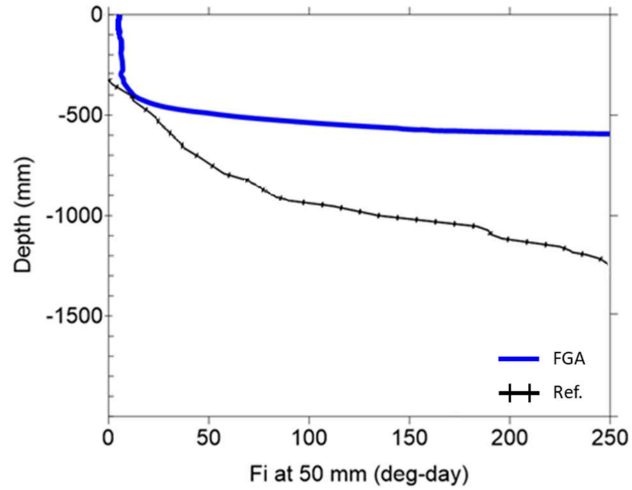


Figure 4. Frost front evolution on laboratory test pit for the structure insulated with FGA (blue line) and the reference without insulated (black line), in function of the progression of Freezing Index Fi measured at a 50 mm depth (Fi)

The evolution of the frost front for each section of the Kingsey Falls structure between December 2015 and September 2020 is presented in Figure 5. At the Kingsey Falls site, the bottom of FGAs and EPS layers are placed at the same level. The evolution of frost depth for the two insulated sections is similar. In both cases, the frost front never exceeds the thermal insulation layers. In comparison, the frost front reaches the subgrade soil in the reference section during 3 out of 5 winters. It is normal to observed that frost fronts penetrate earlier through insulated structures, as the insulating layers keep the soil warm at depth and impede upward heat flow from the ground.

In the most northern experimental site of Rouyn-Noranda, only the winter 2020-2021 data is used for the analysis. The top of FGAs and EPS layers are placed at the same level. Figure 6 shows the evolution of the measured frost penetration, frost heave measured at the surface and the cumulative Fi for the 2020-2021 winter. The maximum frost depths reached do not exceed the insulation layers for both FGAs and EPS. The frost heave for each section is negligeable and despite the under design of the FGA layer thickness, the two sections behaved similarly.

The Quebec City site will not be described here. The site is located in an asymmetrical embankment and the conditions are comparable for the 3 structures. Nevertheless, the same good performance of the FGAs layer is observed as in the other sites.

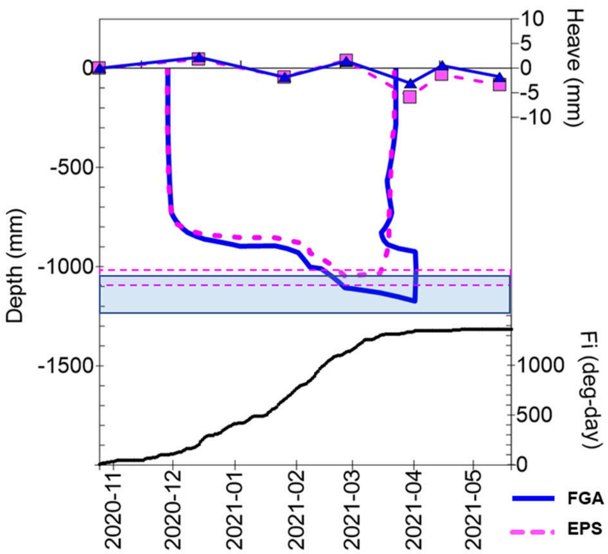


Figure 6. Frost front evolution on insulated pavement at Rouyn-Noranda, mean heaving measured on the surface of each section, and cumulative Freezing Index (Fi) for 2020-2021 Winter. In blue FGAs result an in pink EPS result.

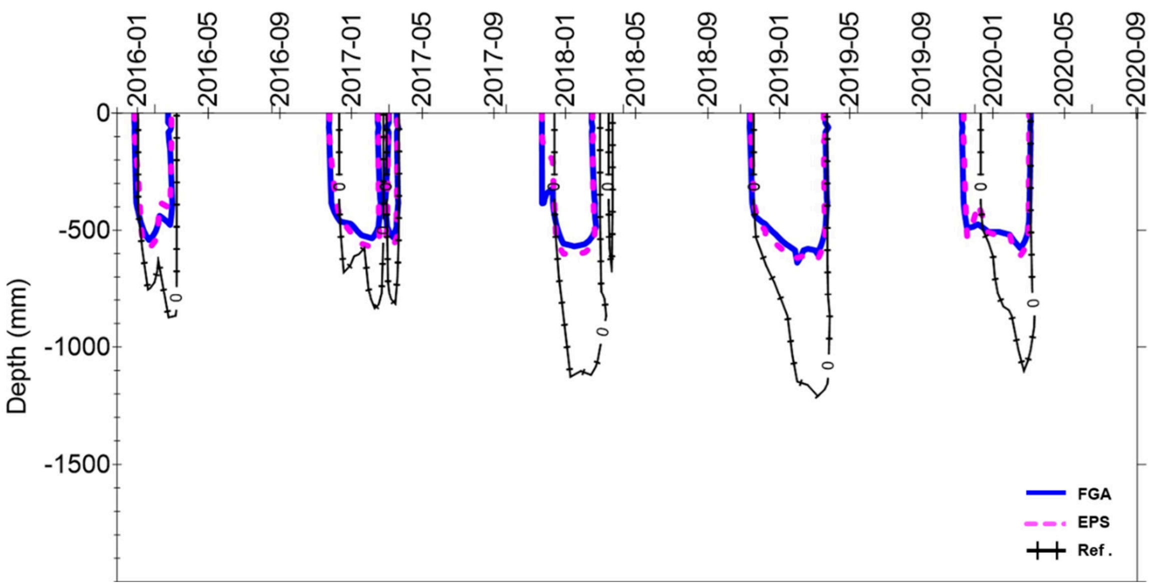


Figure 5. Frost front evolution at Kingsey Falls for the reference without insulated (black line cross out), the structure insulated with FGAs (solid blue line) and the structure insulated with EPS panels (pink dotted line) between December 2015 and September 2020

Based on the observation on frost depth and frost heave made at the experimental sites the use of a FGA layer is effective for pavement insulation applications in cold Canadian climates, with a performance comparable to that of EPS panels.

5 CONCLUSION

This study summarizes the results of thermal behavior of experimental pavements built with FGA monitored over the last few years in the province of Québec, Canada. Different types of flexible pavement designs and two types of FGAs as insulation layer are monitored. As part of the design procedure, each section is optimized to limit frost penetration according to urban practice with EPS panels (position in the pavement structure and thickness). Then the traditional EPS insulating layer was substituted by a FGAs layer 2.4 to 3 times thicker. In addition, laboratory road structures with and without FGA insulation and built with the same materials are studied under static freezing conditions.

For the monitored winters, the frost front never reached the subgrade soil. Moreover, the maximum frost heave observed in Kingsey Falls the is about 30 mm and about 10 mm in Rouyn-Noranda. These values are well below the 60 mm limit defined by design; therefore, adequate frost protection was achieved with FGA layers.

The feedbacks from the presented laboratory and field observations have demonstrated that FGAs technology is a promising solution for designer and manager of road construction projects in Canada, and an effective alternative to polystyrene technology. FGAs have insulation, lightweight and draining qualities that can contribute to the road durability in cold climates and to provide a solution for recycling the glass residues in Québec and in the rest of Canada.

The European construction principles for FGAs are validated by the various monitored test sections. But some improvements and complements are in development at Université Laval to propose an engineering design tool adapted to the specific thermal behavior of a FGAs layer, including the conditions where convection is triggered as well as their mechanical characteristics. Finally, to maximize the full potential of the FGA materials, research projects are in progress to propose modifications of the characteristics of FGAs layer for design in seasonal frost or permafrost contexts.

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