Innovative materials for road insulation in cold climates: Foam glass aggregates.

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2. Abstract

Freezing and thawing cycles cause road network damages associated to differential heaving and bearing capacity loss during spring. As a result, deterioration of the ride quality, cracking of the asphalt concrete layer and finally, increased rutting and pothole formation are likely to occur. This leads to increased maintenance and higher rehabilitation costs. In order to improve the durability of the pavement, thermal insulation is used more and more in the province of Quebec. This protection technique limits frost penetration in the frost susceptible subgrade soil, thus reducing the associated damage and the rehabilitation costs. In Quebec and in Canada, extruded polystyrene is the material commonly used for pavement insulation. New alternative materials are now available, including foam glass aggregates made from recycled glass of various origins. Foam glass aggregates can be considered as lightweight and suitable for insulating granular material. This study will expose the state of knowledge on thermal insulation with cellular glass. It will also describe the results obtained from the tests performed in the laboratory and from monitoring an experimental road site during its first year of use. The test site is composed of three different sections build on frost sensitive soil: the first section is insulated with foam glass aggregates, the second is insulated with extruded polystyrene panels and the third is a conventional pavement structure without insulation. The results from the experimental site will be used to compare the thermal behavior and the performance of the three sections. Special attention will be given to the first section to gather the effect of foam glass aggregates integration on pavement structure. The thermal and performance data collected in-situ will be compared to those obtained in the laboratory. The result obtained from this new product will be used in the design methods for flexible pavements in cold regions.

Introduction

Transportation agencies involved in the design of pavement structures in northern regions have to overcome geotechnical challenges in order to develop and maintain their road network. Indeed, frost is the first cause of pavement deterioration in Norway and the third in Quebec [Øiseth et Resfal, 2006; MTQ, 2014]. The severe climatic conditions and the presence of soft and frost sensitive soils, coupled with a high yearly precipitation of water, are among the challenging conditions for the design of pavement structures. In addition, near large urban centres, the availability of performing construction materials is often an issue. The use of insulation techniques in civil engineering infrastructure design is a well-established yet growing practice in the province of Quebec. It improves the durability of the pavement when field conditions are unfavourable regarding pavement design against frost action [Doré et Zubeck, 2009]. Insulation limits the frost penetration in the sensitive subgrade soil and thus reduces the associated damages, such as differential frost heave and associated cracking, as well as the rehabilitation costs. When frost action is expected to be severe, the amount of granular material needed to meet the required total pavement thickness to ensure adequate protection may be important (more than 1 m). In this context, the use of insulation materials is likely to limit the construction costs by reducing excavation depth and granular material [Bilodeau et al., 2016]. Insulation also enhances the critical frozen depth in piping protection cases.

Using appropriate draining granular materials to limit spring water drainage and limit the loss of bearing capacity during the thaw period can also increase the road structure durability. Lightweight materials may also be used to avoid overloading soft soils, especially when thick embankments are built.

Extruded polystyrene (XPS) panels are a material commonly used for pavement insulation in Quebec and in Canada. XPS panels show satisfactory insulation properties that contribute to retaining heat within the pavement structure. Some technical downsides associated with the use of such panels or blocks are: difficulties in transition area management, checkerboard geometry to avoid joint weakness, and permanent damage induced to the protection layer in case of subsequent intervention within the structure. Another potential problem is due to their chemical composition, in case of hydrocarbon spreading, XPS dissolves which causes the loss of the frost protection due to the chemical damage or the failure of the embankment.

New alternative insulation materials are available nowadays. Foam glass aggregates (FGAs), a granular material made from recycled glass of various origins, are among these new products. Problems of managing glass residue have several origins: contamination from the recovery step, ineffective grading technology and low economic value of the final product. These problems limit the incentives to invest in the recycling of waste glass.

The production of FGAs can be used to resolve recycled glass management issues, as significant yearly overstocks have to be managed in Quebec (90 000 tons per year) [Gagné, 2010]. It may also respond to the need of light, insulating and draining materials for various civil engineering applications.

Historical background and FGA fabrication

The first mention of foam glass was documented during the cork shortage in the 1930’s [Bernardo et al, 2007; Emersleben et Meyer, 2012; Attila et al., 2013]. In 1934, the company Saint-Gobain in France secured the first patent [Pittsburgh Corning, 2014]. The principle of foam glass fabrication is based on mixing, washing and crushing glass, and adding a foam activator (limestone carbonate) afterwards to the prepared crushed glass mix. The mix is placed in a furnace and heated around 800-900°C to obtain the viscoelastic state of glass and the temperature allowing the gaseous decomposition of the activator. This process causes the mixture to foam. 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].

Active research is conducted around the world to decrease the temperature of the process and to introduce some alternative materials to respond to regional concerns, depending on the availability of local materials, and to give some new properties to foam glass. Residual materials from various amounts of cullet, basaltic scoria, zeolites, clay, industrial fly ash and special glass like cathode ray tubes or car windshields are used. Moreover, as activators, carbon, chalk and hydrocarbon are tested [Volland et al., 2012; Attila et al., 2013; Binhussain et al., 2014; Marangoni et al., 2014].

Without a specification standard, European producers follow the test standard 13055-2 [EN 13055-2] and submitted their product to the European organization for technical assessment (EOTA) [EOTA 05/0187, 2005; EOTA 13/0549, 2013] in order to obtain a market consent based on the Deutsch recommendation for lightweight fill.

<u>Previous experiences with FGAs</u>

Since the middle of the 1970's, Switzerland used FGAs in civil engineering practices to build pavements and embankments on soft soils [Emersleben et Meyer, 2012]. Since 1997, Norway allows the commercialization of FGAs produced from recycled waste glass and more than 25 field tests have been instrumented [Aabøe et al., 2005; Øiseth et Refsdal, 2006]. Norway is currently planning to recycle 40 % of the 4 million mercury lamps used every year to produce about 50 000 m^3 of FGAs [Frydenlund et Aabøe, 2002]. Between 1999 and 2004, in Norway and Sweden, 48 296 m^3 of FGAs was used in pavement applications for lightweight embankments and insulation [Aabøe et al., 2005]. Switzerland, Germany and Italy currently consume 500 000 m^3 per year of FGAs for their civil engineering applications [Misapor, 2016]. In 2011, foam glass production also started in Finland [Auvinen et al., 2013].
Globally, compared to competitive products, the price of FGAs is economically favourable. In 2005, in Norway, one m^3 costed 35 - 40 $ including transportation costs [Frydenlund et Aabøe, 2003]. In 2006, another Norwegian study reported that even with a 4 to 5 times thicker design using FGAs instead of polystyrene panels, the costs are comparable for equal thermal performances [Øiseth et Refsdal, 2006].
The SINTEF ("foundation for scientific and industrial research"), a Scandinavian research group, follows different building sites that used FGAs as construction materials. Generally, for insulated pavement structures, the thermal and mechanical properties are satisfactory. The thermal insulation of a FGA is equal to that of other materials used and there is no deformation or excess crushing observed due to the compaction [Øiseth et al., 2006; Øiseth et Refsdal, 2006; Aabøe et al., 2005].
In the case of complex embankment applications, FGAs were found to be a performing filling material in several projects, such as:

- On highway E6 in Klemetsrud (Norway), in the case of a road deviation subjected to heavy traffic, a temporary embankment composed of a 4 m FGA layer was used above pipes. For this application, FGAs were mainly selected to avoid overload on the structure. At the end of the deviation, the FGAs were reused in an access ramp on soft soil. A specific load limitation of 45 kN/m^2 for the densification of FGAs was selected to limit the crushing of particles. The settlements and deformations observed were limited, with a difference of 4 cm between May 2003 and April 2004 [Aabøe et al., 2005].
- On highway E12 in Hämeelinna (Finland), a temporary access road was built for a complex intervention in an urban area subjected to a high traffic volume. In this case, the use of traditional aggregates was forbidden, because of the risk of overloading the soft subgrade soil, as well as due to the severe frost conditions encountered at the site. The use of FGAs helped to reduce settlements, increase slope stability and reduce lateral earth pressures with the benefits of having thermal insulation and frost protection [Auvinen et al., 2013].

- On national road N°17 in Norway, where a landslide occurred along a river (30 m wide). In order to restore the slope and to rebuild the road, an erosion protection base made with blasted rock was completed with a FGA embankment. In this case, a FGA was selected because of its high friction angle and its lightweight properties since a soft soil was found in place. After 2 years, neither cracking nor swelling were observed on the road surface [Frydenlund et Aabøe, 2003].

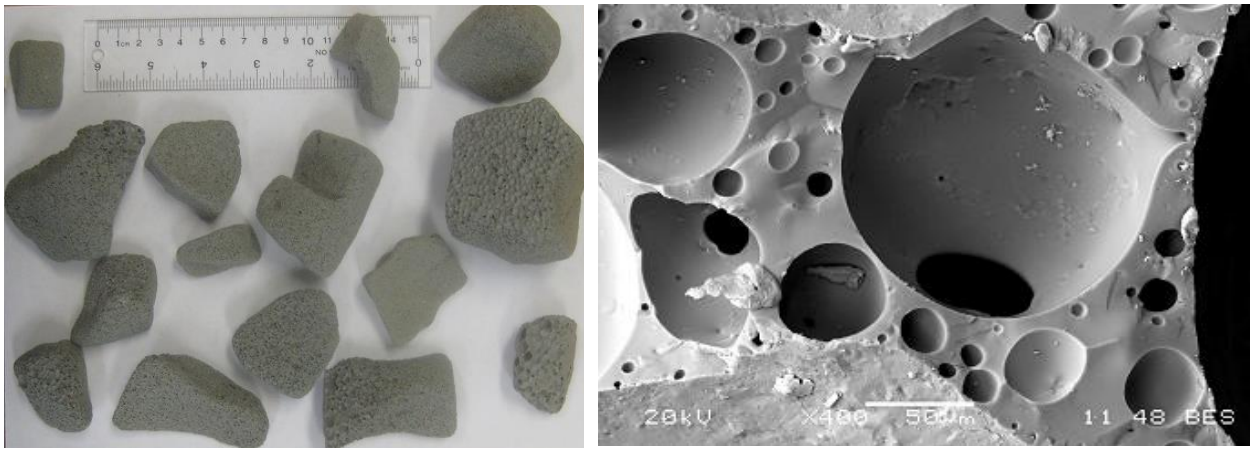
The results collected on various experimental sites are generally positive. The benefits of FGAs can be applied in numerous types of civil engineering structures to provide thermal insulation and frost protection, to reduce vertical and lateral earth pressures, as well as to increase slope stability. As a matter of fact, the FGA bearing capacity and shape make it an easy material to use in earthwork construction. It can be set up using the same construction techniques and equipment as traditional granular material even if some precaution must be taken. FGAs are a “fragile material”, and so the machinery used during roadwork require some special handling to limit excessive crushing. It is not recommended to expose FGAs to dynamic loads exceeding 50 to 75 kPa [EOTA 05/0187, 2005].

FGAs are a relatively new material in road applications with limited background information. Laboratory and experimental tests must be conducted to document their thermal behaviour and mechanical performance in order to optimize the integration of foam glass aggregates in pavement structure. It is expected that the results obtained using this new product will be exploited in the design methods for flexible pavements in cold regions.

Results of laboratory characterization

Cascades Canada ULC imported a batch of FGAs from Europe in order to carry out preliminary tests to characterize the properties of the product and to document its performance in a Canadian climatic environment. Preliminary laboratory results are obtained from the tests performed at Laval University and on the Cascades R & D, a division of Cascades Canada ULC.

As shown in Figure 1.1, FGAs have a gray matrix with a spongy appearance. FGAs are rough and sharp like volcanic pozzolan. A scanning electron microscope (SEM) observation (Figure 1.2) was performed under a vacuum of $1x10^{-3}$ Pa on FGA samples by Au-Pd sputter coating. Figure 1.2 shows that the FGA structure is 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.



1.1) 1.2)

Figure 1 : FGA appearance: 1.1) Bulk (centimetric scale), 1.2) Observed surface with a scanning electron micrograph (scale : 50 µm)

The FGA grain-size distribution obtained by sieving [CAN/BNQ 2560–040] shown in Figure 2 highlights that the material presents a grading mainly concentrated between 20 and 60 mm (80 % in mass). Essentially no particles are found between 1 and 20 mm. Finally, the 20 % of residual materials are composed of sand-size particles smaller than 1 mm. The several stages of transportation (factory/cargo/storage/laboratory) and handling could explain the difference between the grain-size distribution specified by the manufacturer (from 10 to 60 mm) and the one measured in the laboratory. Since the particle edges of FGAs were blunt during these manipulations, it is recommended to monitor the particle size after each test. In order to limit and control the quantity of sand, its production must be studied, as a "contamination" of fine particles could be damaging to drainage and frost sensitivity [Bilodeau et al., 2008].

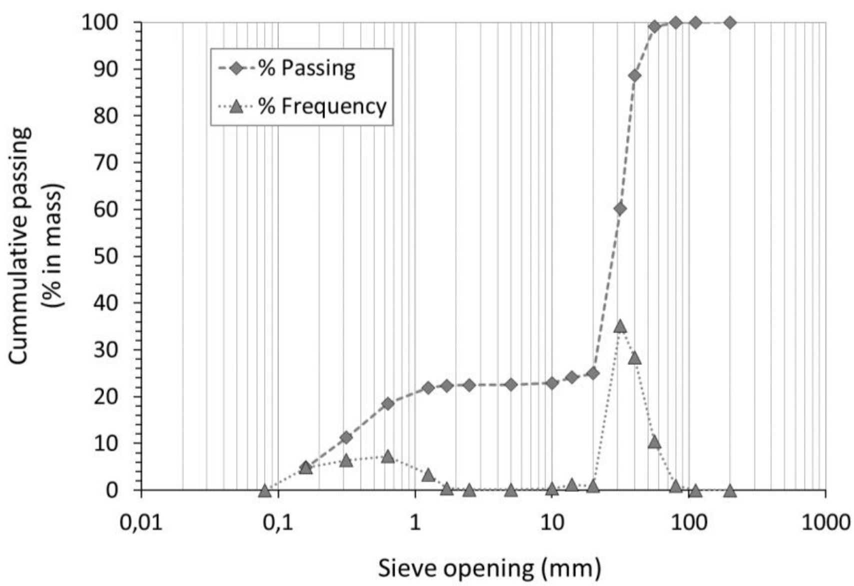


Figure 2 : FGA grain-size distribution.

The main physical characteristics of FGAs according to Quebec standards are summarized in Table 1 in comparison with the data found in literature. Density values obtained of the FGAs are in the range of those observed by other studies. The relatively low compression strength obtained of individual particles of foam glass (1-4 MPa) highlights the necessity to define some limits on load machinery for construction operations.
The thermal conductivity of the aggregate particles was measured with a needle sensor. The needle used was 60 mm long and 1.2 mm wide and is able to measure values of thermal conductivity comprised between 0,02 à 2,00 W/(m.K). The contact between the FGA and the needle was maximized with a silver thermal compound. The measured FGA thermal conductivity varied between 0.06 W/(m.K) for dry conditions and 0.09 W/(m.K) for moist conditions. This result will be completed by measurements on compacted FGA assemblies using an appropriate needle (100 mm long and 2.4 mm wide).

Table 1 : FGA's main physical characteristics.
*[EOTA 05/0187, 2005 ; Øiseth et Refsdal, 2006 ; Zegowitz, 2010 ; Welter, 2012 ; Auvinen et al., 2013 ; EOTA 13/0549, 2013]

	Tested FGA	**Technical literature value***
Granular size [CAN/ BNQ 2560-040]	0 – 60 mm	10- 80 mm
Density [LC 21-067]	300 kg / m^3	Max 350 kg / m^3
Density (dry bulk) [LC 21-060]	145 kg / m^3	100 - 230 kg/m^3
Density (dry compacted) [LC 21-060]	165 kg / m^3	150 - 290 kg/m^3
Compaction factor	1.14	1.15 - 1.3
Absorptivity [LC 21-067]	40 %	-
Water absorption (24h)	57 %	-
Water absorption (1 month)	67 %	30 - 60 %
Compression strength	1 - 4 MPa	-
Compression strength of granular mix at 20 % of deformation	-	0.08 - 0.9 MPa
Resilient-modulus (average principal stress)	-	75 MPa (stress40 kPa) 150 MPa (stress 100 kPa)
E-modulus	-	55 - 70 MPa
Friction angle	-	36- 45°
Thermal conductivity (k-value)	0.06 W/(m.K) (dry) 0.09 W/(m.K) (moist)	0.04 - 0.1 W/(m.K) (dry) 0.11 - 0.15 W/(m.K) (moist) 0.2 W/(m.K) (saturated)

The voids percentage as a function of median particle size for each fraction range is presented in Figure 3. It can be observed that the variation of the voids percentage in a compacted FGA cylinder depends on the particle size according to the method LC 21-060. Compared to a void percentage of 41 % for the initial FGA sample, the voids content can vary between 38 and 44 % depending on the particle size ranges. This interval is an interesting opportunity to study the variation of the thermal and mechanical characteristics of FGAs with respect to grain-size distribution properties.

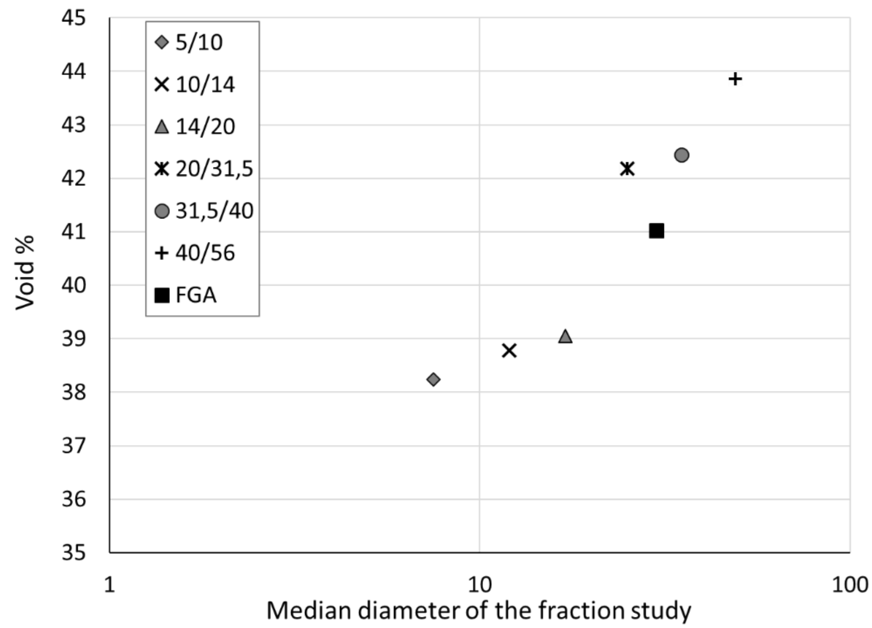


Figure 3 : Void percentage with respect to particle size range of compacted FGAs (minimal diameter / maximal diameter) [LC 21-060].

Initial water absorption is presented in Figure 4. The water absorption is determined by the ratio of the water absorbed by the material relative to the dry mass. It can be observed that there was a fast absorption of water of up to 55 % during the first 30 minutes. After 24h, it reaches a value of 57 %, which represents 85 % of the maximum absorption value. Indeed, the test was carried out for 4 weeks reaching a limit value of 67 %. This absorption value appears significant, but this measurement is strongly influenced by the low density of FGA (300 kg/m^3).
The absorption results show a significant standard deviation (up to 9 %). The important variability between the three tested samples can be explained by the FGA's complex surface, which may decrease the test repeatability.

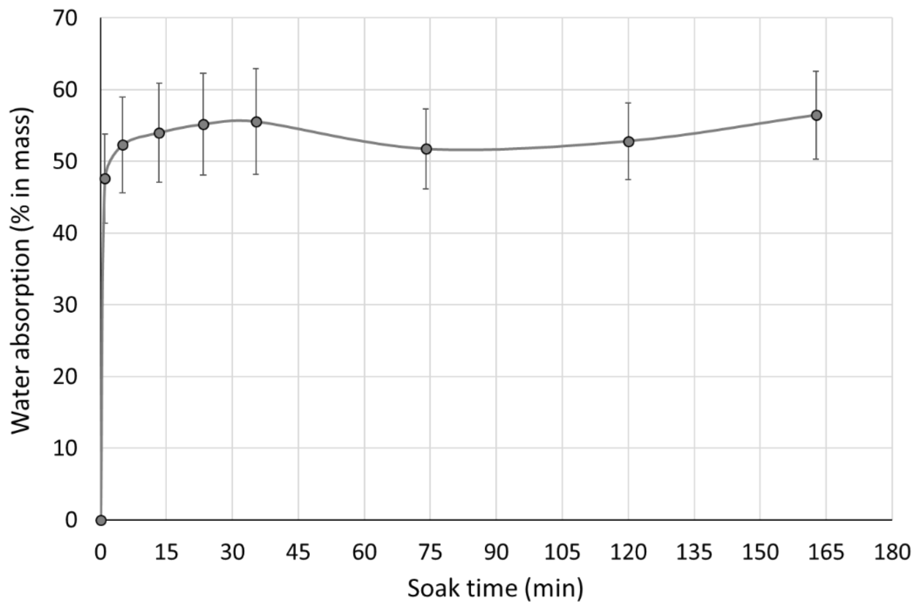


Figure 4 : FGA's water absorption as a function of time.

Results on experimental road site

Sites description

The results of ongoing field monitoring on an experimental site are presented in this section. FGAs were selected for this application as an insulation material within a flexible pavement structure subjected to heavy vehicle traffic. The experimental site is located in Kingsey Falls, Quebec. In this region of Centre-du-Québec, there is a cold climate with several months of freezing temperatures and significant precipitations are encountered even in the driest months. The average annual temperature is about 5.3°C and the annual cumulative precipitations are equivalent to about 1017 mm of water.

The test site is composed of three different sections build on a frost sensitive silty subgrade soil. Two sections of 15 m in length were insulated: the first one using a 150 mm layer of FGAs and the second one using 50 mm of extruded polystyrene panels. The third section (41 m in length) found on the site is a standard pavement used as the reference section where no insulation was used. The test section profiles are presented in Figure 5. The figure describes: the composition and thickness (in mm) of the layers, as well as the position of the temperature sensors.

For the three experimental sections, the excavation depth and the asphalt thickness were the same. The aggregates MG20 and MG112 used as base and subbase materials comply with the size and quality requirements defined in the standard NQ 2560-114/2002.

Each section was designed in such a way to limit frost heave (a maximum of 60 mm was imposed for the control section) using the frost protection design methods recommended by the Ministry of Transportation of Quebec [Savard, 2003]. The two insulation layers were placed at the same depth, but at different thicknesses. The layer of FGA was multiplied by a factor of three, as recommended by the manufacturer, in order to obtain an insulation protection equivalent to that of the XPS layer. A geotextile was placed on both sides of the FGA layer to avoid a contamination of fine soil particles. In order to test several densification techniques, half of the FGA layer was compacted with a steamroller and the other with a caterpillar backhoe. The temperature sensors were positioned in the middle of each section, near

the interface of each layer. These sensors were set to take hourly measurements of the temperature profile within the pavement structures. An overview of the construction site is presented in Figure 6.
In order to compare the performance of the three test sections, the surface profile is monitored with surveys nails installed in the asphalt concrete at the road centre line to quantify frost heave and spring settlements.

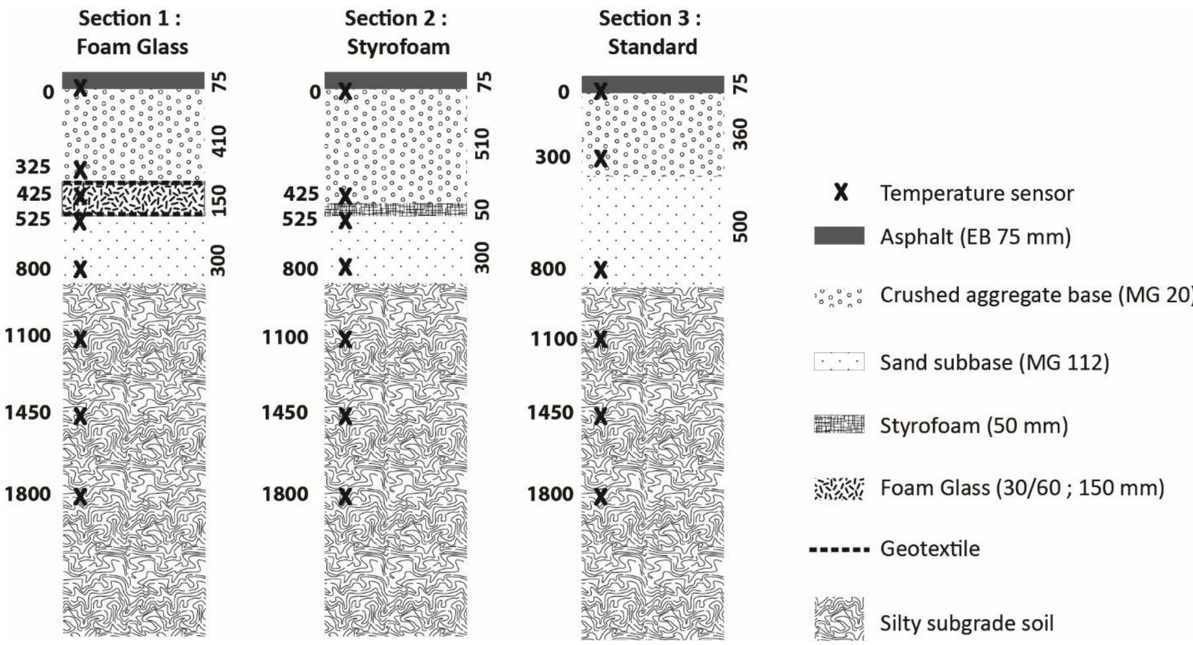


Figure 5 : Description of each test section (layer composition and thickness and temperature sensor position - dimensions in mm).

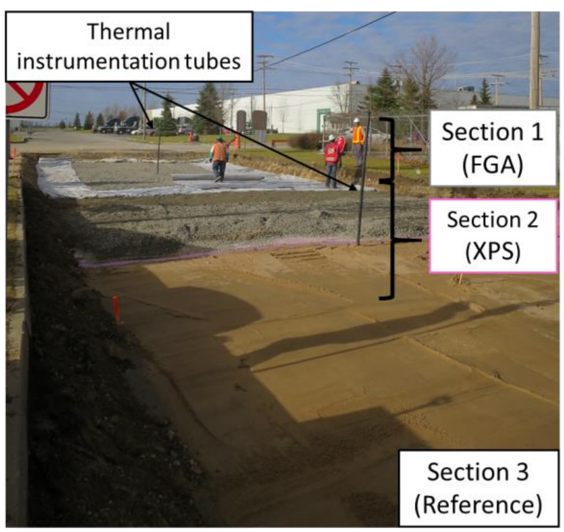


Figure 6 : Construction site overview.

Setting up

As per the manufacturer's recommendations, a geotextile has been installed over and under the FGA layer and a compaction rate of 20 % was targeted. Three compaction technics were tested on section 1 in order to compact the FGA layer:

- The left half of FGAs has been distributed with the caterpillar backhoe and then compacted with a steamroller (about 60 kPa of contact pressure). The final surface was smooth but process caused FGA fragmentation and targeted compaction was not easily obtained.
- The right half has been distributed with the caterpillar backhoe and then compacted with the caterpillar. The 20 % of compaction was more easily achieved.
- The middle area around the thermal instrumentation tube was easily compacted with a vibrating plate (about 50 kPa of contact pressure).

Placing the FGA layer in section 1 was easy and quick despite testing several different methods.

Swelling and hoarfrost

The frost heave that occurred in the three sections during the first winter is presented in Figure 7 (the continuous black line represent the initial state measured on 4th December 2015). It can be observed that the two insulated sections had quite an equal maximum frost heave on March 10th (mean value for the section) of about 15 mm. The reference section, however, shows a slightly higher average frost heave value of about 20 mm. The winter 2015/2016 was exceptionally mild, but the observed surface heave shows that the pavement design was appropriate.
In the morning of December 4th 2015, hoarfrost was observed on both insulated sections (FGA and XPS), but not on the reference section. This fall surface-icing episode shows that the insulating properties of the FGA layer (150 mm) and XPS layer (50 mm) are similar and comparable.

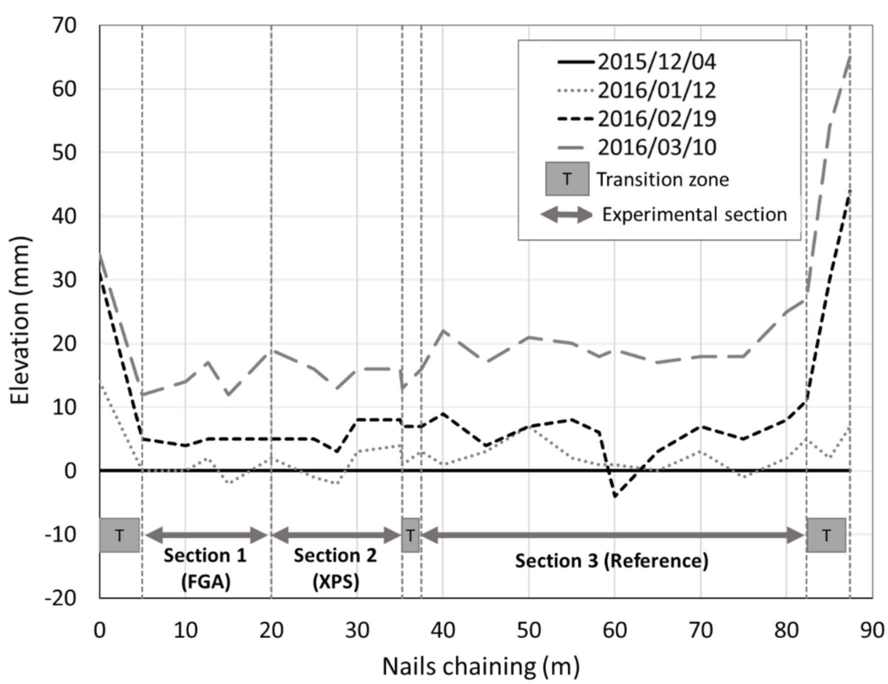


Figure 7 : Elevation (mm) of the road at the Kingsey Falls test site

Temperature profiles

The evolution of the temperature within the insulated sections at an equal depth (FGA and XPS at – 525 mm) is presented in Figure 8. A similar thermal regime is observed for the two insulating materials with an average temperature difference of 0.7°C. The maximum temperature difference (2.2°C) between the two insulated sections occurred in the night of December 2-3th, the eve of the early hoarfrost episode observed on both sections. A comparison with the reference section (where the sensor is placed deeper, at -800 mm) shows the efficiency of the two insulating materials.

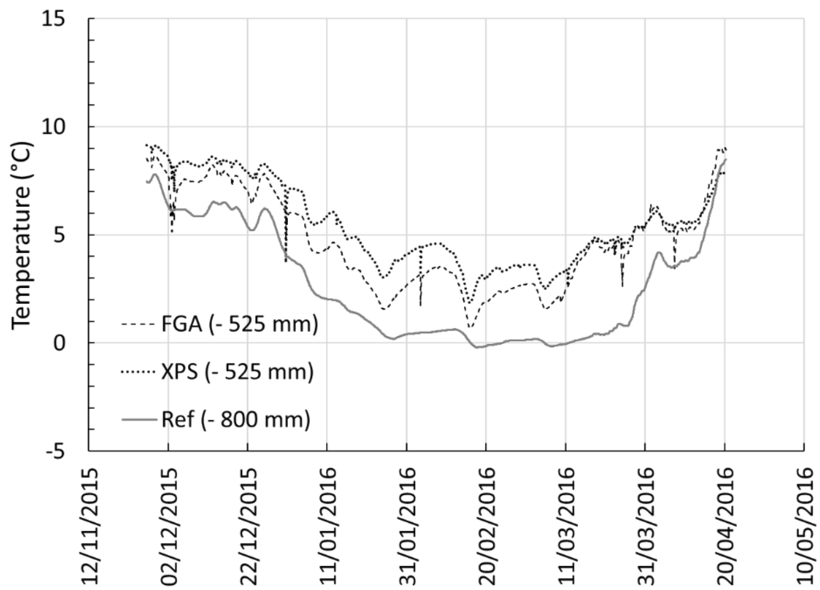


Figure 8 : Temperature under the insulating layers.

The temperature profiles for the three sections at the end of the winter, March 20th 2016, are showed in Figure 9. It is observed that the two insulating layers maintain a positive temperature in the subbase layer. Whereas, in the reference section, the frost penetrated the subbase layer but the used aggregate (MG 20 and MG 112) layer thickness helped to maintain a positive temperature in the subgrade soil. The use of insulating materials made it possible to maintain a significantly higher subgrade temperature (about 4 °C) in comparison with the reference section.

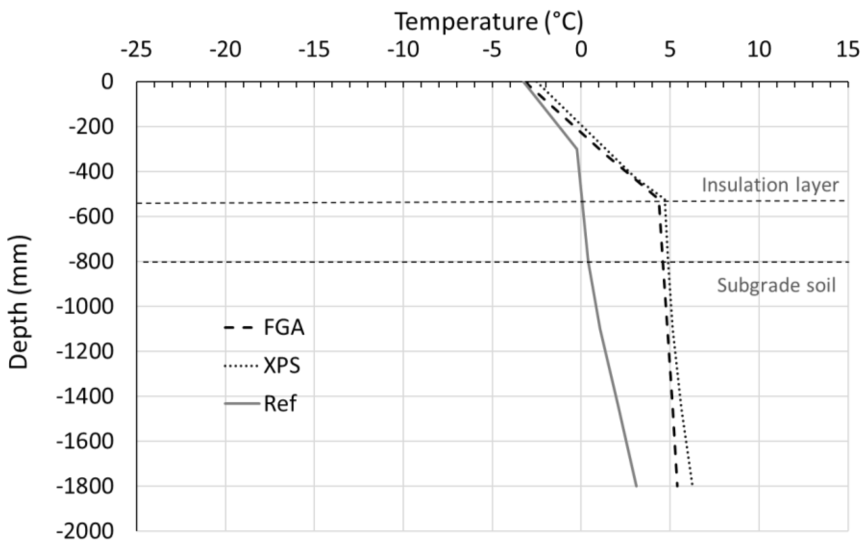


Figure 9 : Temperature profile on March 20th 2016.

Conclusion

Cold climate and soft soil conditions are challenging for the design of performing and durable pavement structures in northern environments. The use of an insulation layer in pavement structures is an efficient solution to increase the durability when significant frost damage is expected. In the meantime, the large amount of waste glass in Canada is a major rising concern. Foam glass aggregates are a promising recycled glass product that could resolve both issues. The results of this study show that:

- FGAs are a lightweight material with a potentially interesting drainage capacity;
- Since FGAs are lightweight, they propose an interesting product for soft soil applications;
- The particular structure and properties of the FGA requires careful handling to limit crushing, however the field test conducted shows that the material can be densified in place using traditional techniques;
- The first data analyzed based on site observations of hoarfrost, frost heave and temperature profiles show that the use of an FGA layer is efficient for pavement insulation applications, with a performance comparable to that of XPS boards;
- The granular structure of FGA, compared to the structure of extruded polystyrene panels, facilitated on-site handling;
- Composed of glass, FGAs could be used in various situations without degradation risks even in the case of acidic or basic leaching or in the most common chemicals products that can be encountered in the pavement environment.

Technical specifications need to be defined to promote the use of FGAs in Canada and to be included in the design methods of flexible pavements in cold regions. In order to propose these technical specifications, more laboratory and fields test are needed.

4. References

Aabøe, R., Øiseth, E. et Hagglund, J. 2005. "Granulated Foamed Glass for Civil Engineering Applications." In *2005 Workshop NR2 - Recycled Materials in Road & Airfield*. Oslo, Norway.

Attila, Y., Güden, M., et Taşdemirci, A. 2013. "Foam glass processing using a polishing glass powder residue." *Ceramics International*. 39(5): 5869–5877.

Auvinen, T., Pekkala, J., et Forsman, J. 2013. "Covering the higway E12 in the centre of ämeenlinna - Innovative use of foamed glass as light weight material of approach embankment." In *the XXVIII International Baltic Road Conference*. Vilnius, Lithuania.

Bernardo, E., Cedro, R., Florean, M. et Hreglich, S. 2007. "Reutilization and stabilization of wastes by the production of glass foams." *Ceramics International.* 33(6): 963–968.

Bilodeau, JP., Doré, G., et Pierre P. 2008. "Gradation influence on frost susceptibility of base granular materials." *International Journal of Pavement Engineering.* 9 (6): 397–411.

Bilodeau, JP., Doré, G., Drolet, FP. et Chaumont, D. 2016. "Correction of air freezing index for pavement frost protection design to consider future climate changes." *Canadian Journal of Civil Engineering*. 43: 312–319.

Binhussain, MA., Marangoni, M., Bernardo, E. et Colombo, P. 2014. "Sintered and glazed glass-ceramics from natural and waste raw materials". *Ceramics International*. 40(2): 3543–3551.

CAN/BNQ 2560–040. 2002. "Granulats — Analyse granulométrique par tamisage". *Canadian Standards Association and Bureau de normalisation du Québec*.

Doré. G. et Zubeck, HK. (ASCE Press). 2009. "Cold Regions Pavement Engineering". pp 416.

Emersleben, A. et Meyer, N. 2012. "The use of recycled glass for the construction of pavements". In *2012 GeoCongress ASCE*. Oakland, USA.

EN 13055-2 (Afnor). 2004. "Lightweight aggregates - Part 2: Lightweight aggregates for bituminous mixtures and surface treatments and for unbound and bound applications".

European organisation for technical assessment (EOTA). 2005. "European technical approuval, ETA 05/0187".

European organisation for technical assessment (EOTA). 2013. "European technical approuval, ETA 13/0549".

Frydenlund, T. E. et Aabøe, R. 2002. "Use of waste materials for lightweight fills". In 2002 *International Workshop on Lightweight Geomaterials.* Tokyo, Japan.

Frydenlund, E. et Aabøe, R. 2003. "Foamglass – a New Vision in Road Construction." In *2003 Proceedings of the 22nd PIARC – C12 technical committee on earthworks, drainage and subgrade*. Durban, South Africa.

Gagné, L. (*Recyc-Québec*). 2010. “Glass, information sheet” (in french). [Viewed 1 april 2016.] https://www.recyc-quebec.gouv.qc.ca/citoyens/mieux-recuperer/quoi-faire-avec-chaque-matiere

Marangoni, M., Secco, M., Parisatto, M., Artioli, G., Bernardo, E., Colombo, P., Altlasi, H., M. Binmajed, M. et Binhussain, M. 2014. “Cellular glass–ceramics from a self foaming mixture of glass and basalt scoria”. *Journal of Non-Crystalline Solids*. *403*: 38–46.

Ministère des Transports du Québec. 2004. “LC 21-060. Granulats - Détermination de la masse volumique et du pourcentage de vide” (in french). *Procédure du laboratoire des chaussées*.

Ministère des Transports du Québec. 2004. “LC 21-067. Granulats - Détermination de la densité et de l'absorption du gros granulat” (in french). *Procédure du laboratoire des chaussées*.

Ministère des Transports du Québec. 2014. “Dossier dégel. La protection du réseau routier : une priorité”.1-33. www.mtq.gouv.qc.ca.

Misapor, 2016. [Viewed 10 april 2016.] http://www.misapor.ch/EN/Movie.html

NQ 2560-114. 2002. “NQ 2560-114/2002. Travaux de génie civil – Granulats.” (in french). *Bureau de normalisation du Québec*.

Øiseth, E., Aabøe. R. et Hoff. I. “Field test comparing frost insulation materials in road construction.” In *2006 Proceedings Cold Regions Engineering – Current practices in cold region engineering*. Orono, USA.

Øiseth, E. et Refsdal, G. “Lightweight Aggregates as Frost Insulation in Roads – Design Chart.” In *2006 Proceedings Cold Regions Engineering – Current practices in cold region engineering*. Orono, USA.

Pittsburgh Corning. 2014. “FOAMGLAS® L’isolant thermique en verre cellulaire pour l’enveloppe du bâtiment. Guide des Solutions”. (in french). [Viewed 20 october 2015.] http://fr.foamglas.com/__/frontend/handler/document.php?id=796&type

Ritola, J. et Vares, S. (Prima Oy). 2008. “Recycling of waste glass in foam glass production” (in finnish). Espoo 2008. VTT Tiedotteita – Research Notes 2458. pp. 51.

Savard, Y. 2003. “Prise en compte du givrage dans la conception des chaussées comprenant un isolant thermique”. *INFO DLC, Direction du laboratoire des chaussées, Bulletin d’information technique*. 8(12).

Shutov, AI., Yashurkaeva LI., Alekseev, SV. et Yashurkaev TV. 2007. “Study of the structure of foam glass with different characteristics”. *Glass and Ceramics*. *64* (9): 297–299.

Volland, S., et Vereshchagin, V. 2012. “Cellular glass ceramic materials on the basis of zeolitic rock”. *Construction and Building Materials.* 36: 940–946.

Welter, M. 2012. “Economical and environmentally insulation with cellular glass” (in deutch). [Viewed 20 october 2015.] http://www.foamglas.com

Zegowitz, A. 2010. “Cellular Glass Aggregate Serving as Thermal Insulation and a Drainage Layer.” In *Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference*. Florida, USA.