Assessment of mechanical and thermal properties of foam glass aggregates for use in pavements

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ABSTRACT

In cold regions, frost heave and bearing capacity loss during spring, induced by seasonal temperature variations, lead to several types of damages on the road networks. The use of FGAs as thermal insulation layer in flexible pavement structures contributes to increase in durability of the pavement and decrease in maintenance and rehabilitation costs. In this technique, FGAs control and limit frost penetration in the frost sensitive subgrade soil which help to decrease freezing and thawing impacts responsible for the bearing capacity loss on the roads and highways. In Quebec and Canada, extruded polystyrene (XPS) is widely used as the only standardized insulating material for pavement insulation. However, application of FGAs presents a double benefit, including environmental advantage by recycling waste glass as well as technical advantage by providing a lightweight, insulating and draining layer to strengthen the roads and highways against permafrost phenomenon. In the present research work, experimental studies including full-scale laboratory and field tests have been conducted to assess the physical, mechanical and thermal characteristics of FGAs when used as a lightweight insulating layer. The same experiments have been carried out on the structures containing natural aggregates and XPS panels as the two reference tests. The results demonstrated that FGAs have the potential of being used as a trusted insulating layer and can be considered as a suitable substitute for the XPS panels. Moreover, in this study a conceptual design chart has been proposed for Québec region illustrating FGA thickness with respect to frost depth. To develop this design chart, the software “Chaussée2” was utilized to conduct the simulations. The simulation results have been then calibrated using the field data obtained from three consecutive winters between 2015 to 2018.

KEYWORDS: Extruded polystyrene (XPS), Foam glass aggregates (FGA), frost penetration, mechanical stiffness, thermal conductivity, thermal insulation.

INTRODUCTION

Road construction is considered as one of the most expensive and time-consuming civil engineering projects. Hence, these kinds of infrastructures must be built with a long design life expectancy which requires innovative designs with advanced materials. Improvement in quality of design and materials use in construction of roads and highways leads to decrease the need for rehabilitation or reconstruction as well as considerable reduction in costs of road maintenance.

The importance of using novel insulating materials to reach properly insulated road structures is more highlighted in cold regions like Canada, where some challenges of pavement design are associated with protection against frost action, as well as to mitigate excessive settlements and permafrost degradation due to the presence of soft and frost sensitive soils, high yearly precipitation, and numerous freezing and thawing cycles.

To prevent frost action, unlike traditional pavement designs, it is clearly advised to increase the pavement thickness to dimensions more than 1 meter to ensure adequate protection (Doré and Zubeck, 2009). To reduce the construction costs reduction of excavation depth and granular material quantity is required. To achieve this goal, use of proper insulation materials may offers an economical and technical solution (Bilodeau et al., 2016). Insulating layer retains heat in pavement structures and limits the frost penetration in 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. Despite few technical downsides of extruded (XPS) and expanded (EPS) polystyrene panels or blocks, such as their chemical composition, which may lead to the partial or total loss of frost protection, they are widely used for pavement insulation as the only standardized insulating material in the province of Québec and in Canada. Nowadays, alternative insulation materials such as Foam Glass

Aggregates (FGAs) are available. FGAs are produced from various glass residues with about 2% of foaming agent. When baked at high temperatures, glass and foaming agent react together resulting in a lightweight and insulating material characterized by unconnected millimetric and micrometric alveoli.

Currently, in many European countries, FGAs are used successfully to protect road and building foundation, pipe insulation and light embankment (Emersleben and Meyer, 2012). As mentioned previously production of FGAs presents a double advantage. This type of materials has a great potential to help the recycling industry to face the challenges associated with the valorisation of glass, as 90,000 tons of glass are dumped or buried every year in Québec (Gagné, 2010). In addition, it can respond to the increasing demand for lightweight, insulating and draining materials for various civil engineering applications.

A cooperative research project was initiated in Quebec to optimize the characteristics of this material. Laboratory tests were performed to document the physical, mechanical and thermal properties of FGA. To perform a full-scale laboratory experiment, an indoor heavy vehicle simulator was setup to study the performance of a pavement structure insulated with FGAs. Test sections were also built to monitor the long-term thermal and mechanical response of pavement structures with FGAs in comparison with sections built with polystyrene panels or sections without insulation. Moreover, results collected from two field experiments conducted in “Bergemont” avenue in Quebec City, and “Kingsey Falls” located in Quebec province have been presented in this paper. Therefore, this study presents a summary of the main findings regarding the most relevant engineering parameters and observations that were obtained from the laboratory tests and field trials.

Foam Glass Aggregates (FGAs)

Foam glass is generally composed of 98% recycled waste glass of various origins and 2% of foaming agent.

Civil engineering applications of FGAs

Foam glass aggregates have the potential of being used in a variety of civil engineering applications including underground piping jackets (Fig. 1), tank and vessel insulation covers, basement walls, foundations (Fig. 2), floors and roofs, terrace and garden covers, rooftops and parking areas as well as many application in city infrastructure construction such as parks and yard areas, pedestrian and bicycle paths, railway embankments, sports fields and etc. (Ayadi et al., 2010; Yousefi et al., 2016).

Fig. 1 Pipeline construction project, Lustenau, Austria, September 2008
Source: GEOCELL® foam glass gravel

Fig. 2 Building insulation below floor slab: sub-base insulation with foam glass gravel
Source: GEOCELL® foam glass gravel

Physical properties of FGA materials tested in this study

The FGA materials used in this study were imported from Europe (Austria, Scandinavia, Switzerland, Italy, etc.). The preliminary characterization tests were carried out to document their performance and compatibility with the Canadian climate atmosphere. The main physical properties of FGAs obtained from laboratory tests carried out at the Université Laval laboratory and Cascades R & D center, with respect to Québec standards, are summarized in Table 1.

Table 1. Main physical properties of FGAs vs. XPS and natural aggregates (Limestone, Granite, Gneiss)

	Tested FGA	*Value proposed in technical literature**
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 of a granular	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)
Friction angle	-	36- 45°
Thermal conductivity (k-value):	0.06 W/(m.K) (dry)	0.04 - 0.1 W/(m.K) (dry)
- single aggregate	0.09 W/(m.K) (moist)	0.11 - 0.15 W/(m.K) (moist)
- compacted aggregate in mold	0.15 W/(m.K) (dry)	-
	0.25 W/(m.K) (moist)	-

**(Auvinen et al., 2013; EOTA 05/0187, 2005; EOTA 13/0549, 2013; Øiseth et Refsdal, 2006; Zegowitz, 2010)*

Furthermore, in Table 2 the achieved results for FGAs have been compared with physical properties of the two reference materials including extruded polystyrene (XPS) and natural aggregates from various geological sources (granite, gneiss, limestone) traditionally used as base materials in road construction projects. The FGA layer and XPS panels have the same function in a roadway or an embankment.
In Québec, there are no specific standards for lightweight aggregates such as FGAs, therefore it is necessary to work in terms of equivalent volume whereas standards for conventional base granular materials express quantities in mass. Samples are compacted with a vibrating hammer.

Table 2. Main physical properties of FGAs vs. XPS and natural aggregates (Limestone, Granite, Gneiss)

		TESTED FGAS	***XPS***	***NATURAL AGGREGATE MG20***
Density	kg/m^3	300 [a]	50	≈ 2 700 [d]
Dry Density (Compacted)	kg/m^3	165 [b]	-	1 900 – 2 200 [d]
Compression Strength of A Granular	MPa	1 - 4	0.25 - 0.4 [c]	100 – 600 [d]
Thermal Conductivity (K-Value)*:	W/(m.K)			
- Single Aggregate - Dry		0.06	0.03 – 0.06 [c]	2 - 4
- Moist		0.09	-	-
- Compacted Aggregate - Dry		0.15	-	0.3 – 0.6
- Moist		0.25	-	0.3 – 2.5

(LC 21-060 [a]; LC 21-067 [b]; MTQ 14301 / ASTM D1621 [c]; NQ 2560-114 [d])

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Thermal conductivity values were measured with a KD2 Pro sensor from Decagon Devices. The needle used on single aggregate particles is a KS-1 (60 mm long and 1.2 mm wide). On molded compacted aggregates a TR-1 needle (100 mm long and 2.4 mm wide) was used.

Preliminary tests showed FGA properties indexed between those of the reference materials:

1. FGAs solid and compacted densities are approximately 10 times lower than those of natural aggregates materials and 6 times higher than those of XPS panels;
2. FGAs axial compressive strength is almost 100 times lower than that of conventional aggregates but is 4 to 15 times higher than the minimum requirements for XPS panels required by the Ministère des Transports du Québec (MTQ);
3. Thermal conductivity of a compacted FGAs sample is 3 to 5 times higher than that of XPS panels, while thermal conductivity of a foam glass particle is 10 times lower than that of conventional aggregate particles. The thermal conductivity measurements on compacted FGA assemblies vary between 0.15 W/(m.K) - watt per metre kelvin - for dry conditions and 0.25 W/(m.K) for moist conditions. In future works, large-scale tests (1 m^3) will be conducted on FGA assemblies with a heat transfer cell to validate these results.

Comparative study on three types of FGA

A comparative study has been conducted on three different types of foam glass aggregate including Silicon carbide (SiC) which is visible in ash gray color, Glycerine which is visible in dim gray color, and Manganese dioxide (MnO_2) which is visible in sienna color. (Fig. 3)

The main physical and thermal properties of SiC, Glycerine and MnO_2 have been investigated and provided in Table 3, for the ease of comparison between these three types of FGA which may lead to an adequate recommendation on selection of the best FGA type with the most optimized mechanical and insulating performances.

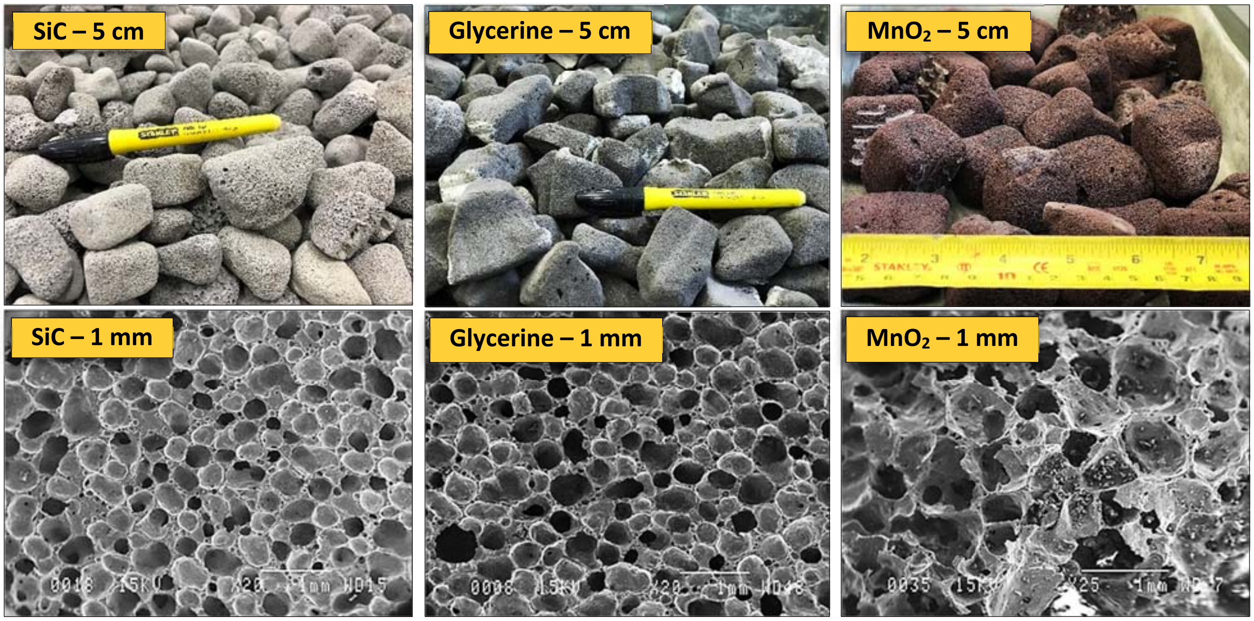

Fig. 3 FGA type SiC (left), FGA type Glycerine (middle), and FGA type MnO_2 , in 5cm and 1mm scales.

Furthermore, Fig. 4 shows the graphs of water absorption versus immersion time for the three types of FGA. As illustrated Glycerine has the minimum water absorption while MnO_2 has the maximum water absorption.

Table 3. Main physical and thermal properties of three types of FGA: SiC, Glycerine and MnO_2

	SIC	GLYCERINE	MNO2
BULK DENSITY	0,29	0,28	0,40
LOOSE MV (KG/M^3)	150	130	200
COMPACTED MV (KG/M^3)	175	147	237
ABSORPTION ($\%_M$)	38	29	130
VOID RATIO (%)	40	47	42
CONDUCTIVITY (W/(M.K))			
(DRY PARTICLES: 20°C / -10°C)	0,06 / 0,05	0,06 / 0,07	0,05 / 0,08
(WET PARTICLES: 20°C / -10°C)	0,09 / 0,10	0,11 / 0,09	0,27 / 0,36
MR (MPA) – 400 KPA	120-150	-	-
CBR	15-19	11-17	8 - 21

EXPERIEMENTAL PROGRAM

Several experimental studies have been carried out within the Quebec City and Quebec province to evaluate the insulating potential and mechanical properties of foam glass aggregates in Quebec climate atmosphere. From the mentioned experimental studies a laboratory full-scale test which has been conducted with the Université Laval heavy vehicle and climate simulator, and the two field works including the "Bergemont" project in Quebec City, and "Kingsey Falls" project located in Quebec province have been presented in this paper.

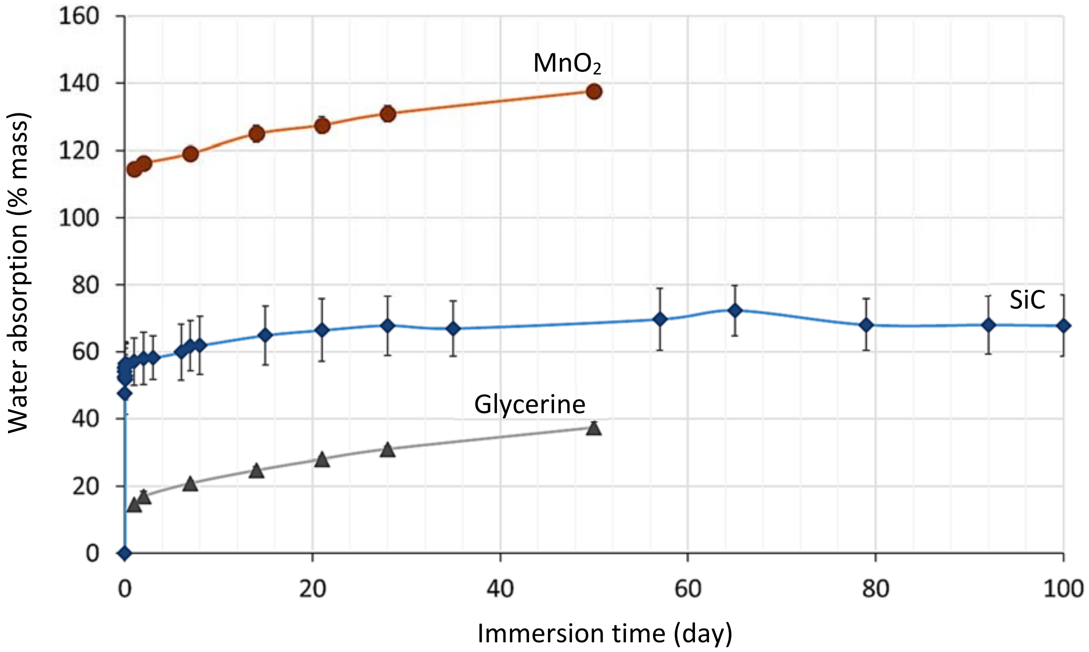

Fig. 4 Water absorption of the three types of FGA

Resilient Modulus Test

The resilient modulus M_R under repeated deviatoric load in a triaxial apparatus is measured following the standard AASHTO T307-99 for granular base and subbase materials. Three samples were tested for each particle gradation tested 20-31.5 mm and 0-31.5 mm. FGA is a non-coherent material, so some adaptions were developed to build the sample inside a 150 mm diameter and 300 mm height ± 10 mm cylindrical mold. FGA are placed in water for 24h and allowed to drain for 1 min. After compaction with a vibratory hammer (in 7 layers) in the mold, the mold is placed in a freezer for 24h. The sample is wrapped with a woven plastic fabric to protect the membrane. Finally, the sample is placed in the press chamber and thawed for 24h before the test. The stress dependency of M_R can be expressed as a function of the sum of the principal stress θ(kPa) using a model referred to k – θ as which is defined (Equation 1):

$$M_R\ (\text{MPa}) = k_1\, \theta^{k2} \qquad [1]$$

With k1 and k2 are material specific regression coefficients.

Laboratory Full-Scale Test

To perform this test an experimental pit section with dimensions of 2 m × 6 m × 2 m (depth of 2 m), located in an indoor facility at Université Laval excavated and then a pavement structure was built up (Fig. 5). At the bottom of the pit, the temperature and the groundwater level were controlled. The Université Laval heavy vehicle and climate simulator were used to quantify the insulating and mechanical behavior of a structure subjected to representative traffic and environmental conditions. The half axle has a dual tire assembly and can be loaded between 1 ton and 10 tonnes (i.e. twice the legal load on a single half-axle in Québec).

Fig. 5 Laboratory Full-Scale Test

Also, insulation panels are installed around the simulator to help the heating/cooling system stabilize the test pavement surface temperature, which can be set between –15°C and 30°C.

The pavement structure tested consists of a 100 mm asphalt concrete layer, a 200 mm unbound granular base layer, a 200 mm FGA layer and a 250 mm subbase layer underlain by a 1 100 mm silty subgrade soil. Detailed information about the pavement structure and the sensors used are shown in Fig. 6.

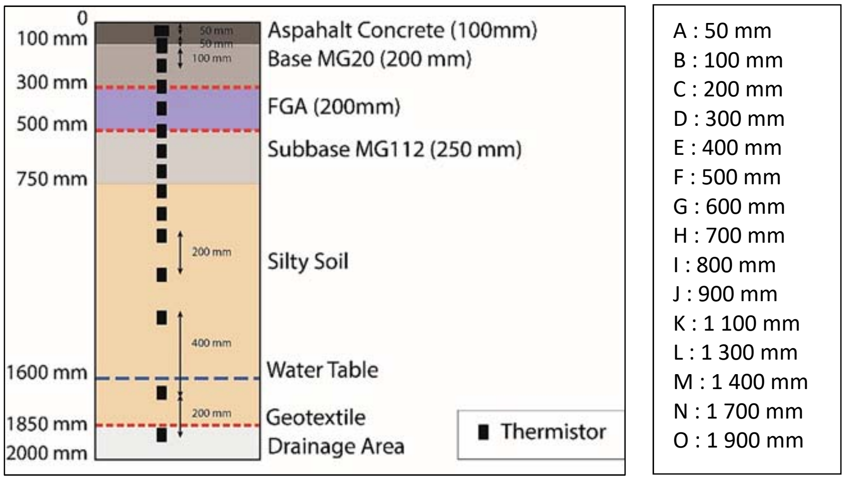

Fig. 6 Pavement structure and sensors instrumentation

Experimental pavement in Laboratory Pit and Heavy Simulator

When positioned above the experimental test pit, a loading carriage with dual tires assembly is used to simulate real traffic loading (raised on the picture near the rear dolly). The detailed information about the pavement structure and the sensors used are shown in Fig. 7. The half axle carriage was loaded between 2 000 kg and 6 000 kg for a total of 230 000 passes corresponding to a total of 502 000 ESAL (Equivalent Single Axle Load).

The Multi-Depth Deflectometer (MDD) is a multiple LVDT (Linear Variable Differential Transformer) deflection-measuring device installed during the pavement construction. The MDD is composed of three concentric pipes attached to plates placed at depths of 300, 500, 750 and 2000 mm. Close to the surface, each pipe end is connected to a LVDT. The MDD can measure either the elastic or plastic deflection under moving wheel, as well as the accumulation of permanent deformation of each layer in the pavement system.

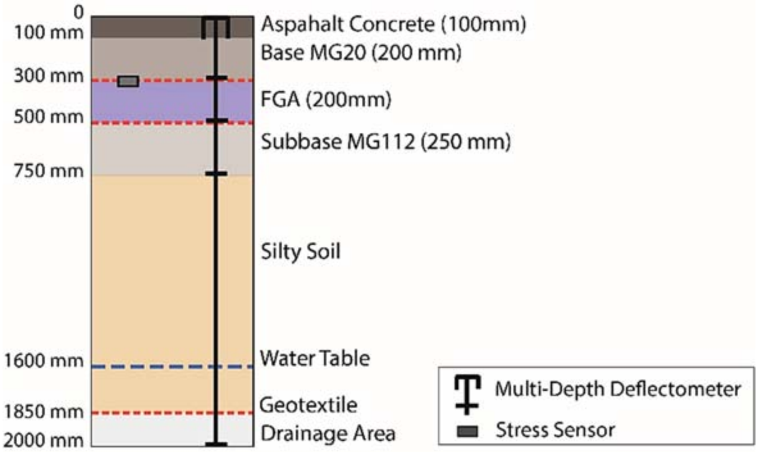

Fig. 7 Pavement structure and sensors instrumentation

Field Experiments (Road Sites)

As mentioned previously, two field works including Bergemont and Kingsey Falls presented in this paper.

Bergemont project

Bergemont project, which is located at Bergemont avenue in Quebec City, consist of three section including section A constructed using traditional aggregate materials, section B constructed using FGA materials and section C constructed using XPS panels. The two sections of A and C are considered as the reference sections and section B is considered as the test section (Figs. 8 and 9).

Fig. 8 Bergemont project consist of sections A: Ref., B: FGA, and C: XPS.

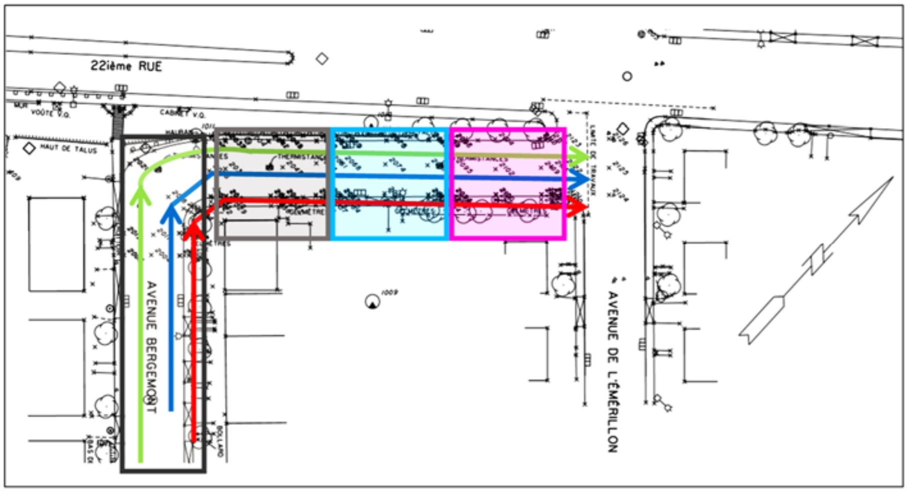

Fig. 9 Plan of Bergemont project illustrating the three sections and directions of construction

Kingsey Falls project

Ongoing field monitoring results of an experimental site are presented in this section. The experimental site is located at Kingsey Falls, Qc, in a sector subjected to considerable heavy vehicle traffic, and is built on a frost sensitive silty subgrade soil. This region has a cold climate with several months of freezing temperatures and significant precipitation. The average annual temperature is about 5.3 °C and the normal historical freezing index (FI) is 1014 °C-day, with FI defined as the accumulation of the number of degree per days below 0°C during a specific time period. The annual cumulative precipitations are on average 1017 mm of water equivalent.

For the three experimental sections, the excavation depth and the asphalt thickness are similar. The aggregate base material (MG20) and subbase (MG112) comply with requirements defined in the NQ 2560-114/2002 standard. Each section was designed to limit frost heave (a maximum of 60 mm was imposed for the control section). The two insulation layers were placed at the same depth, but have different thicknesses; the design of section 1 and 2 aimed to obtain an insulation protection equivalent following European construction principles. Three different flexible pavements sections were tested:

- section 1 was insulated with a 150 mm layer of FGAs (15 m in length);
- section 2 was insulated with a 50 mm of XPS panels (15 m in length);
- section 3 is a standard pavement structure used as a reference section without insulation (40 m in length).

The test section structures with the materials, layers thickness (in mm) and temperature sensor positions are presented in Fig. 10.

As recommended by the manufacturer (European construction principles), in order to obtain an insulation protection equivalent to that of the XPS layer, the FGA layer was made 3 times thicker than the XPS insulation layer. The FGA layer is wrapped in a geotextile to avoid contamination by fine soil particles, and is placed with a targeted compaction rate of 20 % with a caterpillar backhoe. The temperature sensors were positioned in the middle of each section, near the interface of each layer, and were set to take hourly measurements.

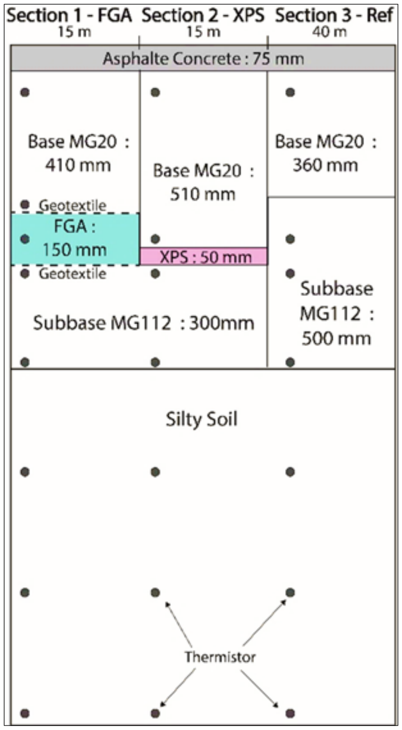

Fig. 10 General configuration, layer composition, thickness and thermistor depth and position

Experimental pavement site and falling weight deflectomer - FWD test

The location, condition and design of the field test is the same as mentioned above in Kingsey Falls section and illustrated in Fig .10.

For each experimental section, falling weight deflectometer (FWD) tests have been performed the first year (June 2016) and the third year (October 2018). The FWD tests were used at the experimental site to compare the structural response of each section and to monitor their evolution over time. The FWD is mounted on a trailer (Fig. 11). The test consists in simulating an heavy wheel load impulse with increasing load impact (28 to 70 kN) and to measure the pavement deflection basin with nine geophones. The geophone response in the center of the loading plate D_0 or D_{max} is associated with the pavement global behavior, while the geophone placed at 1500 mm from the load (D_{1500}) is associated the behavior of the subgrade. The pavement behavior is quantified based on the maximum deflections. Pavement layer moduli are estimated using back-calculation with Bakfaa software (FAA, 2013). FWD deflection basin back-calculated with Bakfaa were standardized for a load of 40 kN. The reliability of the back-calculated stiffness for each sensor was checked by the fit quality of the measured and calculated deflections (an error of 2% max is tolerated between measurement and calculation).

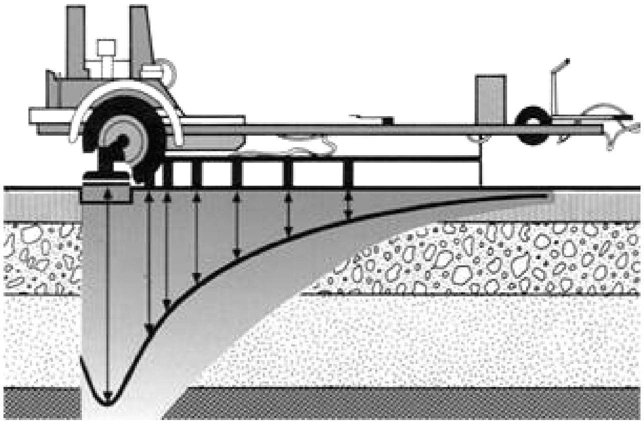

Fig. 11 Falling weight deflectometer (Deblois et al. 2010 modified from St-Laurent 1995)

RESULTS AND DISCUSSION

Results of Resilient Modulus Test – Mr.

The index properties of the FGA samples prepared by compaction for the M_R test are presented in 4.

Table 4. Compacted FGA index properties for the M_R test.

Granular size	(mm)	20 – 31.5	0 – 31.5
Dry density	ρs (kg/m^3)	201.3	202.5
Water content	(%w)	41.1	47.6
	(%v)	8.3	9.6
Porosity index	n (%)	32.9	32.5
Resilient-modulus	M_R400 (MPa)	150	120

The evolution of the M_R as a function of the total applied stresses for the two types of tested FGA samples (20-31.5 mm and 0- 31.5 mm) are presented in Fig. 12.

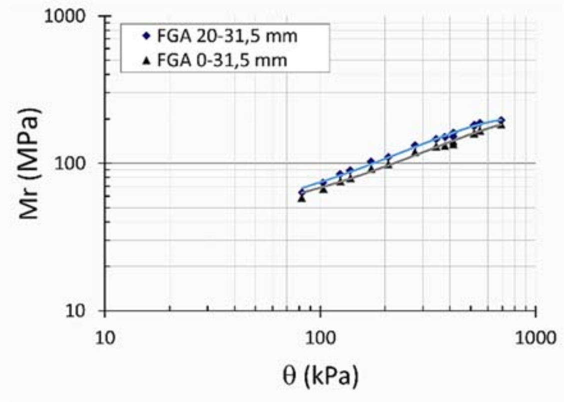

Fig. 12 Resilient modulus (M_R in MPa) as a function of the total stresses for specimens composed of aggregates between 20 - 31.5 mm and 0 - 31.5 mm.

The two types of sample show similar behavior. The 20 - 31.5 mm sample curve is above the 0 - 31.5 mm sample. This result agrees with the behavior previously observed on natural crushed granular materials and shows that the coarse fractions are beneficial for elastic properties (Bilodeau et al., 2010). For a total stress (θ) of 400 kPa (middle of the characterization range), FGA specimens have Mr_{400} values between 120 and 150 MPa as compared to a M_{R400} of 300 and 400 MPa measured for natural crushed granular materials (Bilodeau et al., 2010). At the end of the M_R tests on FGA, the gradation, especially fines content (<80 microns), did not change significantly.

Results of Laboratory Full-Scale Test

Fig13 shows the temperature profiles in the structure containing FGAs at the beginning of the freezing cycle (dotted blue curve) and for an FI of 250 ° C-day (solid blue curve). These results are compared with a reference pit set up as part of a project in collaboration with MTQ (brown curve). The corresponding pit stratigraphy is indicated on the right-hand side of Fig. 13. Both pits used the same materials and test conditions except the FGA layer.

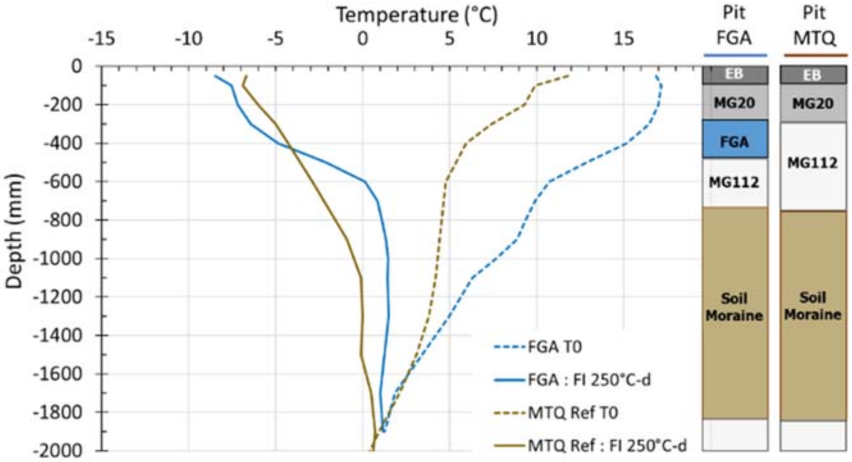

Fig. 13 Temperature profiles in structures tested at the beginning of the freeze cycle (T0) and for a freezing index of 250 ° C-day:

Temperature profiles at the end of the freezing cycle show the FGA pit was clearly affected by the presence of the insulation layer. For the same FI, the frost front of the FGA pit stopes around 600 mm (close to the bottom of the insulating layer) versus 1500 mm (close to the water table level) in the MTQ Ref pit.

Based on the pit temperature profiles for an FI equal to 250 °C-d, the effective thermal conductivity of the FGA layer (λ'FGA) is estimated to be 0.20 W/(m.K). This approach is based on several hypotheses:

- When steady state thermal regimes are reached in the two sections;
- Heat exchanges occur only by conduction;
- The heat transfer is unidimensional.

The effective thermal conductivity calculated is within the range of values measured in laboratory on compacted FGAs in dry and wet conditions (0.15 - 0.25 W/(m.K) (Table 2).

Resilient modulus measured on laboratory pavement section

As shown in Fig. 14 the resilient modulus of the FGA layer interpreted from MDD's and total stress calculated in the middle of FGA layer in the pit with WinJULEA Software (400 mm deep). It can be observed that the FGA layer submitted to a total stress (θ) varying between 100 and 300 kPa showed a resilient modulus M_R between 120 and 200 MPa.

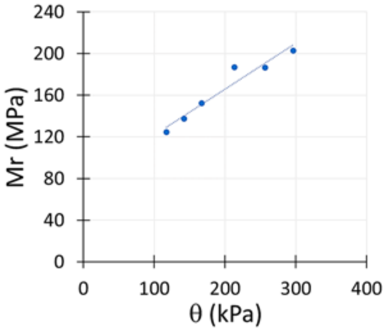

Fig. 14 Resilient modulus of FGA layer results interpreted from MDD's measures and stress calculated in the middle of FGA layer in the pit with WinJULEA Software.

Results of field projects

In this section obtained test results and observations have been presented.

Results of Bergemont project

As illustrated in Fig. 15, in reference section (A) maximum pavement swelling of about 9.8 mm occurred, while in isolated sections containing FGA and XPS (B & C) almost equivalent swellings happened.

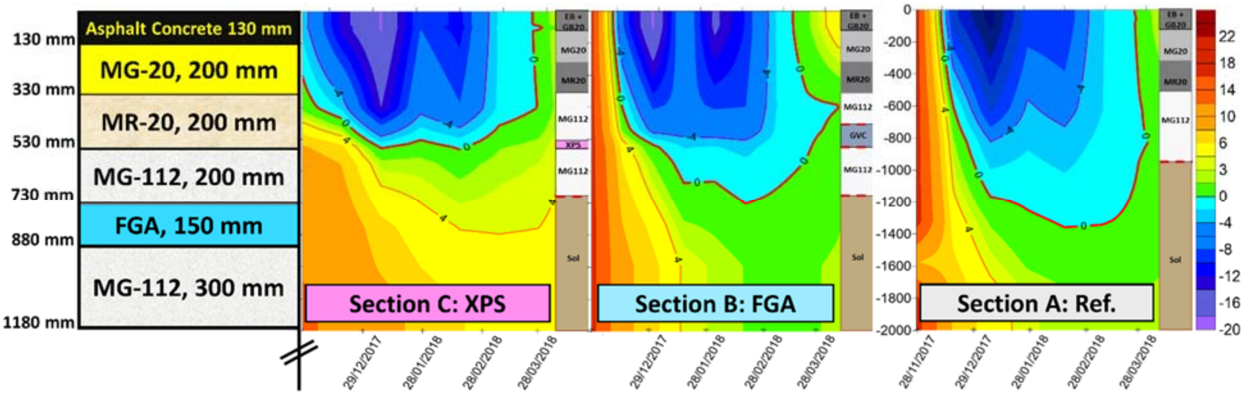

Fig.15 Illustration of pavement design, layers thickness, and frost penetration of three sections A, B & C.

Results of Kingsey Falls project

The evolution of the temperature profiles for each section between the end of the construction in November 2015 and May 2018 are presented in Fig. 16. The temperature profiles are derived from the temperature sensors. On the right side of each graph, the pavements structures are indicated. For this period, the FIs recorded are 672, 793 and 1 093 °C-d for winters 1, 2 and 3, respectively. The thermal regime of the two insulated sections are similar. In both cases, the frost front never penetrated the thermal insulation layers. In comparison, the frost front reaches the subgrade soil in the reference section during the last monitored winter (2017-2018). In addition, for the winter 2017-2018, the thaw period was nearly three weeks longer for the reference section than for the two insulated sections. Based on the observation site's temperature profiles, the use of an FGA layer is effective for pavement insulation applications, with a performance comparable to that of XPS panels.

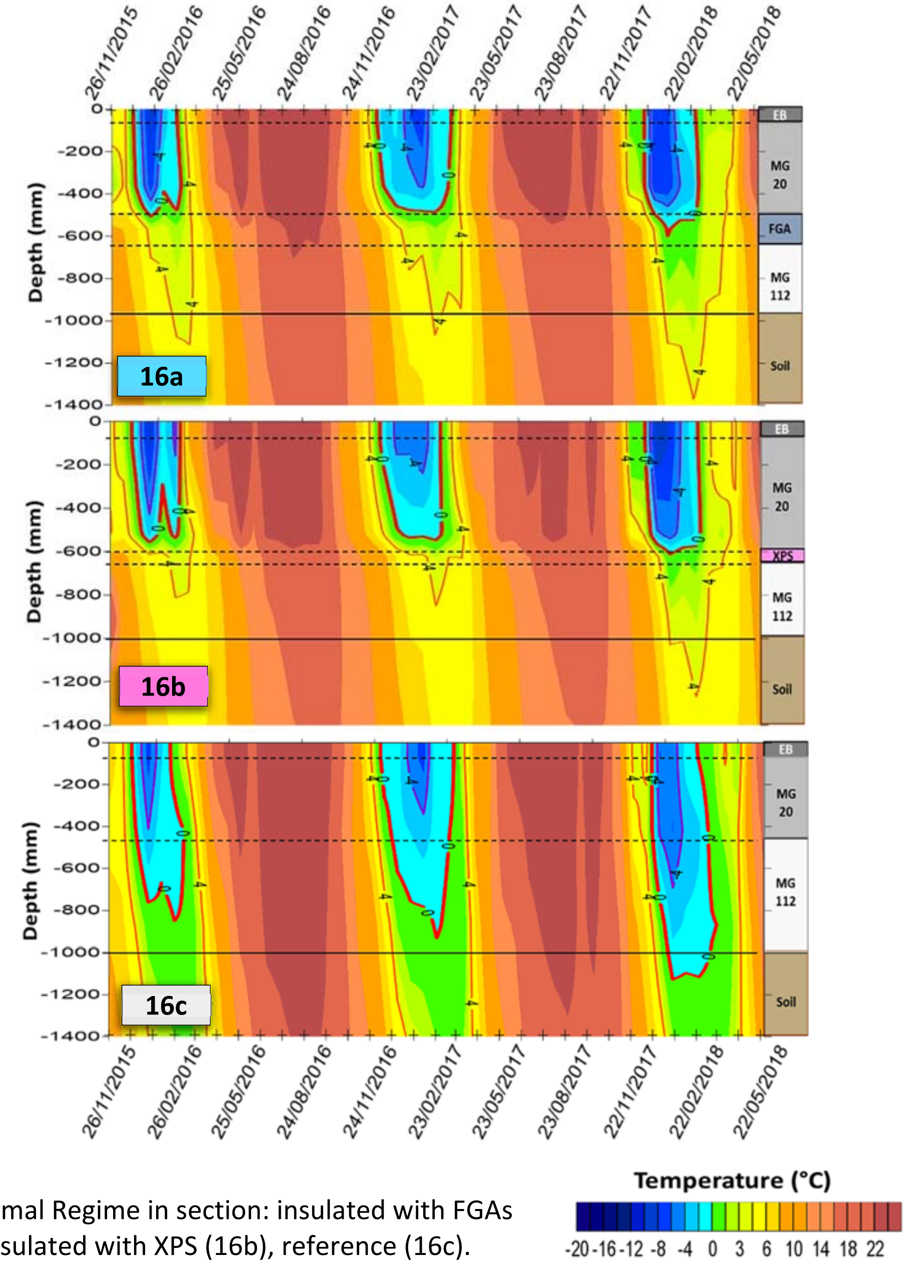

Fig. 16 Thermal Regime in section: insulated with FGAs (16a), insulated with XPS (16b), reference (16c).

Global response of experimental pavement site and modulus back-calculation

The maximum deflection D_{max} recorded is presented Fig17 and is associated with the combined global response of each pavement layer, in this case subjected to an applied load of 40 kN the first year of the structure (2016-06) and the third year and (2018-10).

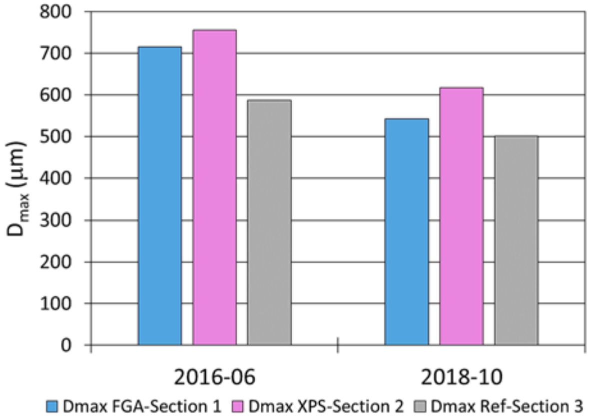

Fig.17 Maximum deflection recorded (D_{max}) for each section submit to a load of 40 kN on 2016-06 and 2018-10**.**

For all the sections, the maximum deflection under load have decreased in 2018 and imply a possible increase of all layer's modulus due to post-compaction with the time. From a deflection perspective, FGA pavement shows an intermediate response between the Reference pavement and the XPS pavement, the reference pavement being the stiffest, and the XPS's pavement is the softest. Based on pavement structure and FWD deflection basin standardized for a load of 40 kN, Modulus layer of FGA pavement measured on 2016 and 2018 are back-calculated using the software Bakfaa (FAA, 2013) and showed in Table 5.

Table 5. Back-calculated layers modulus of FGA pavement in 2016 and 2018

		EB	***MG-20***	***FGA***	***MG-112***	***Soil***
2016-06	M_R(MPa)	5268	131	55.7	21.5	186
	Poisson Ratio	0.35	0.35	0.35	0.35	0.45
2018-10	M_R (MPa)	9844	155	55	27	241
	Poisson Ratio	0.35	0.35	0.35	0.35	0.45

Back-calculated modulus from FWD measurements are an order of magnitude lower. Determination of the modulus of a relatively thin layer with a stiffness very different than the surrounding materials is difficult (Grenier, 2007). Indeed, usually the back-calculation method overestimated the M_R of the underlying layers affecting thus the modulus of the FGA layer.

The FGA M_R determined with FWD and back-calculation, is in order of 55-56 MPa for an estimated total stress (θ) included between 52 and 53 kPa (according to WinJULEA Software in the middle of FGA layer in section 1 at 560 mm deep).

Despite the difference between the several testing approach (direct measure vs back-calculation), the limitations of the back-calculation procedure and also by the different stress states, the type of set up, the degree of compaction and moisture content, a good correlation between FGA resilient modulus is found.

MODELING AND DESIGN CHART

Based on FGAs laboratory characterization, as well as thermal regimes observed in the pit and in the experimental road sites, a first conceptual design chart was developed. This design chart is presented in Fig. 18 and is valid for a specific flexible pavement structure. This first structure consisting of a 100 mm asphalt concrete layer, a 450 mm unbound base layer, an FGA layer with a thickness varying between 0 and 500 mm (a k_{FGA} equal to 0.2 W/(m.K) and a water content of 30 % was used), a 300 mm subbase layer and a silty subgrade soil.

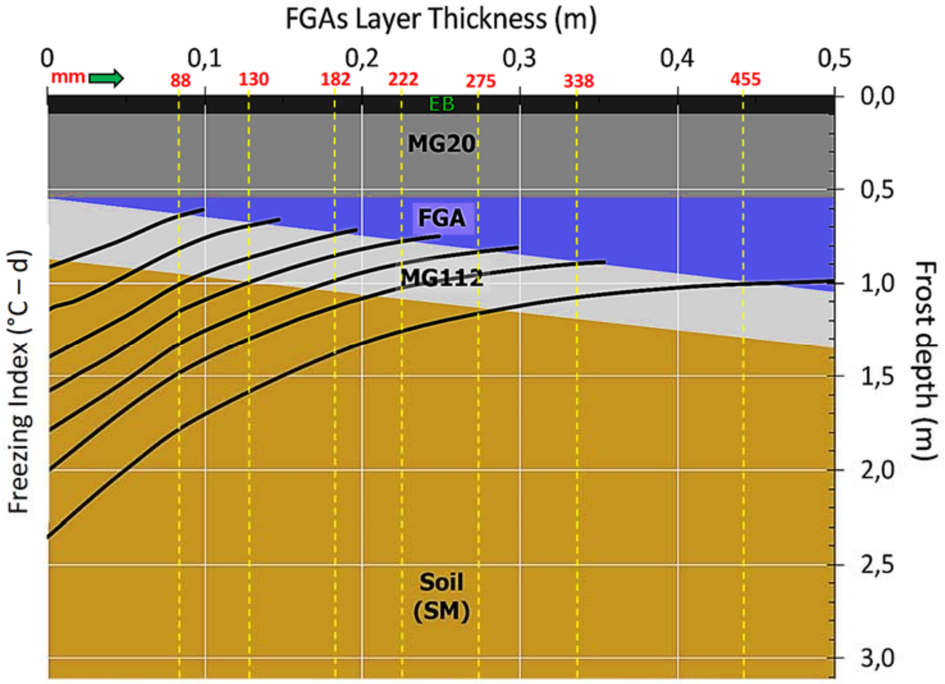

Fig. 18 Conceptual design chart: Frost front for Québec's normal with respect to the FGA layer thickness (k = 0.2 W/(m.K)).

The proposed conceptual design chart shows FGA thickness with respect to frost depth. It was developed using simulation results from the pavement design software "Chaussée2" (Saint-Laurent, 2006). Then these results were calibrated using in-situ data from the first three winters between 2015 to 2018. The frost module GEL in Chaussée2 uses historical climate data from meteorological stations; these data include the annual mean temperature, the normal freezing index, and the standard deviation on the freezing index. Several normal FIs representative of Québec regions are used, from Montreal (45.5 °N) to Chibougamau (49.9 °N). Material characteristics input in the Software are typical of Québec region according to the default value from Chaussée2. This 1D numerical simulation is limited to the study of thermal exchanges by conduction. Some improvement needs to be done to include all the total thermal exchange on FGA layer (contribution of conduction, convection and radiation in heat exchanges), and also the selection of the modeling parameters needs to be completed with mechanical parameter. Finally, further studies on various pavement structures need to be completed.

CONCLUSION

The design of durable pavement structures in northern environments and soft soil conditions is quite challenging. The use of an insulation layer in pavement structures is a growing practice and is an efficient solution to increase the durability of road network when significant frost damages are expected. In parallel, in Canada, the large amount of waste glass is a major concern. Foam glass aggregates are a promising recycled glass product that could help resolve both problems. Indeed, the granular structure of FGA, compared to the panel structure of extruded polystyrene, facilitated on-site handling and potential future rehabilitation work on the infrastructure.

The results presented demonstrate FGA technology has the potential to improve the road durability in cold climates and to provide a solution for recycling the glass residues in Québec and in the rest of Canada. FGAs may be considered as an effective alternative to XPS panels in road construction projects. This material has the potential to improve the durability of road infrastructures in a northern context due to its insulation, lightweight and draining characteristics.

- FGA behavior exhibited non-linear stress-dependent resilient modulus properties during the laboratory tests with repeated loads (triaxial and simulator);
- When used as an insulation layer, FGA have a significant mechanical stiffness under repeated loads as showed by the maximum deflection recorded (D_{max}) with FWD ;

FWD testing on three experimental pavements sites to evaluate in a comparative way the global mechanical behavior of a pavement insulated with FGA give encouraging results for the durability of such an infrastructure.

FGAs are a relatively new material in road applications with limited background information. These first laboratory and experimental test sites - laboratory and site experiments - were made following the Canadian standards and validated the European construction principles for FGAs. Nevertheless, further research needs to be done in order to improve the understanding of FGA thermal behavior for design adaptations for specific contexts (seasonal frost or permafrost). The respective contribution of conduction, convection and radiation in heat exchanges needs to be determined. In addition, pavement design principles will need to improve and integrate the mechanical characteristics of FGA layers.

In order to propose these technical specifications, more laboratory and field tests are needed and are planned as part of the research project.

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