Engineering and Environmental Assessment of Foam Glass Lightweight Aggregate for Pavement Application

by

Yassaman Yousefi

A thesis
Presented to the University of Waterloo
in fulfillment of the
Thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2019

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Foam-Glass Lightweight Aggregate (FG-LWA) is an innovative lightweight material based 95% on waste and recycled glass. Several European countries use this type of material in the pavement structure and mainly as lightweight fill material. The major advantage of the FG-LWA is being more than 10 times lighter than traditional mineral aggregates, which makes it an ideal solution in cases where the dead load of the aggregates is an issue. The objective of this thesis is to evaluate and assess the potential of using FG-LWA, as an alternative to other lightweight fill materials such as Expanded Polystyrene (EPS) Blocks, in flexible pavements structures.

Physical and mechanical properties of two commercially provided types of FG-LWA were previously studied at the CPATT laboratories of the University of Waterloo. To this end, particle size distribution, particle density, water absorption, minimum and maximum dry densities, California Bearing Ratio (CBR), Los Angles (LA) abrasion, resilient modulus, Mico-Deval and freez-thaw resistance of the material were evaluated by Schneider (2016). The results from this previously conducted study are summarized in this thesis and are used to determine whether the FG-LWA material is suitable to be employed as an alternative granular material in pavement construction, and whether it conforms to the requirements of the Ontario Provincial Standard Specification (OPSS) 1010 for granular A, M, O, S and B.

In this thesis, it was deemed necessary to further investigate the effect of changes in the manufacturing processes on the formulation and microstructure of the FG-LWA with the aim of enhancing its mechanical properties for pavement construction applications. Therefore, the manufacturing processes were modified to adjust the microstructure (e.g. shapes and sizes of the pores) and phase compositions. Furthermore, in order to produce an enhanced FG-LWA, the application of ceramic colors, other glassy raw materials and glass-ceramics with a controlled microstructure was also investigated in this thesis. Examining the microstructure of the products indicated improvements in the physical characteristics of the enhanced FG-LWA as compared to the original product containing waste glass. Incorporation of coloring oxides in the foam formulation was also examined as an innovative method to increase the mechanical strength of a colorful product. In addition, chemical evaluation was conducted based on the results of leachate test. The results were evaluated thoroughly, and further tests were conducted at the Golder & Associates laboratories, accordingly.

Given the considerable economic, environmental and societal impacts related to pavement construction and maintenance activities, it is crucial to evaluate the sustainability of the proposed pavement structure with FG-LWA. Several techniques are available to measure sustainability of a pavement structure. In this thesis, the mechanistic pavement design approach, along with a conceptual Life Cycle Assessment (LCA) model are used to evaluate the effectiveness of using FG-LWA as an alternative lightweight fill material as compared to the commonly used Expanded Polystyrene (EPS). For the purpose of mechanistic evaluation of FG-LWA application in the pavement structure, an existing Ministry of Transportation (MTO) project was re-evaluated and the results were used as the baseline of this study. The re-evaluation consisted of two phases of pavement design. Under phase one, the same pavement structure proposed by the MTO was adopted identically, except that the EPS in the original design was replaced with the same thickness of the FG-LWA material. In the second phase, four scenarios with different structural layer types and thicknesses were studied. The objective of the second phase was to find different, but equivalent, pavement structures with the use of FG-LWA, while achieving equal or smaller values than the original MTO design for the critical strains at the bottom of the asphalt layer and on top of the subgrade layer. To this end, KenPave program was used to determine the stresses and strains in the pavement layers using a multilayer elastic approach.

Finally, LCA approach was used to quantify the relative environmental impacts of using FG-LWA and EPS in the pavement structure. The SimaPro software program was used to analyze the performance of the products with respect to sustainability measures. Two flexible pavement structures, previously designed at the University of Waterloo for a specific set of traffic and climatic conditions (Schneider, 2016), were used in the LCA study. The first pavement structure, considered as the reference scenario, used Expanded Polystyrene (EPS) as lightweight fill material. In the second scenario, the EPS was replaced by FG-LWA, and thicknesses of all other layers (i.e. asphalt concrete and granular layers) were determined using the AASHTO 93 Pavement Design Approach, hence the two pavement structures could be assumed equivalent and structurally comparable. The environmental impact categories considered in the LCA studies included: Ozone depletion potential, global warming potential, acidification potential, eutrophication potential, carcinogens, noncarcinogens, smog potential, respiratory effects, ecotoxicity, and fossil fuel depletion. The impacts are calculated using the characterization factors from the TRACI 2.1 LCA model. Two methods of manufacturing foam glass are evaluated, namely using electricity versus natural gas in Ontario. Based on this comparison, it was determined that it is feasible to transfer the new foam glass technologies to Canada's road network instead of using other non-environmentally friendly materials.

The results indicate that FG-LWA can be used as a light fill material in the flexible pavement structure to achieve better or equivalent structural capacity as compared to the traditional EPS. The environmental impacts assessments also indicate lower emission level and environmental impacts when using FG-LWA instead of EPS for pavement construction.

Acknowledgements

I would like to first acknowledge and appreciate my supervisor, Professor Hassan Baaj, for giving me this opportunity to pursue my goal for graduating my MASc program at the Centre for Pavement and Transportation Technology (CPATT) and for all his patience, support and guidance through my rough journey. I would like to also appreciate my co-supervisor, Professor Susan L. Tighe for all the support and guidance she provided me with. Also, I would like to appreciate Dr. Sina Varamini and Professor James Craig for serving as members of the review committee for my thesis.

Additionally, I would like to extend my acknowledgement to Professor Goretty Dias from the School of Environment, Enterprise and Development for her help, guidance and support through the completion of the Life Cycle Assessment part of my thesis.

I would also like to personally thank many current and former CPATT members for their support and encouragement throughout my studies. In particular, I would like to thank Dr. Pezhohan Tavassoti-Kheiry, Research Associate, and my colleagues Taher Baghaee Moghaddam, Yashar Azimi Alamdary, Ata Nahidi, Hanaa al-Bayati and Mr. Daniel Pickel.

I would also like to appreciate the Foamyna Canada group, Dr. Abbas Youssefi and Dr. Ahmad Youssefi, for supporting me through my research and providing me with appropriate facilities and resources.

Dedication

This thesis is dedicated to my family – my parents, Shahla and Abdollah, and my sisters Maryam and Niloofar – without whose love and support this would never have been possible.

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Chapter 1: Introduction

1.1 Problem Statement and Research Goal

The main objective of this thesis is to propose an engineering solution to address an existing environmental concern about the abundant waste glass, and at the same time, contribute to the current practice of flexible pavement construction in Canada. In Ontario, the municipalities have been impacted by the waste management challenges related to the increasing volume of the waste glass stockpiles. According to the Statistics Canada, about 400,000 tonnes of waste glass is produced in Ontario, but only less than 30% of it is recycled. However, this waste material can offer great advantages due to its potential of being recycled multiple times. Nowadays, different types of glass-based products such as container mixed glasses, float glass, windshield glass, and contaminated CRT glass are being vigorously collected, but are poorly recycled. Therefore, in this thesis, the waste glass is evaluated as an economically feasible source of manufacturing lightweight aggregates for pavement application.

From the engineering point of view, lightweight materials have been used in pavement application mainly to either protect the pavement structure from the detrimental effects of frost penetration, or to alleviate the possible failure due to a poor subgrade soil. In the former phenomenon, which occurs during freezing cycles, the thermal insulation characteristic of a light weight fill material would be of interest, and can significantly help with protecting the pavement structure against frost heave failure. While the latter application majorly benefits from the light weight of the material, since the major issue is poor bearing capacity of the subgrade soil which requires minimizing the deadload of superstructure (i.e. pavement layers). In both phenomena, Expanded Polystyrene (EPS) blocks have been used as the solution. In other words, in the first phenomenon the EPS is used as an insulation material, and in the second phenomenon the EPS is used as a lightweight fill material. This thesis is focused on the second phenomena, aiming to investigate the possibility of using Foam Glass Lightweight Aggregates (FG-LWA) in pavement construction as a more environmentally friendly alternative product to the EPS blocks.

FG-LWA is considered as a potential alternative material for building and road construction applications. The basic components of foam glass are waste glass with a mass portion of 95%, clay or Kaolin with a mass portion of 5% and Calcium Carbonate, Graphite or Silicon Carbide (SiC) with a mass portion of 3% as the foaming agent. The end product is generally shaped differently depending on the application of interest. The available shapes on the market are aggregates, blocks and granules.

1.2 Research Scopes and Objectives

Previously, due to the lack of raw materials (mainly recycled glass) and therefore higher manufacturing cost, foam glass application was limited to underground piping and tank and vessel insulation covers. Recently, the abundance of recycled glass and advances in new technologies for the production of FG-LWA, have opened new doors for the production of a more economically feasible material. Foam Glass as a lightweight, high strength insulating material has been manufactured for many years and mainly in Europe. However, researchers, in collaboration with the industry, have been recently focusing more on improving the properties and investigating new applications for the use of this innovative material in different industries.

Flexible pavement construction is among the potential application areas for the use of FG-LWA. However, this requires modifying the original material properties and thorough examination of its suitability for pavement application from both engineering and environmental impacts perspectives. Therefore, the objective of this research is twofold. First, to investigate the engineering properties of FG-LWA and its impact on the pavement structural response from a mechanistic design point of view. Second, to evaluate the environmental impacts and the consequent life cycle costs when FG-LWA is used as an alternative to the traditionally used EPS.

1.3 Thesis Outline

The organization of this thesis is summarized as follows: Chapter 1, provides a brief introduction about the use of lightweight fill materials for pavement application. A summary of the problem that this research aims to address is presented followed by the research goal and objectives. Chapter 2 provides a review of the literature on the FG-LWA and EPS applications in construction in general, as well as the existing knowledge about their application to pavement construction. A review of the history of FG-LWA manufacturing is then provided at both national and internationally levels. Also, materials properties pertinent to the scope of this study are gathered and presented in this chapter. Chapter 3 discusses the effect of changes in the FG-LWA formulation and manufacturing processes on the physical properties and microstructure of the products. The chemical and environmental assessment of the FG-LWA product is described in Chapter 4. The results from the leachate tests are summarized and are compared to check for the compliance with the Ontario Drinking Water Standards (ODWS) and Canadian Freshwater Fisheries Water Quality guidelines (CFFWQG). Chapter 5 focuses on the effect of incorporating FG-LWA layer on flexible pavements from the mechanistic structural response point of view. An existing MTO pavement section which was built using the EPS blocks was used as the case study in this chapter. The results of replacing the EPS layer with FG-LWA materials is evaluated using KenPave program and is demonstrated in this chapter. Chapter 6 presents the Life Cycle Assessment (LCA) studies and environmental impacts evaluation for the use of FG-LWA in pavements. This chapter also compares the feasibility of using electricity and natural gas to produce foam glass in Ontario. Finally, the research findings and conclusions are summarized in Chapter 6, followed by suggested future work.

This thesis contributes to better understanding the effect of some manufacturing conditions on the microstructure of the FG-LWA, evaluating the possibility of using FG-LWA in the road construction from an environmental and chemical point of view, assessing the potential of using FG-LWA in flexible pavement structures as an alternative lightweight fill and finally examining the environmental impact of the FG-LWA use and manufacturing in Ontario. In order to compare the Environmental impact of the two materials (i.e. FG-LWA and EPS), a Life Cycle Assessment approach was used. The SimaPro software program, which is Life Cycle Assessment software, was used to collect, analyze and monitor the sustainability performance of products and services. Two flexible pavement structures, designed for a specific set of traffic and climatic conditions, are used in the LCA study. The following sections provide details of the aforementioned research efforts.

Chapter 2: Literature Review

2.1 Background

Research on designing sustainable pavements by means of using innovative and environmentally friendly materials has been gaining momentum during the last few decades. A major part of such research has been focused on the use of recyclable materials to reduce the environmental impacts due to the pavement construction and rehabilitation projects. Advancement in further incorporation of Reclaimed Asphalt Pavements (RAP) toward producing new asphalt mixtures to reduce the consumption of natural resources can be one among many relevant examples (Kowalski et al., 2016). As indicated by Celauro et al. (2010) by controlling the homogeneity of recycled materials it is possible to obtain high-performance mixtures. While currently RAP is one of the major sources of recycled materials application in pavement construction, there are other valuable sources of waste materials that can be utilized to improve the practice of flexible pavement construction. Foam Glass is such material, and hence is investigated from different perspectives in this thesis. FG-LWA can be used in both building construction: foundations, walls and roofs; and road construction; for embankments and as lightweight aggregate fill material. The main driver for foam glass application is the high-energy efficiency standards for construction industries. Recently there have been new research efforts focusing on the application of Foam Glass for road constructions due to its water permeability and drainage capacities. It has been investigated that the material could be used both as a lightweight fill and/or insulation material in pavement applications.

Despite the application of foam glass for more than 15 years in Europe (Finland, Norway, Switzerland and Germany) there has not been enough work on this material in North America and Canada. Since 1997, Norway allows the commercialization of FG-LWA produced from recycled waste glass and currently Switzerland, Germany and Italy consume 500,000 m^3 per year of FG-LWA for their civil engineering applications. In 2011, foam glass production also started in Finland (Segui P, 2016).

The severe cold climate along with the presence of wet weak soil in many areas in Canada pose a serious challenge to durability of pavement structures. Frost heave is known as one of the important causes of pavement deterioration in cold regions. Therefore, the use of a layer of thermal insulation material in pavement structures is a commonly used solution to improve durability when significant frost damage is expected. Ivanov et al. (2017) discussed that deep freezing of the soil combined by excessive humidification is the main cause for the decrease of the service life of pavement structures. Further in their research, Ivanov et al. (2017) investigated the effect of heat insulation type on the thermal gradient across the pavement layers. They also compared the results for the cases where layers of EPS and Foam glass were used in the pavement structure. Findings of Segui et al. (2016) and Ivanov et al. (2017) are consistent and indicate that the frost penetration depth in pavements can be reduced by using either EPS or FG-LWA.

2.2 Existing Research on FG-LWA

2.2.1 FG-LWA Specifications

Increasing demand for FG-LWA as lightweight fill material in civil engineering applications, such as backfills, embankments, slope stabilization and pavement construction have been reported by several researchers (Horpibulusk et al. 2014; Arulrajah, et al., 2015). More specific applications of foam glass materials for thermal insulation of building foundations, cellar plates and as backfilling for voids have also been documented by other researchers (Janetti and Bianchi, 2015; Ayadi et al., 2011).

The major component of foam glass is mixed glass and recycled glass. Other types of waste glass can also be used such as windshield, windows or Cathode Ray Tube (CRT) glasses. Research on FG-LWA production CRT glasses has been growing lately, because of the recent advancements in electronics recycling industries that provides waste glass discarded from computers and TV monitors (Mugoni et al., 2015; König et al., 2015).

FG-LWA material is available in three different shapes depending on the specific application. Table 1 presents different shapes of the material along with descriptions of their primary application. Table 2 provides the engineering properties and characteristics of the foam glass material used in this study. Comparing to EPS, FG-LWA is also available in grades with a high compressive strength. The fact that the material density is about 120 to 150 kg/m^3, and its thermal conductivity is approximately less than 0.08 W/mK makes FG-LWA and ideal option for both purposes of thermal insulation and reducing the pavement structure dead weight. Steures (2014) investigated the mechanical properties of FG-LWA through the use of different types of compression tests. He concluded that the stiffness of the material depends on the applied load, density of the material, degree of compaction and the porosity of the aggregate particles. Arulrajah et al. (2015) investigated the engineering properties of foam glass. Based on the gradation curve they suggested that the material includes gravel and sand size particles with no fines. Following the Los Angeles abrasion (LA) and California Bearing Ratio

(CBR) results they concluded that the material falls within the range of the specifications requirements for the structural embankment fill material and not suitable to be used for heavier applications such as base and subbase according to the Australians Road Authority (Arulrajah et al., 2015).

Table 1: Different shapes and descriptions of Foam Glass Lightweight material

Term	Description	Graphic
Granule	Foam glass granules are designed to incorporate into other secondary products. These can include drywall, lightweight concrete or other construction materials	
Blocks	Blocks consist of foam glass output in various shapes and characteristics to suit various applications in the construction industry. These can include lightweight non-load bearing partitions, piping and insulation	
Aggregates	Foam glass aggregate is shaped like natural stone aggregate but is manufactured from the foam glass process. It is primarily used in the construction industry applications such as backfill, road construction	

Table 2: Engineering Properties and Characteristics of Foam Glass Aggregates (Foamyna, 2014)

Properties	Value
Thermal Conductivity, dry	<0.08 [W/mK]
Thermal Conductivity, wet	0.11 [W/mK]
Design value of Compressive strength	275 [kN/m2]
Compressive strength (10% compression)	>=570[kN/m2]
Density	150 kg/m^3
Granular size	Approx 10-60 mm
Internal water absorption	0 [Vol%]

2.2.2 Production of Foam Glass

Different formulations and proportion of raw materials will result in producing foam glass aggregates with different properties. Silicon Carbide (SiC) is the most used foaming agent for the production of foam glass lightweight material. The waste glass is sorted and broken before running through a multi-stage segregation and crushing process. The pieces of glass up to 10 mm in size are then ground to ultra-fine glass powder in a ball-mill. The particle size range is between 70 and 100 microns. The foaming agent is added into a turbo mixer. The mixture of micronized glass and foaming agent (formula) is fed into the heating kiln by the means of a moving belt, and the mixture is baked at a temperature ranging between 700 and 1100 °C. The thermal regime selected, is to increase the temperature linearly at a rate of 10 °C/min up to 850 °C. Foaming zone is associated with the part of the process that happens at the temperature range of 800 °C to 1100 °C. Characteristics of the foam, and consequently the viscosity of the melted glass will vary depending on the time that it takes for the feedstock to pass through the foaming zone (Hurly, 2003). The main role of the foaming agent is to release gas as it decomposes through the production process and to create air bubbles inside the glass particles. Further details regarding the production process of FG-LWA can be found in the U.K.

market survey provided by Hurly (2003). Hurly (2003) also indicates that the glass foam panels are about 300 to 400 °C when they leave the furnace. As a result, a very swift cooling processes can induce thermal stress cracks, which cause the panels to break into grains of 3 to 5 cm. Aabøe et al. (2005) indicates that the final product of foam glass generally consists of 8% of glass by volume and 92% gas bubbles. A thin impervious glass wall encloses each bubble.

2.2.3 Case Studies on Road Construction using Foam Glass

While every single particle of FG-LWA is almost impervious, a layer composed of FG-LWA exhibits high water permeability. Therefore, due to its excellent drainage characteristics, it can reduce the potential of the pavement failures due to the presence of entrapped water in the pavement structure that can lead to frost heave under freezing and thawing cycles (Yousefi et al., 2016).

There are only a few documents available that discuss the actual placement of FG-LWA in pavement construction. Frydenlund et al. (2002) explained the placement of the foam glass material in a way that the material is delivered on site by large trucks and side tipped into slide area. The materials will then be distributed and placed in layers of 0.5 m thick by means of a 30 tonnes crawler mounted excavator and compacted by 3 to 4 passes of the crawler belts. The composition and thickness of the road pavement placed on top of the foam glass depends on the pavement design. The study by Arulrajah et al. (2015) indicated that the total energy consumption related to the use of foam glass as a construction material is close to none.

In another case study, Cascade Inc. examined three different construction alternatives through an ongoing field monitoring project and by building three different sections on a frost sensitive silty subgrade soil. According to Segui et al. (2016) the pilot sections included: 1) a section built on a 150 mm layer of FG-LWA, 2) a second section built on a 50 mm of EPS, and 3) a third section of a standard pavement which was used as the reference section where no insulation was used. The thicknesses and composition of each layer were carefully designed and the temperature sensors have been placed in the middle of each section. The evaluation of temperature on both insulating layers indicates similar thermal regime for both materials with the difference of 0.7 °C.

2.2.4 **Physical and Mechanical Properties of FG-LWA**

A few studies have recently investigated the engineering properties of foam glass through laboratory testing with the aim of characterizing the material for different building and civil engineering applications. The physical and mechanical testing of the FG-LWA materials used in this study have already been conducted as a part of another research project. The engineering assessments include particle size distribution, particle density, water absorption, minimum and maximum dry densities, California Bearing Ratio (CBR), Los Angles (LA) Abrasion test and Resilient Modulus, Mico-Deval and freezing and thawing resistance testing. Schneider (2016), a former MASc. student at the CPATT of the University of Waterloo, focused on the physical and mechanical properties of FG-LWA. This research was the first study conducted in Canada. For the purpose of this research, the Foamyna Company provided CPATT with two different samples of manufactured FG-LWA materials. Both samples were produced using similar production processes, by melting down the recycled glass, and mixing it with specific chemical additives in order to form a highly porous rigid foamed glass product with a bulk and absolute density.

Also, Arulrajah et al. (2015) investigated the engineering properties of foam glass based on the Australian standard AS 1996. Determining the particle size distribution according to the MTO standards LS-602 and the Australian standard AS 1996, the foam glass material used in this study was previously classified as gravel and coarse aggregates with no fine (Schneider 2016, Arulrajah et al. 2015). In the work by Schneider (2016), all of the material passed the 75mm sieve, with the 63mm sieve being the largest size upon which any material was retained. Arulrajah et al. (2015) reported that 66% of the gravel grain size they used was between 4.75mm and 40 mm, while 20% was retained on 60 mm sieve. For both samples in Schneider's work, less than 10% of the aggregate by mass passed through the 19.0mm sieve. As a result, he concluded that the material conforms to the OPSS 1010 requirements for Granular A, M, O, S and could be used as an innovative lightweight material in pavement application. (Schneider, 2016) Figures 1 and 2 show the gradation curve for foam glass used in Schneider (2016) and Arulrajah et al. (2015) studies.

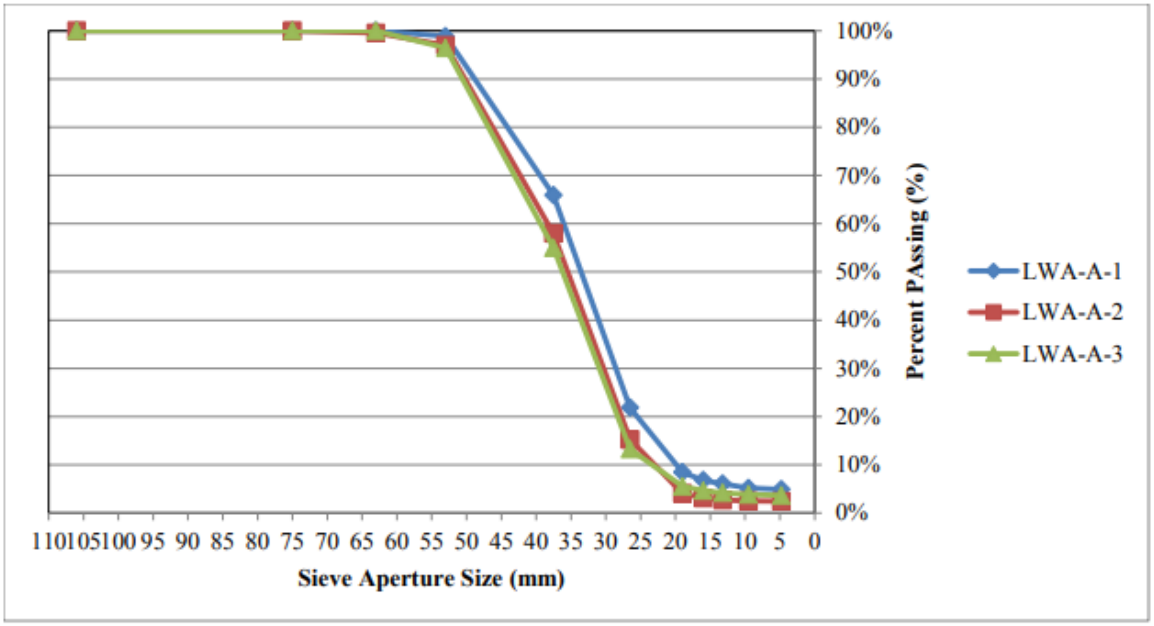


Figure 1: Gradation curve for foam glass (Schneider, 2016)

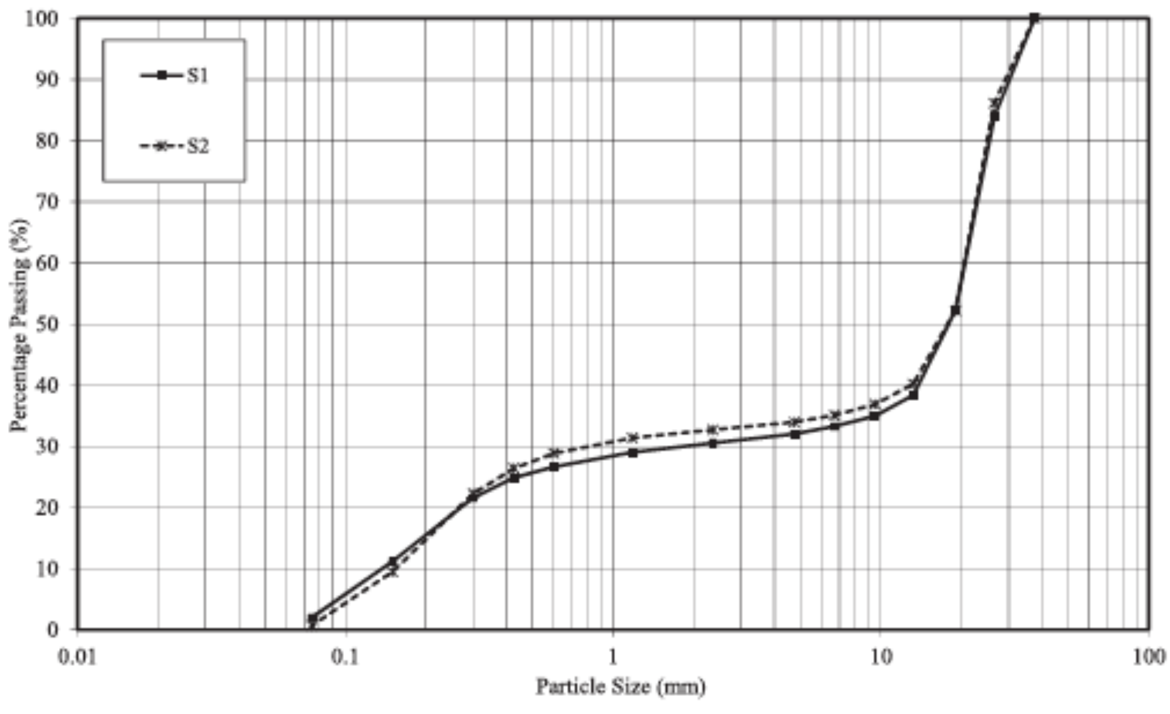


Figure 2: Gradation curve for foam glass (Arulrajah et al., 2015)

Percent crushed particles testing was performed by Schneider (2016) on the samples according to the MTO laboratory standard LS-607. One sample has an overall average of 99.5% crushed particles, and the other one consisted of 100% crushed particles. For both materials, it compares favorably to Ontario Provincial Standard Specification (OPSS) 1010. OPSS 1010 prescribes a minimum of 50% crushed particles by mass for Granular S class materials, 60% crushed particles for Granular A and Granular M, and 100% crushed particles for Granular B Type II and Granular O.

Evaluation of the particle density and particle water absorption is also essential to characterize FG-LWA. Arulrajah et al. (2015) determined the particle density and water absorption tests of the coarse aggregate, retained on the 4.75mm sieve, and fine aggregate, passing through the 4.75mm sieve, and indicated that FG-LWA particle density values were lower than the density of water.

Another important aspect to be studied is abrasion resistance of the particles. Schneider (2016) performed the abrasion resistance test using a Micro-Deval apparatus in accordance with the MTO laboratory standard LS-618, Method of Test for the Resistance of Coarse Aggregate Apparatus. Due to the low density of the foam glass material, Schneider (2016) modified the test to account for the inherent lower density of the FG-LWA as compared to the mineral aggregates. The percent losses during Micro-Deval tests were found to be 5.9% for one sample and 3.1% for the other, which fall within the range established by OPSS 1010. OPSS 1010 specifies maximum coarse aggregate abrasion percentage losses by mass of 21% for Granular O, 25% for Granular A, Granular M and Granular S, and 30% for Granular B (Types I, II and III).

CBR values are usually determined for the granular materials as an indication of their quality to be used in different layers in pavement structures. Arulrajah et al. (2015) performed the CBR test under standard compaction for both dry and soak samples according to the Australian standards AS 2003. The results were within the range for the local road authority requirements. They discussed that as the load increases the penetration increases until it reaches a peak value, then a slight decrease will happen. They state that particle crushing occurs at the peak state, and then again rearrangement of crushed particles contributes to a higher strength.

In addition to the abrasion resistance mentioned above, resistance to freeze-thaw cycles is another important measure of materials durability. Freezing and thawing resistance testing was conducted by Schneider (2016) on materials based on the MTO laboratory standard LS-614. As the LS-614 specification does not cover lightweight aggregates, some modifications were made to the original test procedure. To this end, he adopted the European Standard BS EN 13055-2 Annex B, which specifies a procedure for testing of freezing and thawing resistance of lightweight aggregates. In this procedure, a sample volume of 1500 mL is required for freeze-thaw cyclic testing of materials which have a maximum aggregate size of 16mm to 32mm. Schneider calculated the percentage losses of 0.3% and 0.5% for the first and second sample, respectively. Again, this compares favorably to the OPSS 1010 standard, which specifies a maximum unconfined freeze-thaw percentage loss of 15% for Granular O, with no limits stated for other classes of granular materials.

Finally, the value of resilient modulus for the FG-LWA material was reviewed in this thesis. The resilient modulus testing conducted on FG-LWA samples according to the Ministry of Transportation of Quebec standard LC 22-400 indicates that for the lighter samples, the resilient modulus varies from 66.14 MPs to 203.36 MPa and for the heavier sample it ranged from 65.41 MPa to 184.75 MPa (Schneider, 2016).

2.3 Expanded Polystyrene (EPS)

EPS is a polymeric geo-synthetic material with a cellular closed cell structure containing 98% air. It is produced from heating the expandable beads of polystyrene with steam, and then the placement of these heated expanded polystyrene beads into molds to create block shapes. There are numerous applications of EPS including construction of pavement on low-bearing capacity sub-grade soil (soil stabilization), thermal insulation, noise insulation, landscape architectural and bridge abutments.

Density of EPS is about 15-50 kg/m^3, and its thermal conductivity coefficient is approximately 0.04 W/mK. Mohajerani et al. (2017) describes the major limitations of using EPS to be inadequate design, lack of proper construction practice and inherent flammability. The properties of the EPS evaluated in this thesis are extracted from Forte EPS Solutions, one of the leading EPS manufacturers in Ontario. It is worthwhile mentioning that EPS has generally a very low Poisson's ratio, which is assumed to be approximately 0.1. Padade et al. (2012) proposed calculating the value of Poisson's Ratio (ν) for EPS using Equation 1, where p is the Density of Geofoam (kg/m^3). Table 3 presents the engineering specifications of the EPS produced by Forte manufacturing company.

$$\nu=0.0056p+0.0024 \qquad \text{(Eq. 1)}$$

Table 3: Engineering properties and characteristics of EPS (Forte EPS solution)

Property	Units	Type I
Thermal Resistance (R-value) Minimum @ at 24C(75 F)	M^2.C(W.25mm) Ft^2.hr.F/(BTU.in)	0.65 3.75
Water Vapour Permeance Maximum	Ng/(Pa.s.m^2) perms	300 5.2
Dimensional Stability	% Linear change	1.5
Flexural Strength Minimum	kPa psi	170 25
Water Absorption Maximum	% by volume	6.0
Compressive Strength Minimum @ 10% Deformation	kPa psi	70 10
Limiting Oxygen Index Minimum	%	24

2.3.1 Raw Material and Production of EPS

With regard to raw materials needed to produce EPS, it is assumed that one kilogram of EPS foam requires one kilogram of polystyrene resin. As Amao (2016) explains, generally an overall input value is used instead of breaking the materials up into styrene and water, when evaluating the raw materials for polystyrene production. According to Arellano (2005) manufacturing of EPS has two phases: first phase includes polymerization and pre-expansion of the polystyrene resin beads followed by the second phase, which includes molding. In other words, the styrene monomer has to be first polymerized by mass suspension in water. After the polymerization, the resulting powder per beads is pre-expanded using steam and will be aged for 12-48 hours. The molding process takes the loose expanded beads and forms them into a solid mass by feeding them into the desired shape and injecting steam between the beads to expand them again and fuse the beads (Amao, 2016).

2.3.2 Road Construction Using EPS

EPS has been used in different embankment design projects when the subgrade soil has a low bearing capacity. As an example of such application, the Norwegian Public Roads Administration successfully placed the bridge foundation directly on top of the EPS layers. In case of installing EPS during the pavement construction, research indicates that many hours of man-work need to be included. According to Arellano (2005) implementation of a cement-treated layer on top of the EPS subbase substantially increases the design life of the pavement structure. According to this research, usually an EPS is placed in a subbase layer above the layer of compacted sand/soil on the base of the roadway with a desirable height. According to the pavement design, other layers are placed over the top of the EPS. The separation layer may be used between the layer of EPS and the overlaying pavement structure if needed. The separation layer could be either for the functional enhancement by providing reinforcements or increasing durability by enhancing the filtration.

2.4 Raw Materials and Production of Hot Mix Asphalt

According to Yang et al. (2015) Hot Mix Asphalt (HMA) is by far the most widely used material in the roadway construction industry. Vidal et al. (2013) explain that HMA production includes the following processes: screening, drying, mixing, and storing. In a batch mix plant, the aggregates and the filler are dried using a fuel-fired rotary dryer, where then they are sorted and finally mixed in a separate mill with asphalt cement that is preheated to about 150^{o}C using a fuel oil boiler. In the continuous mix plant, the dryer is used not only to dry the aggregates and the filler but also to mix the heated and dried aggregates and filler with the preheated asphalt cement.

The HMA used in the following chapters of this thesis is assumed to be consisted 95% by weight of gravel and sand, and 5% by weight of the asphalt cement. During the production process, most of the energy consumption is associated with drying and mixing stages. Normally the distances for transporting the raw materials to the asphalt concrete production plant is 60 miles, 25 miles, and 50 miles for the binder, sand, and crushed gravel aggregates, respectively. Table 4 presents the average energy consumption per production of one tonne HMA – including all the processes for all the materials – according to the Natural Resources Canada. The most energy consumptive stages in the HMA production are mixing and drying.

Table 4: Energy Consumption for production of 1 tonne HMA (Natural Resource Canada)

	Physical unit	Physical quantity	Energy equivalent for 1kg (MJ)
Liquid propane gas	L	0.52	53.27
Heavy fuel oil	L	0.72	47.06
Diesel fuel	L	1.24	45.78
Waste (used) oil	L	2.95	41.84
Purchased electricity	KWh	2.12	
Natural gas	M3	4.66	

Furthermore, results from Ambaiowei's (2014) research on the evaluation of pavements sustainability, are used in Chapter 6 of this thesis to illustrate the applicability and impact of utilizing RAP in HMA mixture based on Ontario's pavement sustainability rating system "greenpave". In the aforementioned research, two layers of asphalt concrete were assumed for the analysis: the surface course being SP 12.5mm FC1 mix, and the binder course being SP 19mm (Ambaiowei, 2014). This thesis uses the case D-control mix with no recycled components in the surface and binder course. Table 5 presents the results of PaLATE output data (Green House Gas (GHG) emissions, Energy and Water usage) estimated for initial pavement construction using HMA. Ambaiowei has assumed the transportation distance to be 120km. The volume of the HMA used in case D is 322 m^3 with a density of 2.83 t/m^3; therefore, the total amount of HMA used is 911.26 tonnes. Based on these input values for initial pavement construction, the total energy is calculated for the placement of the pavement as well as the transportation.

Table 5: Energy, Emissions, and water usage for construction using HMA (Ambaiowei, 2014)

Description	Case comparison
	Case D-control HMA
Energy (MJ)	1,270,975
Water consumption (kg)	70
NOx (kg)	718
PM10(kg)	244
SO2(kg)	9467
CO(kg)	263
Hg(g)	1.72
Pb(g)	83
RCRA Hazardous Waste Generated (kg)	17342
Human Toxicity Potential (Cancer)	273,267
Human Toxicity Potential (Non-Cancer)	163,574,204

2.5 Life Cycle Assessment

Sustainability is defined based on three pillars of environmental, social, and economic needs. For many years, the economic component has been the dominant decision-making factor, but more recent years have seen the growing emergence of both the environmental and social components. Van Dam et al. (2015) included to sustainability in the context of pavements to system characteristics that encompass pavements ability to:

- Reach structural and engineering goals,
- Decrease the effect on the ecosystem and humans, and
- Use financial resources economically.

One of the critical challenges in the area of pavement engineering is to meet the increasing demand for sustainability of construction and maintenance projects. This is generally addressed by employing environmentally friendly materials. Huang et al. (2009) developed an LCA model for pavement constructions to evaluate the environmental impacts of the materials and the processes. To that end, Huang et al. (2009) recommended considering different asphalt compositions and materials, use of recycled materials (e.g. glass, RAP, etc.), different placement, and recycling techniques and maintenance. Overall, LCA provides a systematic approach to consider the initial costs (including materials cost, construction), users' costs, environmental impacts, and other agency costs (including maintenance). According to the Federal Highway Administration (FHWA), currently Pavement LCA is mostly used for selecting the most suitable materials for structural pavement design in conjunction with the Life Cycle Cost and Environmental Assessment, as well as evaluating conservation, maintenance and rehabilitation strategies and scenarios at the network level.

Several studies are available on evaluating the potential environmental impacts of replacing traditional pavement materials with innovative, recycled and more sustainable materials and the corresponding strategies using life cycle assessment tools (Anthonissen et al., 2015; Chen et al., 2018; Vidal et al., 2013; Yang et al., 2015). This method can also be used more specifically for further exploring a given aspect of pavement projects. For example, Yang et al. (2015) defined a LCA model to estimate the environmental impacts of their proposed new pavement structure over the course of its life cycle, and compared the results with the case where using recycled materials was introduced. As another example, Anthonissen et al. (2015) studied a different perspective of the environmental effects of pavement structures, where they investigated the possibility of reducing the life cycle environmental impacts by optimizing the mechanical properties of the asphalt mixtures, and consequently improving the service life of the pavements. The longer the service life of a road is, the lower the natural resources and energy consumption are. Given that application of recycled materials can have impacts on the required thicknesses of the asphalt concrete layer and can reduce the use of virgin asphalt cement and aggregates, it would be beneficial to understand the impacts of incorporating recycled materials on the project. For that reason, Yang et al. (2015) have provided a sustainability framework for agencies as they investigate the use of recycled materials in their design. To develop such framework, Yang et al. have made some assumptions about the life cycle environmental impacts of using recycled materials such as RAP and Reclaimed Asphalt Shingle (RAS) in the flexible pavement design. In another study Chen et al. (2018) investigated the aspects of environmental benefits and reduction in GHG emission when incorporating RAP at different rates and performance levels in flexible pavement designs as compared to the pavement with no RAP. They further discussed the case study on a runway pavement rehabilitation to show the significance of the results.

According to Huang (2007), the LCA framework for pavement design should have the following elements:

- Goal and Scope Definition,
- Life Cycle Inventory (LCI) analysis,
- Life Cycle Impact Assessment (LCIA), and
- Life Cycle Inventory Analysis.

To better understand the goal of the study, the primary function(s) of the system must be clearly defined to describe why does the system exist and what is the specific intended application. Baumann et al. (2004) discusses the functional unit, which is defined as the performance that the systems under study have in common. From the LCA point of view, it is preferable to have two products of an equal functionally. According to Azarijafari et al. (2016) in pavement Life Cycle Assessments, the functional unit should consider the definition of physical properties of the pavement. In this thesis, the aforementioned elements are also defined and discussed for both FG-LWA and EPS use in pavement application. The details are presented in Chapter 6.

It is assumed that system boundaries of the LCA analysis are to include all processes and activities that encompass raw materials sourcing, composite materials production, construction operations, and maintenance works during pavement service life (Torino et al., 2015). Azarijafari et al. (2016) describes system boundaries as a selection of activities and processes included within the life cycle phases of the pavement. It includes material production, pavement construction, use, fuel consumption and emissions (due to surface roughness and traffic delay), maintenance and repair and End of Life (EOF). There are different impact categories that are considered in each LCA study:

- Impacts on people (humans)
- Impacts on nature (ecosystems)
- Depletion of resources

In this thesis, two categories of environmental assessment were included. The first is based on the chemical properties of the material. Leachate tests were conducted for this purpose to evaluate the impact of using the material on the environment. The second is Life Cycle Assessment from an environmental impacts point of view. This included several categories such as ozone depletion potential, global warming potential, acidification potential, eutrophication potential, carcinogens, noncarcinogens, smog potential, respiratory effects, ecotoxicity, and fossil fuel depletion using the characterization factors from the TRACI 2.1 LCIA model. Table 6 provides the description for each of these impact categories (Amao, 2016; Huang, 2007).

Results from a previously conducted project at the University of Waterloo (Schneider, 2016) indicates that Life Cycle Cost Assessment (LCCA) plays an important role in pavement design projects. In this recent study, used LCCA for both FG-LWA and EPS implementation in pavement structure. The two scenarios where designed according to the AASHTO 1993 method to provide comparable structural capacities. The results of his research are summarized in Table 7. He concluded that the overall cost of the pavement using EPS as insulation lightweight fill is higher than the pavement using Foam glass lightweight fill.

Table 6: Description of impact category of life cycle assessment (Huang, 2009)

Impact category	Characterization factor	Description
Ozone Depletion	kg CFC11-eq	Effects on the ozone layer as the effects of the chemicals released into the atmosphere
Acidification	kg SO2-eq	Release of hydrogen ion (H*) acidification caused by SO2 and NOx
Global warming	kg CO2-eq	Increase of infrared radiative forcing
Eutrophication	kg PO4-eq	Deposition of N/P equivalent in biomass
Eco-toxicity	kg 1,4-dichlorobenzeneeq	Predicted concentration
Fossil fuel depletion	MJ surplus	Non-renewable resources combusted to generate energy (oil, coal, natural gas)

Table 7: overall cost assessment of pavement design using Foam glass versus EPS (Schneider, 2016)

Design LW Fill	LWA	EPS
Design ESALs	1x10	1x10
Initial Cost of HMA	$492,443	$1,231,106
Initial Cost of Granular base	$96,698	$96,698
Initial Cost of Granular base	$80,582	$80,582
Initial Cost of LW fill	$6,387,053	$8,927109
Total Cost of construction	$7,056,775	$10,335,494
Total Cost of Rehabilitation	$342,198	$536,414
Overall Cost	$7,398,973	$10,871,909

The results of this recent study, conducted at CPATT, will be also used towards developing LCA models in this thesis. Chapter 6 of this thesis describes the details of data collection and provides experimental methods used.

2.6 Summary

Review of the literature presented in this chapter reveals that FG-LWA aggregate has a great potential for being used in pavement applications, both as a lightweight fill and as an insulating material. It can be concluded that while foam glass has been used in several industrial applications, its use in road construction industry has seen very limited attention. It can be concluded that the formulation and manufacturing of FG-LWA should be further investigated to come up with a material which would be suitable to be used in pavement application. Similar to FG-LWA, this chapter also provides a summary of the information on EPS, as pertinent to the scope of this research. This information is later used in the following chapters in order to compare the effects of using FG-LWA versus EPS in a flexible pavement project. General concepts of the Life Cycle Cost and Environmental Assessment was also discussed here. The necessary components needed to perform the LCA on pavement projects using FG-LWA and EPS are identified from the literature and are used in the model implementation phase in Chapter 6 of this thesis. The following chapter provides details of an extended study on the effect of formulation and manufacturing process of FG-LWA on the microstructure of the products.

Chapter 3: Formulation and Microstructure of FG-LWA

3.1 Background

Foam glass properties can be strongly affected by varying the details of the manufacturing process (e.g., furnace temperature, heating duration, heating rate, etc.), raw materials, and material formulation (proportion of different components, foaming agent, etc.). In order to produce a FG-LWA material, which could be suitable for pavement application, it was deemed necessary in this research to further investigate the effect of changing these parameters on the quality and microstructure of the end product. In addition, the possibility of producing colored FG-LWA was also investigated and the results are discussed in this chapter.

3.2 Extended work on Formulation and Microstructure of FG-LWA

Materials considered for the preparation of colored and non-colored FG-LWA are listed below. Other than the foaming agent, the main raw material and other additives used in FG-LWA production should have glassy molecular structures.

1. Mixed recycle container glass;
2. Waste flat glass;
3. Dumped CRTs from TVs and computer monitors;
4. Ceramic frits and glazes (transparent and opaque);
5. Foaming agents such as silicon carbide (SiC);
6. Steel industry slag;
7. Color oxides and ceramic pigments; and
8. Other additives such as clays

In this research, different combinations of the above materials were used to produce the foam glass samples. The products should be assessed for their quality with respect to the application of interest.

3.2.1 Choice of the Method

Two different methods, i.e. direct and indirect, were employed in this study. In the direct method, the ingredients were used without being processed prior to the mixing stage, whereas in the indirect method, waste materials of a non-glassy nature were selected and processed to acquire a glassy structure prior to being used in the formulation. The latter allows for the creation of additional favorable characteristics. Choosing the proper method depends on the type of wastes used in the foam formulation.

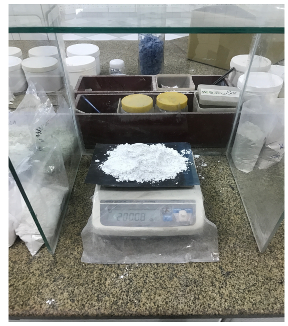
Sieving 	Weighing 
First baking of the samples 	Sample preparations 
Grinding and mixing 	Mixing 

Figure 3: Sampling steps for Foam-Glass Lightweight Aggregate (FG-LWA) (Foamyna Canada Inc)

The first step in the sampling of the new composition foam glass is to pulverize all the raw material prior to weighing and mixing. It is then ground in ball mills to reach a D90 of smaller than 75 microns in particle size. Afterward, the powder should be sieved and milled repeatedly so that all particles would be under 75 microns (μm). At this point, the binding agent should be added, and the mixture would be formed, using an appropriate forming apparatus. Finally, the foams are fired under a specific thermal cycle to achieve the required stability and uniformity. Figure 3 illustrates the process of preparing the samples which was carried out at the Research and Development Institute of Foamyna Canada.

3.2.2 Results and Discussion

Wastes from ceramic frit manufacturing plants can universally be used as the basic element in making foam glass. Any kind of melted frit with an amorphous structure will be useful in this process. The main advantage of frits over other materials for use as the base element in foam production is its basic molecular structure, which provides more suitable physical and chemical properties. As in any other industrial product, chemical and physical characteristics of different frits can vary. It is therefore recommended to consider these properties and modify the frit in accordance with the final foam requirements.

In addition, changing frit percentage in the formulation can conveniently control foam characteristics. In this thesis, the effect of changing frit percentage on the microstructure of the end product was studied. Through this process, important parameters including density, mechanical strength, thermal conductance, flammability, coefficient of thermal expansion and chemical strength can be adjusted for any application requirement. This makes waste frits an ideal ingredient in the formulation recipe.

In this research, Scanning Electron Microscopy (SEM) was used to study the microstructure variations in different foams. Figures 4, 5, 6 and 7 show examples of the microstructure capture using SEM for different FG-LWA produced with different foam formulations. As can be seen in Figures 4 and 5, an approximately homogeneous microstructure with uniform cellular shape and size was obtained by using waste of ceramic frits and glazes under a firing condition of 800°C and 30 minutes of firing cycle. Whereas in case of the experimental samples shown in Figures 6 and 7 the microstructure of foam glass was damaged when using waste of ceramic frits and glazes produced under a firing condition of 900°C and 30 minutes of firing cycle. It was observed that an increase in the firing temperature from 800°C to 900°C destroyed the cellular structure of the foam glass. This observation indicates the significance of using proper manufacturing processes.

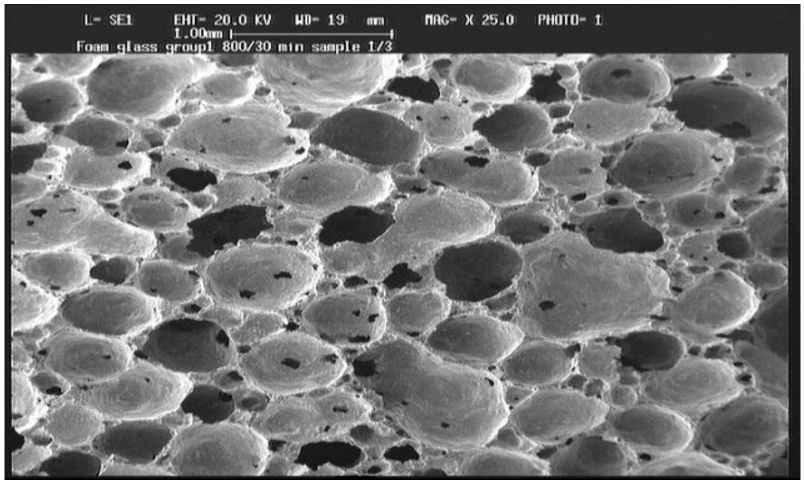


Figure 4: Homogeneous Micro-structure of foam glass

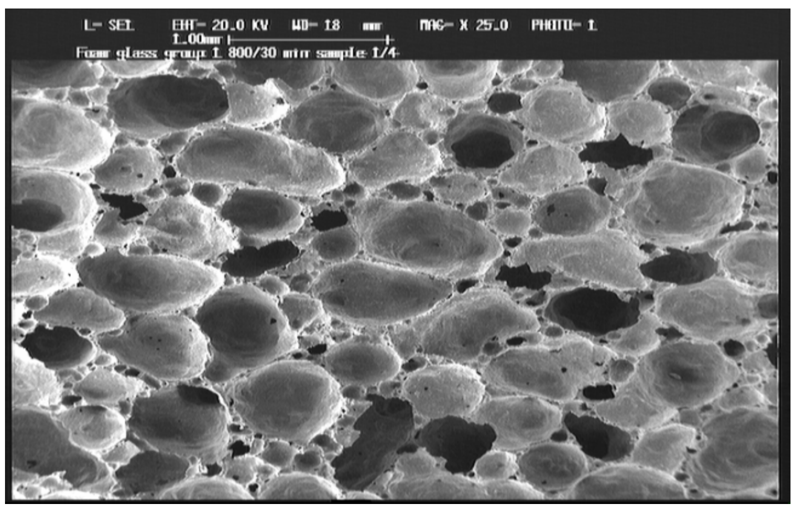


Figure 5: Homogeneous Micro-structure of foam glass

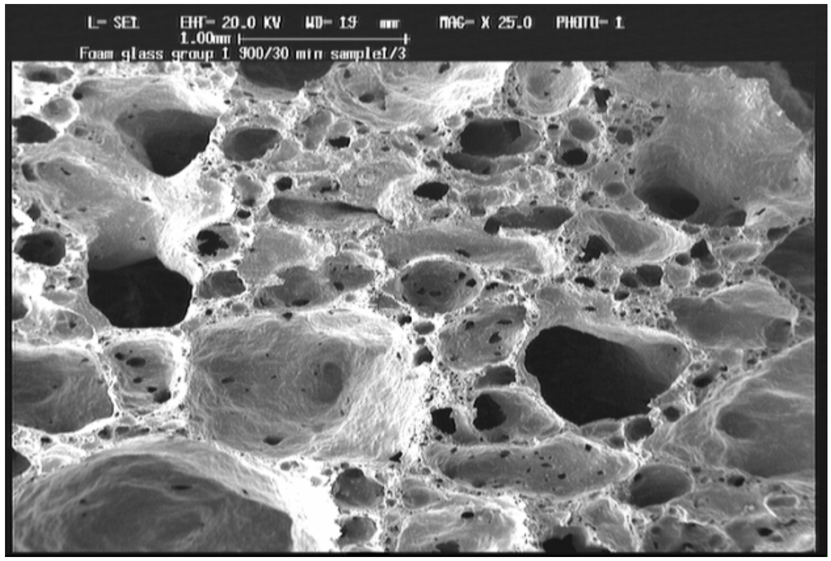


Figure 6: Damaged Micro-structure of foam glass

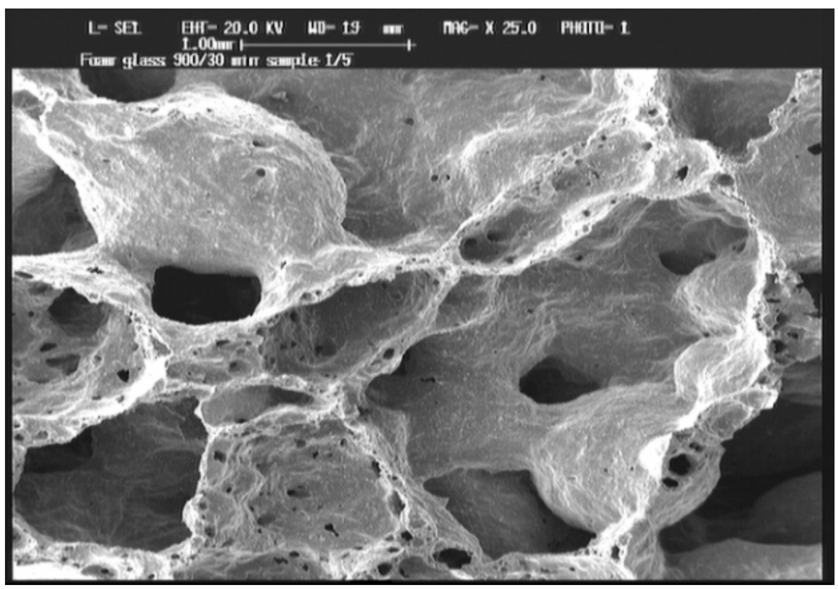


Figure 7: Damaged Micro-structure of foam glass

Foaming agents also play an important role in the course of foam development. It was found that pure silicon carbide possesses superior foaming capacity, especially when ceramic frits and glazes are part of the components in the formula. In this thesis, an experimental study was carried out to determine the optimum foaming agent with respect to the end product features. Therefore, different SiC contents were used at a temperature range of 800-900°C, and using a 30-minute heating cycle.

Figures 8 and 9 show the foam structure for a sample containing 19.6% waste transparent frit as compared to the standard foam glass produced using 2% SiC with the firing temperature of 800°C. Figure 10 shows different foam glass types produced using from ceramic frits and glazes, but with varying SiC contents. Studying the different foam configurations in samples produced by using ceramic waste frits and increasing SiC content indicates that as temperature increases to 850°C, a uniform foam structure is developed (Figure 10). Raising the temperature beyond 850°C has caused unfavorable random deformation in the microstructures of foams.

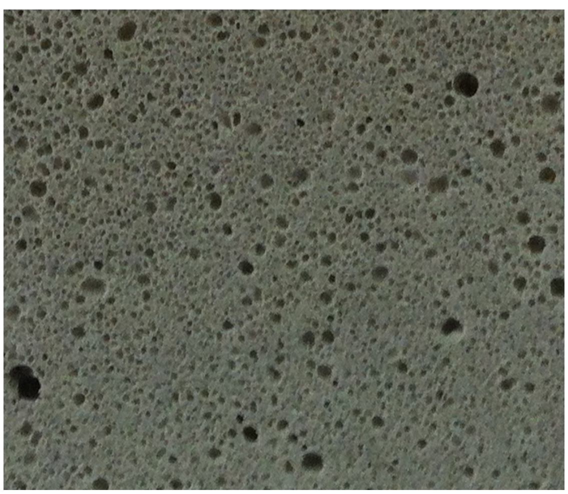


Figure 8: Foam Glass containing waste frit

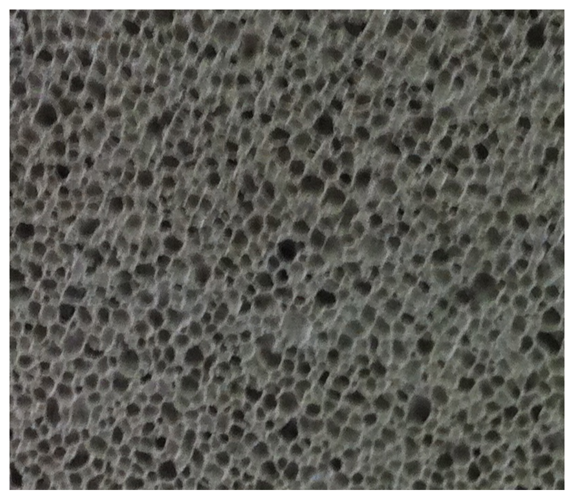


Figure 9: standard foam glass

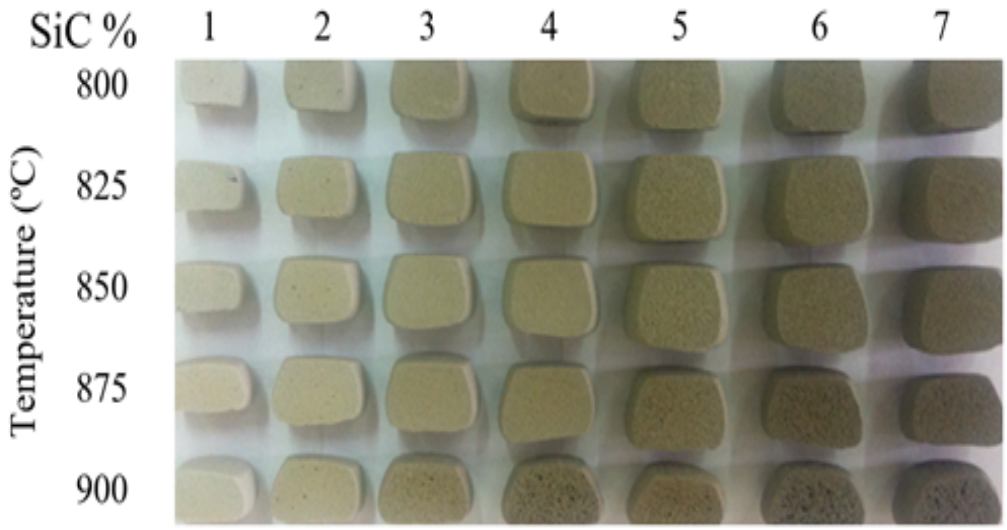


Figure 10: Image of foam glass from ceramic frits and glazes with varying SiC contents

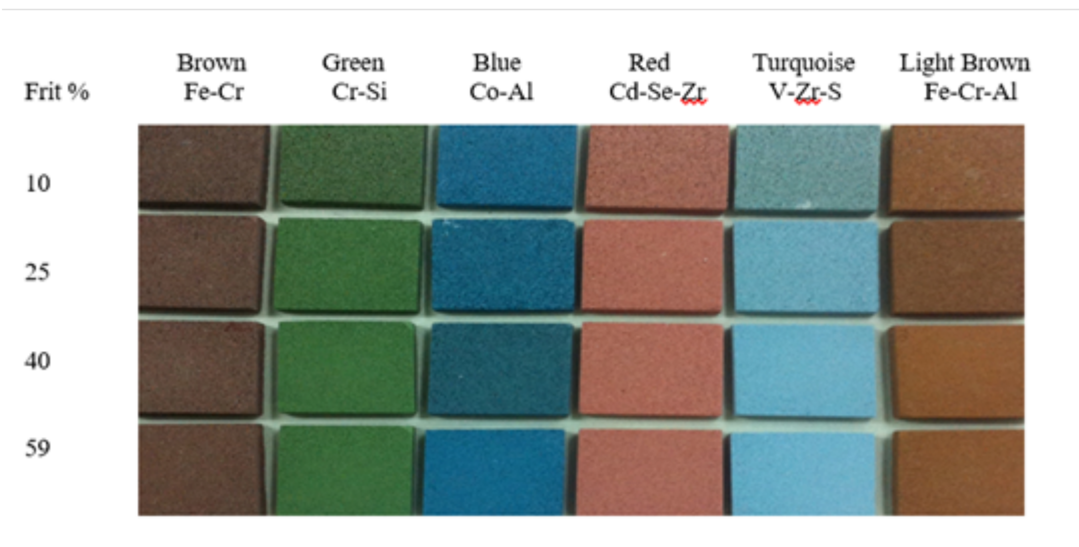


Figure 11: Direct Method producing coloured Foam Glass by adding percentage of waste ceramic frits and glazes to mix glass

Another promising aspect of the present work was development of colored foams, which are expected to have potential applications in urban roads and highway markings. Preliminary studies showed that inclusion of ceramic pigments in the glaze composition yields a wide range of shades with excellent quality. Therefore, it can be concluded that presence of ceramic frits or glazes in the foam composition helps to enhance its colors quality. It should be noted that transparent frits increase the color density and produce darker shades, whereas the so-called opaque frits have tendency to produce light pastel colors. Figure 11 demonstrates various colored foams produced by direct pigment inclusion in this study. Colored foams such as LWA can have various applications in road industry. Raising the temperature over 850°C causes the deformation in microstructure. Foaming agents are formulated in such a way as to obtain maximum performance with minimum quantity. Pure silicon carbide is the main bubbling agent in this test and is used as foaming component with darker products. Other agents are employed to give soft color and clear effects. The work conducted in this chapter contributes to the first objective of this thesis which is to investigate the engineering properties of Foamglass Lightweight Aggregates.

Chapter 4 Chemical Properties through Leachate Testing

4.1 Chemical Evaluation and Standards

In order to use the FG-LWA material in the pavement construction, it is necessary to evaluate the material with respect to its chemical properties and identify any potential risk it may pose to the environment. Therefore, the focus of this chapter is on evaluation of the chemical properties of the samples of FG-LWA, provided by Foamyna Canada Inc. Company, through a series of leachate tests conducted at Golder Associate Laboratories. The results of these tests are among the first chemical evaluations carried out on foam glass lightweight material in Canada (at the date of this thesis). This phase of the research was conducted in support of using foam glass by the Ministry of Transportation of Ontario (MTO) as a lightweight fill aggregate (LWA) in the Designated Source of Materials (DSM) database. The sampling procedures conformed to the Ontario Ministry of the Environment (MOE) "Protocol for Analytical Methods used in the Assessment of Properties under Part XV.1 of the Environmental Protection Act". The following standards were followed at the Golder Associate laboratory:

- Environmental product declaration according to ISO 14025 and EN 15804 by Misapor foam glass 10/75 Misapor AG
- European Technical Approval No.ETA-05/0187

The FG-LWA material conformed favorably to the requirement of Ontario Provincial Standards Specifications (OPSS) document OPS.MUNI 1010 (OPSS 1010) which governs requirements for granular fill materials in use in pavements in Ontario for Granular A, M, O, B or S. OPSS 1010 requires a minimum of 50% crushed particles by mass for Granular S materials, 60% crushed particles for Granular A and Granular M and 100% crushed particles for Granular B Type II and Granular O. As the samples have 100% crushed particles it falls within the specifications' limits. The only exception was that the gradation testing did not conform to the requirements for natural aggregates, but given that the FG-LWA is not a natural mineral aggregate, these gradation specifications are not considered to be applicable.

This chapter describes the analysis of the chemical composition and characteristics of the material and its leachate, as well as the interpretation of the outcomes. The procedures completed on the samples were as follows;

- Bulk testing to determine the composition,
- Distilled water leachate testing to simulate leaching due to precipitation,
- Acetic acid leachate testing to simulate leaching under acid/worst case condition

4.2 Bulk Testing

The bulk testing of the FG-LWA material included analysis of the following parameter groups:

- Trace metals and inorganics
- Volatiles
- Semi-volatiles
- Polychlorinated biphenyls (PCBs)
- Total biological oxygen demand (BOD) and total chemical oxygen demand (COD)
- Phenols
- Turbidity, total suspended solids, and total dissolved solids, and
- Hydrogen Sulphide and Sulphur content

In the absence of screening guidelines applicable to LWA material, these results compared to the general soil site condition standards as per the Ontario Ministry of Environment (MOE) document entitled "Soil, Groundwater and Sediment Standards for use under Part XV.1 of the Environmental Protection Act". MOE specifications contain two tables with the first table representative of background soil concentrations in Ontario, and the specifications in second table are generic guidelines to protect potable groundwater uses at the industrial, commercial and community properties. Although using the limits provided in MOE helps identify whether the LWA material is similar to background soils, it was considered more relevant to compare the materials characteristics to the MOE specifications provided in second table related to the protection of the potable groundwater. These standards considered the potential for contaminants to leach into groundwater and affect nearby surface water for the protection of aquatic life or potable water sources for the protection of human health. These pathways are the most likely to be of importance for the lightweight fill materials application as a road base material.

The results of the bulk testing and associated screening indicate that all tested parameters met their respective criteria in the MOE standards, except for the antimony. The tested material had a concentration of 15 μg/g, while according to the background soil concentration standard this value should be limited to 1.3 μg/g. However, the results met the other class in the standards related to potable groundwater protection of 40 μg/g.

Given that the potable groundwater protection criteria are met for all parameters, risks to human health and the environment are considered to be negligible by the bulk testing. The odor was not included in the analytical suite for the bulk testing given that no volatile substances are expected with respect to the composition, recycled glass, and non-volatile additives. Bulk testing confirmed that the Hydrogen Sulphide and all volatile compounds were less than detection limits. As a result, the FG-LWA is not expected to generate odors.

In addition to the bulk testing, whole rock analysis was conducted to provide composition percentages of the LWA material sample submitted for analysis. The results of the testing indicated that the FG-LWA material is primarily composed of silica (SiO_2) at 66.9% with lesser amounts of oxides of sodium (Na_2O) at 12%, calcium (CaO) at 10.7%, aluminum (Al_2O_3) at 1.84% and magnesium (MgO) at 1.39%.

4.2.1 Distilled Water Leachate Testing

The distilled water leachate extraction (DIWE) testing was completed on metals, inorganics/general chemistry, hydrides, uranium, semi-volatiles, volatiles and polychlorinated biphenyls (PCBs). Analytical results are compared to the Canadian Freshwater Fisheries Water Quality Guidelines (CFFWQG) from the Canadian Council of Ministers of the Environment (CCME) and schedule 2 of the Ontario Drinking Water Quality standards (ODWS), Ontario Regulation 163/03. Although the concentrations of most parameters were less than laboratory reporting detection limits and less than their respective CFFWQG and ODWS, some metals exceedances of these guidelines were identified in the distilled water leachate as listed below:

- Chromium VI (measured concentration of 3.2 μg/L versus the CFFWQG of 1μg/L)
- Aluminum (500 μg/L versus the CFFWQG an ODWS of 100 μg/L)
- Antimony (40.3 μg/L versus the ODWS of 6 μg/L)
- Arsenic (85 μg/L versus the CFFWQG of 5 μg/L and the ODWS of 25 μg/L)
- Cadmium (0.108 μg/L versus the CFFWQG of 0.09 μg/L)

- Copper (7.51 μg/L versus the CFFWQG of 2 μg/L)
- Lead (12 μg/L versus the CFFWQG of 1 μg/L and ODWS of 10 μg/L) and
- Selenium (2.50 μg/L versus the CFFWQG of 0.5 μg/L)

Table 8 compares the measurement results with the limits stated in the guideline provided by the manufacturer. Initially for the purpose of pH measurements, crushed samples were used, which is not fully representative of how foam glass material is applied in the field unless a full dissolution of the materials happens which is unlikely to be the case as the Los Angeles Abrasion Test results were very good (Schneider, 2016). Therefore, a sample that was not crushed was retested for pH and resulted in a pH of 7.37, which is within the acceptable ranges given by CFFWQG and ODWS.

Table 8: Limit value of the important chemical substances in sample of Foam Glass (Golder Associates)

Chemical substance	Measured	Limit value [µg/l]
Arsenic (As)	8	10
Lead (Pb)	7	7
Cadmium (Cd)	<0.5	0.5
Chromium III (Cr)	3	7
Copper (Cu)	7	14
Nickel (Ni)	9	14
Mercury (Hg)	<0.2	0.2
Zinc (Zn)	10	58

4.2.2 Acetic Acid Leachate Testing

The acetic acid leachate testing was carried out using Method 1311 Toxicity Characteristic Leaching Procedure (TCLP) from The United States Environmental Protection Agency, while the distilled water leachate testing (DIWE) was carried out using a similar method to 1311 except the reagent used in the test was distilled water. In brief, both methods involved crushing the LWA material, immersing the material in the given reagent at a ratio of 20:1, and mixing the solution end-over-end for 18 ±2 hours. The screening results indicate that all parameters were less than laboratory reporting detection limits except for arsenic and lead. However, the reported detection limits of the TCLP leachate results were higher than those obtained for the DIWE leachate. The concentrations of arsenic and lead were above their respective applicable guidelines as summarized below:

1. Arsenic (0.2 mg/L versus the CFFWQG of 0.005 mg/L and ODWS of 0.025 mg/L)
2. Lead (0.3 mg/L versus the CFFWQG of 0.001 mg/L and ODWS of 0.01 mg/L)

These findings indicate the certain provisions need to be followed in cases where the water table level is very shallow. This is further discussed in the following section. The restriction related to Lead in particular may represent a major limitation for some applications.

4.3 Environmental considerations

Comparing the leachate concentrations from the DIWE and TCLP tests with the applicable CFFWQGs and ODWSs criteria assessed leachate that generated from the LWA material. Concentrations of some metals exceeded these criteria, indicating that leachate may have the potential to adversely affect potable water and aquatic resources and the natural environment. Therefore, the environmental impact of the use of the LWA material was evaluated.

The DIWE and TCLP tests were conducted to determine whether the concentrations of various parameters that could leach from the bulk material into soil and water might pose a potential risk to human health or the environment. Given that the TCLP method was initially designed to be used for waste classification and is carried out using an aggressive acid leaching technique that is not representative of the natural environmental situation, the test conditions under the DIWE method were considered more appropriate as a basis of assessing potential risks to human health or the environment.

In the DIWE method, the LWA material fully saturated with distilled water is considered to be more representative of a typical environmental condition wherein the LWA material may come into contact with groundwater and potentially leach some elements into the groundwater. Therefore, the results of the DIWE leachate are assessed further below, concerning the potential for the leachate to pose a potential risk to human health or the environment.

The DIWE leachate results were compared to the concentrations typically measured in groundwater in Ontario (Ontario Typical Background), which is represented by the 9.5th percentile of several hundred individual measurements all across the province. In addition to background, the report compared the DIWE leachate values to the risk-based component values that were considered in the derivation of Table 2 standards. Especially, the GW1 component values represent concentrations that are associated with a negligible health risk if used as a drinking water source. The GW3 component values represented concentrations that associated with negligible aquatic risk if present in groundwater that may leach to a nearby water body.

Based on the comparison shown in Table 9, Chromium, Cadium, Copper, and Selenium are not expected to pose a potential risk to either human health or aquatic life. Below are further assessment of the leachate concentrations of aluminum, arsenic, and Lead:

Table 9: Comparison of leachate results for the samples with Ontario Background, GW1 and GW3 (Assessed at the Golder Associates)

Parameter	**Ontario Background (μg/L)**	**GW1 (μg/L)**	**GW3 (μg/L)**	**Leachate (μg/L)**
Chromium VI	25	25	140	3.6
Aluminum	86.9 (0.1-1440)	NV	NV	500
Arsenic	13	25	1900	85
Cadmium	0.5	5	2.7	0.108
Copper	5	1000	87	7.51
Lead	1.9	10	25	12
Selenium	5	10	63	2.5

- Aluminum for human health: Health Canada in its guidelines for Canadian Drinking Water Quality (October 2014) indicates that there is no viable evidence that the presence of aluminum in drinking water is associated with an adverse health effect. Additionally, the

British Columbia Ministry of Environmental (BC MOE) under schedule 6 of its contaminated sites Regulation has developed a drinking water standard of 9500 μg/L. As a result, the maximum concentration of aluminum in the leachate of 500 μg/L is not considered to pose a potential risk of human health and no restrictions on its use are considered to be required.

- Aluminum for aquatic life: neither Ontario nor BC MOE developed standards for aluminum specifically for the protection of aquatic life. The lowest standard available from these two jurisdictions is the BC MOE schedule 6 standard of 5000 μg/L which is protective of irrigation, livestock watering, and drinking water; no value derived for the protection of aquatic life. Given that the BC MOE schedule 6 standards are intended to be protective of pathways including aquatic life and the maximum concentration in the leachate of 500 μg/L is less than these available standards, aluminum is not considered to pose a potential risk to aquatic life, and no restrictions on its use are considered to be required.
- Arsenic for human health: the maximum concentration of arsenic in the leachate of 85 μg/L exceeds the GW1 component value of 25 μg/L, which adopted from the ODWS, although it is less than the GW3 component value of 1900 μg/L which is protective of aquatic life. Therefore, while not a concern for aquatic life, it may be a concern for human health. As a result, the recommendation is that FG-LWA, with leachate concentrations in this range, be placed away from potable water sources.
- Lead for human health: the maximum concentration of lead in the leachate of 12 μg/L is only marginally higher than the drinking water standard of 10 μg/L.
- Therefore, metals in DIWE leachate are not expected to pose a potential risk to human health or the environment when used for road construction if placed away from potable water resources.
- For testing pH, 500mL of distilled water used, and samples of foam glass rocks yielded a pH of 7.37. As a result, pH in the leachate is expected to be within the ranges provided by CFFWQG and ODWS when used without crushing as indented.

With regard to classification of the FG-LWA from the environmental perspective, the criteria for use are the restrictions defined by the MTO for placement of the LWF materials based upon its leachate properties. The criteria for use for LWA materials fall into four categories; unrestricted, restricted-Level 1, Restricted-Level 2 and prohibited based upon the leachate quality through TCLP testing. The

TCLP leachate quality compared to the Leachate Quality Criteria (LQC) defined under schedule 4 of Ontario Regulation 347/558/00 and the ODWS. Table 10 summarizes the criteria for use.

Based on the TCLP results discussed earlier, the TCLP results for samples tested identified arsenic and lead exceedances of their respective ODWS. These results indicated that the FG-LWA would fall within the "restricted Level 1" and "Restricted Level 2" categories based on arsenic and lead. However, in consideration of the greatest exceedance, the TCLP leachate generated results in Restricted – Level2 category for use. This means that the use of FG-LWA is restricted for greater than 2m above the nominal groundwater level, greater than 100m away from potable water wells and greater than 30m away from water bodies.

Table 10: The criteria for the use of lightweight aggregate in Ontario (Golder Associates)

CATEGORY FOR USE	LEACHATE QUALITY (tested in accordance with the Toxicity Characteristics Leaching Procedure TCLP)	CRITERIA FOR USE
Unrestricted	<=5% LQC (<=5 x ODWS)	None
Restricted-Level 1	<=10% LQC (<=10 x ODWS)	>2m above the nominal groundwater level >30m away from potable water wells
Restricted-Level 2	<=30 % LQC (<=30 x ODWS)	>2m above the nominal groundwater level >100m away from potable water wells >30m away from water bodies
Prohibited	>30% LQC (>30 x ODWS)	Not applicable

4.4 Compliance

Overall, the foam glass LWA material conformed to the requirements of the OPSS 1010 for granular A, M, O, S and B. The only exception was that the gradation testing did not conform to the requirements for natural aggregate, but given that the LWA material is not a natural mineral aggregate, these gradation specifications are not considered to be applicable.

Based on the acidic leachate testing (Toxicity Characteristics Leaching Procedures or TCLP) of the LWF sample analyzed, the TCLP testing identifies arsenic and lead exceedances (8x and 30x, respectively) of their respective Ontario Drinking Water Standards (ODWS) and Canadian Freshwater Fisheries Water Quality guidelines (CFFWQG). It should be noted that no exceedances of the leachate quality criteria in schedule 4 of Ontario regulation 347 were identified. This indicates that the FG-LWA material would fall within the RESTRICTED-LEVEL 2 category for use. This category requires that the use of LWA material is restricted to a depth greater than 2m above the nominal groundwater level, distances greater than 100m away from potable water wells and distances greater than 30m away from water bodies. It is important to consider that the source of the recycled glass is a critical factor in the leachate quality.

4.5 Summary

In summary, the proposed use of the FG-LWA material is not expected to have an adverse effect on environmental or human health when placed away from potable water sources and it is not considered necessary to impose any restriction on the placement or use of the LWA material for its intended use as a lightweight road base from an environmental perspective. However, a more severe leachate condition was evaluated through TCLP testing in addition to the standard DIWE tests, to be on the prudent side. Based on the DIWE and TCLP test results, concentrations of some metals exceeded their respective CFFWQG and ODWS criteria. Given that the TCLP method was initially designed to be used for waste classification and is carried out using an aggressive acid leaching technique that is not representative of natural environmental situations, the test conditions under the DIWE method were considered more appropriate as a basis for assessing potential risks for human health or the environment. Therefore, based on the above results, metals in the DIWE leachate are not expected to pose a potential risk to human health or the environment when used for road construction if placed away from potable water sources. In case TCLP measurements are used as the reference, the materials will be categorized as restricted-2 level. Therefore, it would be required to use the LWA material be restricted to a depth greater than 2m above the nominal groundwater level, distances greater than 100m away from potable water wells and distances greater than 30m away from water bodies.

Chapter 5: Pavement Design using FG-LWA as alternative Lightweight fill material

5.1 Case Study Evaluation

In order to use the proposed FG-LWA in real pavement construction, it is necessary to evaluate its effect on the structural response of the pavement structures. To this end, this chapter investigates some alternative pavement structures when FG-LWA is used to replace or in addition to the conventional granular materials. Therefore, some existing pavement construction and rehabilitation projects in the Ministry of Transportation (MTO) jurisdiction were reviewed. Finally, one completed project which involved the use of EPS was selected for further evaluation in this chapter. The project included the structural replacement of Mckeller & Ripple Creek culverts including minor reconstruction at East approach to McKeller Cr. of Highway-17, 7.8 km west of little Pic River bridge. The purpose of the work was to construct a permanent realignment of the Highway-17 to the north of the existing culvert site and then to replace the existing Mckellar Creek culverts with a new concrete culvert (Figure 12).

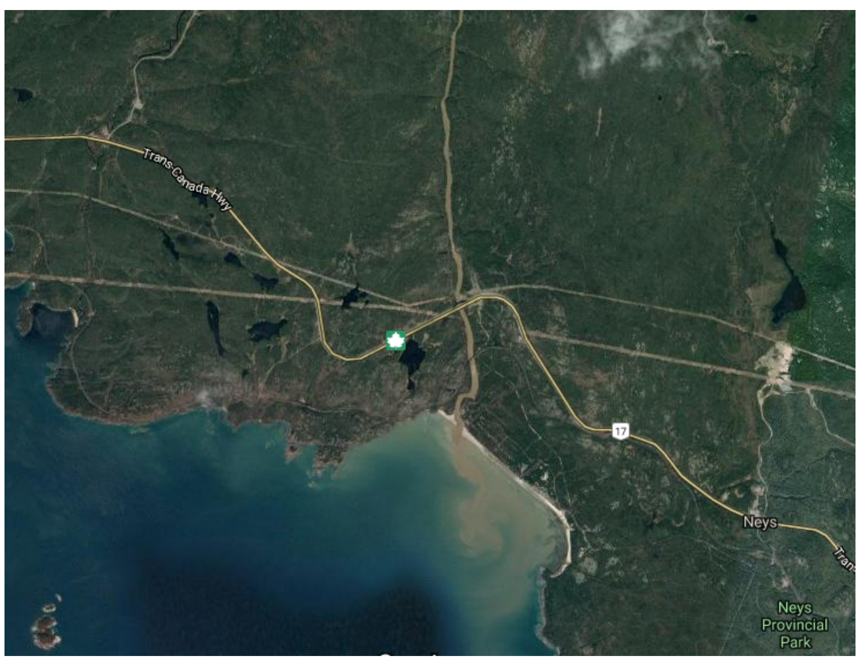


Figure 12: Highway 17 McKeller Creek Culverts (Google map)

According to the MTO reports, the topography is very rough with many steep rocky hills surrounding small lakes and swamps. The investigation indicated that the proposed new alignment generally consists of shallow topsoil over bedrock and/or sandy silt to silty clay (wet-moist) overlying bedrock. Therefore, the expanded polystyrene (EPS) was used as lightweight fill material for the new MTO design. After a thorough evaluation of different sections, section 14+590 to 14+860 has been selected and used in this research, due to the use of EPS as lightweight fill material on top of the subgrade soil after full-depth removal of the existing pavement. The Highway 17 is classified as an undivided rural arterial highway with a design speed of 110 km/h (URA-110). The existing MTO pavement design recommended the following layers and materials to be used for this section:

- The surface course be paved with 60mm of HL4
- The binder course be paved with 60mm of HL4
- The base course is filled with 120 mm of Granular A,
- The subbase course be filled with 120 mm of Granular B,
- The subgrade is filled with Expanded Polystyrene as lightweight fill material with the quantity of 10972 m^3 and the estimated thickness of 198 cm

According to the OPSS, Granular A is a well-graded material with 100% of the particles passing 26.5mm sieve size and having at least 50% crushed particles and no greater than 8% passing 75µm sieve. As a subbase course, Granular B is a material with 100% of the particle passing the 150mm sieve and no greater than 8% passing the 75µm sieve.

5.2 Design Scope

In order to evaluate the effectiveness of using FG-LWA as the lightweight fill compared to the Expanded Polystyrene, a mechanistic pavement design approach was used in two phases. Under phase one, the same pavement structure proposed by the MTO was adopted, but the EPS layer was replaced by the same thickness of FG-LWA material. In other words, the layer thicknesses and material properties remained the same for the asphalt concrete and unbounded granular layers as in the MTO project design. Figure 13 illustrates the schematic of the two pavement structures evaluated in phase one.

The second phase includes evaluation of four scenarios with different structural layers and thicknesses, where FG-LWA would be used as an alternative to the EPS. These four scenarios were designed with the aim of achieving equal or smaller values for the critical strains at the bottom of the asphalt layer and on the top of the subgrade layer.

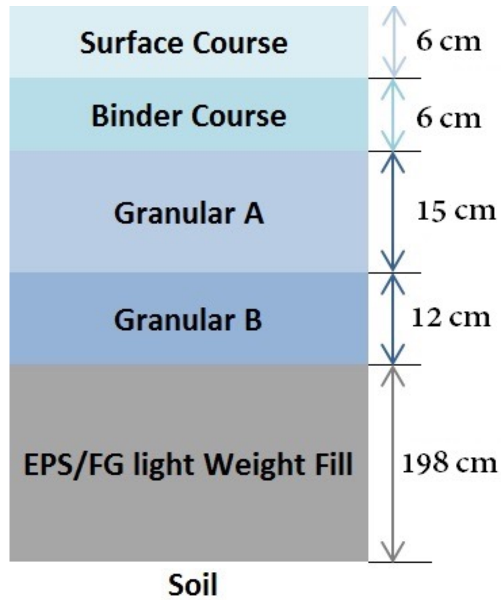


Figure 13: Pavement structural design

5.3 Mechanistic Pavement Design using KenPave Program

Kenpave program provides two separate platforms, namely Kenlayer and Kenslab, for evaluation of flexible and rigid pavements, respectively. Kenlayer is a layered elastic model that can calculate stresses, strains and deflections in different layers of a given flexible pavement structure, as well as conducting damage analysis if needed. The strain and stress responses can them be used along with the existing empirical models to estimate the pavement service life with respect to fatigue cracking and rutting. To this end, the tensile strain at the bottom of the asphaltic layer and the vertical compressive strain on top of the subgrade are considered critical and should be calculated.

While KenPave is capable of using complicated material models and changes in materials properties at different periods of the year, the main objective in this section is to compare the effect of using FG-LWA versus EPS on the pavement responses. Therefore, the damage analysis was not used in this study, and the critical strains were used to evaluate the pavement responses. The primary inputs of the model are material properties for each layer; including modulus of elasticity (E) and Poisson's ratio (V); thicknesses, layer interface types (i.e. fully bonded or frictionless) and the loading groups and details.

5.3.1 Thickness

The Number of Layers (NL) is defined as the first step in modelling of the pavement section. In the first phase of the project, the number of layers for both designs are selected to be six, with regard to the original MTO design which can represent two asphalt concrete layers, two granular layers, one layer of EPS/ FG-LWA, and the semi-infinite layer of subgrade soil. The number of Z-coordinates for the analysis purposes represents the points at which the responses would be calculated during the design process. Table 11 illustrates the points of interest and the critical response points used towards analyzing the pavement sections. In the first phase, the total of eight Z-coordinates were defined as follows:

- Immediately under the wheel load indicating surface deflection
- At the interface of the two bituminous layers
- At the bottom of the second bituminous layer to determine horizontal tensile strain (an indication of fatigue)
- At the bottom of the Granular A (base)
- At the bottom of the subbase layer
- Middle and bottom of the EPS/ FG-LWA layer
- On top of the subgrade layer to identify the vertical compressive strain

Table 11: The design analytical points and the application

Pavement Surface	Deflection	Used in imposing load restrictions during spring thaw and overlay design
Bottom of HMA layer	Horizontal tensile strain	Used to predict fatigue failure in the HMA and rutting
Top of the intermediate layer	Vertical compressive strain	Used to predict rutting failure in the base and subbase
Top of subgrade	Vertical compressive strain	Used to predict rutting failure in the subgrade

5.3.2 Phase 1: Pavement Responses using FG-LWA Layer

As discussed above in the first phase, the two pavement structures will have identical thicknesses and material, except for the material properties of the EPS layer (see Figure 13). Table 12 shows the Z-coordinates of each response point in the first phase of the design evaluation.

Table 12: Z-coordinates of each response point

Point No.	ZC
1	0
2	6
3	12
4	12.01
5	27
6	39
7	237
8	237.01

Table 13 provides the Poisson's ratios assumed for each layer during the design process in this section. For two designs in the first phase (one with EPS and one with FG-LWA layer) the Poisson's ratio for HMA layer, Granular A, granular B, and the soil will remain constant. The only variable is the lightweight fill layer. Similar to the inputs for thickness, moduli for all the layers will remain constant except the lightweight fill layer as the moduli of EPS and FG-LWA is different.

The resilient modulus values for different layers can be estimated using the correlation charts provided by Huang (2007) and according to the MTO pavement Design manual. The modulus of elasticity for EPS was experimentally determined by Adam Schneider (2016), and has been used in this research accordingly. The material properties for the Foam-Glass Lightweight Aggregate (FG-

LWA) were selected in accordance to Steurer (2014). Table 14 summarizes the elastic modulus values used to model the pavement structures in this study.

Table 13: Poisson's Ratio of each layer

Layer No.	Layer Label	Poisson's Ratio
1	Surface	0.25
2	Binder	0.27
3	Granular A	0.38
4	Granular B	0.40
5	EPS	0.1
6	Foam Glass	0.46
7	Soil	0.45

Table 14: Elastic modulus of each material in pavement design

Layer	E (KPa)
Surface	3,100,000
Binder	3,000,000
Granular A	193,000
Granular B	145,000
EPS	6,000
Foam Glass	65,400
Soil	4,000

A single axle load was used for both design scenarios. Table 15 provides details of the load.

Figures 14 through 17 compare deflection gradient; vertical stress variation, horizontal strain variation and vertical strain variation with depth under the wheel load (X=0, Y=0) for both EPS and FG-LWA scenarios.

Table 15: Summery of load information

Load	Contact Radius (cm)	Contact Pressure (kPa)	YW	XW	NR or NPT
0(single axle)	10.75	580	0	0	3

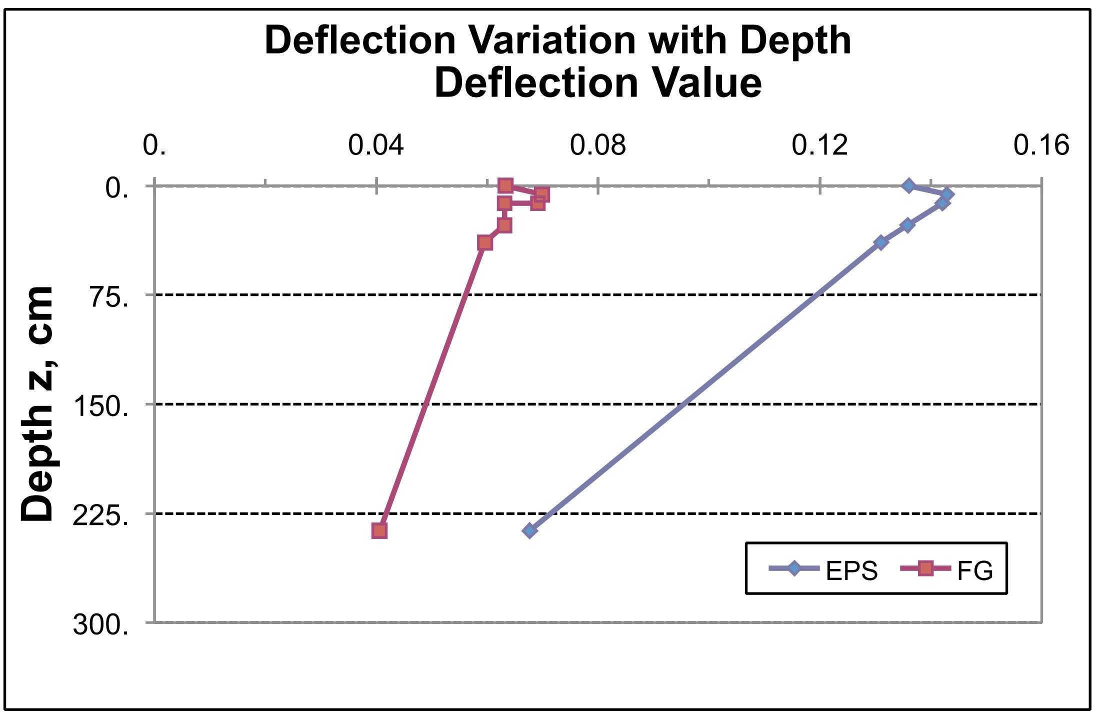


Figure 14: Deflection Variation with Depth

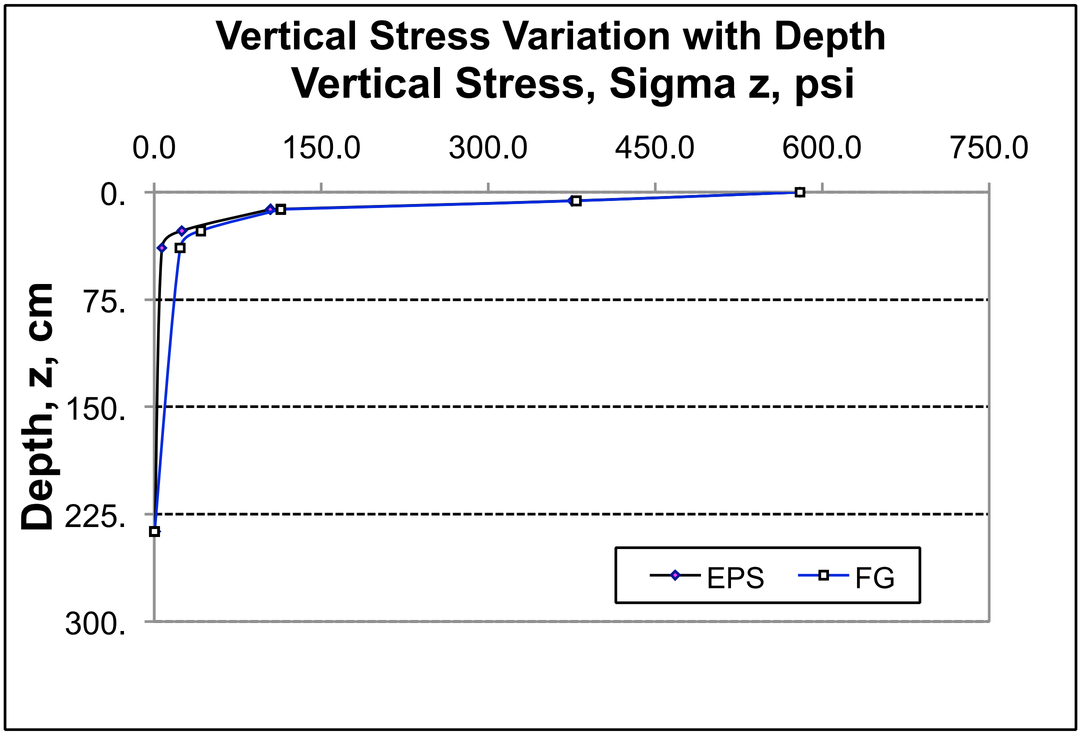


Figure 15: Vertical Stress Variation with Depth

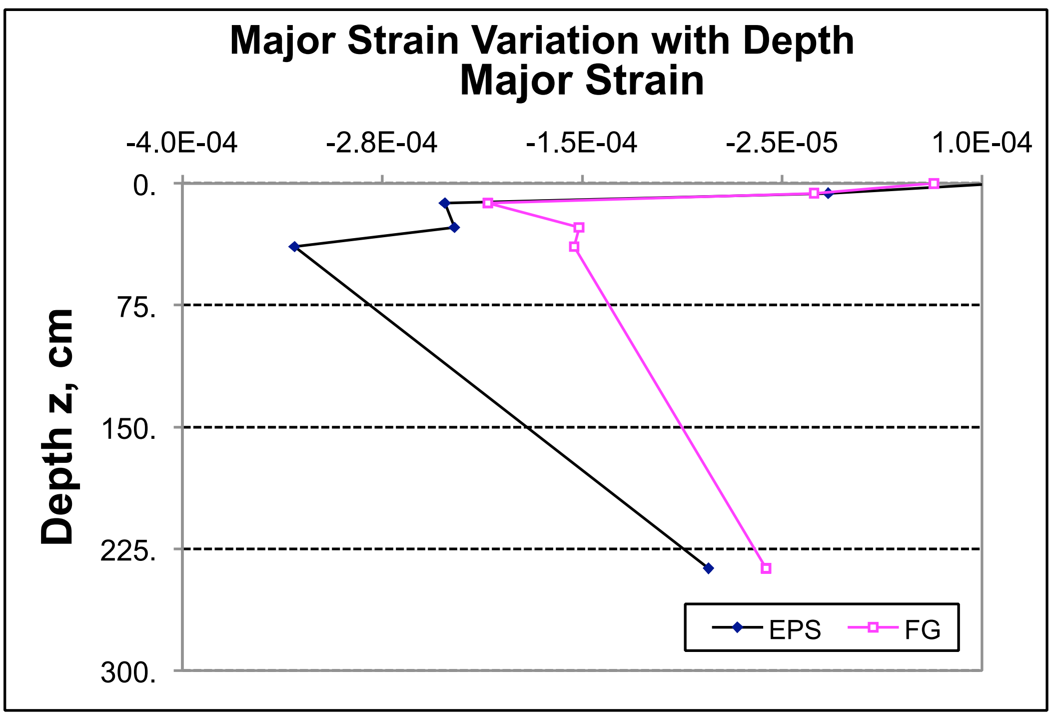


Figure 16: Major Strain Variation with Depth

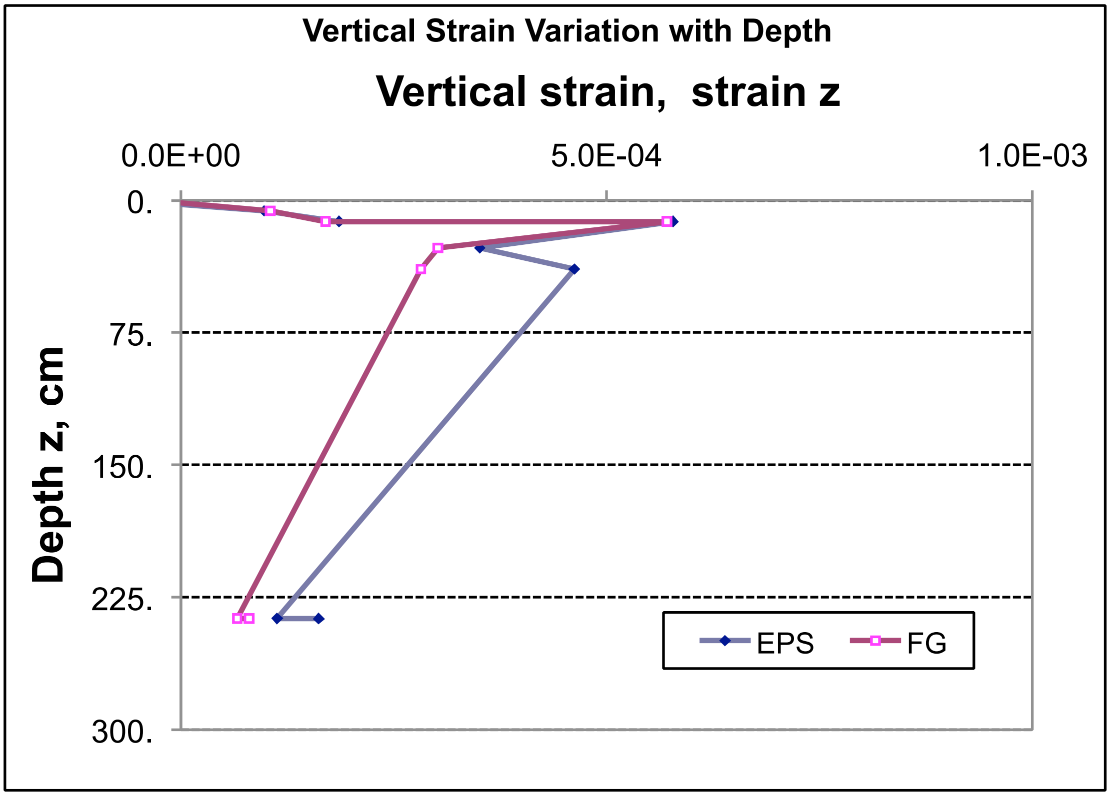


Figure 17: vertical strain variation with depth

In all of the cases it can be recognized that using FG-LWA improved the pavement response as compared to the cases where EPS was used. It can be concluded that replacing the EPS layer with the same thickness of the FG-LWA will result in a better mechanistic response. Therefore, the next phase of the pavement design evaluation aimed to determine equivalent pavement sections, which can result in the approximately same critical strain values as the original design.

5.3.3 Phase 2: Finding Alternative Equivalent Sections using FG-LWA

In phase 2 of the pavement design evaluation study, different scenarios are defined to investigate how the application of foam glass would benefit pavement construction projects by either reducing the required thickness of the asphalt concrete layer or reducing the Granular "A" layer or both. Table 16 and 17 provide details of the scenarios used in this phase of the study. All the thicknesses are in cm.

Table 16: Thicknesses of the layers (cm)

Scenario	Surface Thickness	Binder Thickness	Granular "A" thickness	Granular "B" Thickness	Foam glass Thickness	Soil
1	5	6	15	12	199	Const.
2	6	6	10	10	205	Const.

Appendix A provide the results obtained from changes in the thicknesses of the layers. Two more scenarios were also defined in this section considering: 1) Replacing the granular "B" layer with FG-LWA, and 2) replacing the Granular B with foam glass and also using Recycled Cement Aggregate (RCA) in subgrade.

Table 17: Thicknesses of the layers (cm)

Scenario	Surface Thickness	Binder Thickness	Granular "A" thickness	Foam glass Thickness	RCA Thickness	Soil
3	6	6	15	210	0	Const
4	6	6	15	198	12	Const

5.3.4 Comparison of Pavement Responses

Figures 18 and 19 illustrate the deflection variations, vertical stress variation, horizontal strain variation and vertical strain variation with depth at point 1 (X=0, Y=0) for both EPS and Foam glass in the second phase of the pavement response evaluation study. It can be recognized from the figures that in all cases, the sections with FG-LWA materials exhibited a more favorable mechanistic response as compared to the reference section with EPS.

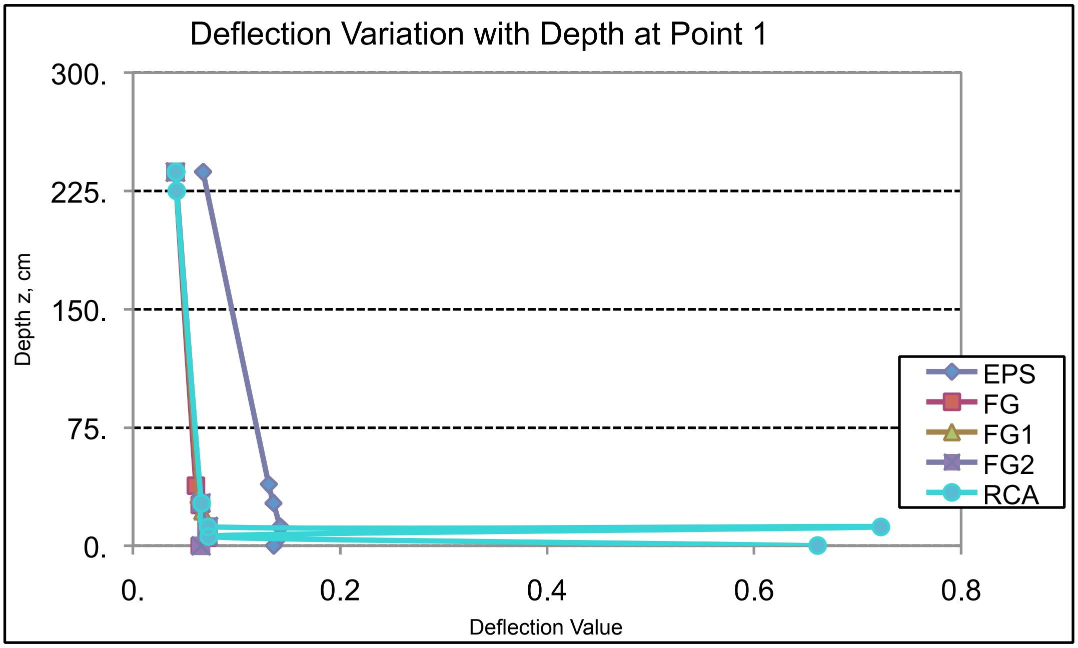


Figure 18: Deflection variation

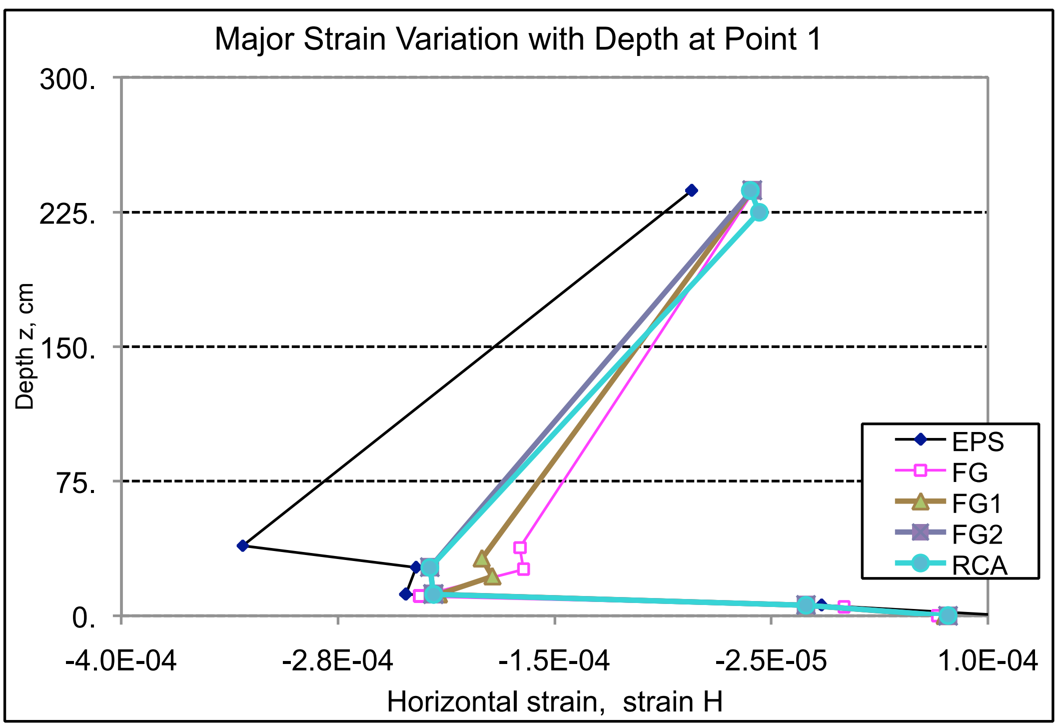


Figure 19: Major strain variation with depth

In order to compare the expected service life of each pavement design scenario, the allowable number of load repetitions to failure was calculated using the empirical fatigue model developed by asphalt institute:

$$N_f = f_1 \ (\varepsilon_t)_2^{-f} \ (E)_3^{-f}$$

(Eq. 2)

Where

f1=0.0796, f2=3.291, f3=0.854, εt= tensile strain at the bottom of HMA layer, E= modulus of elasticity of the asphalt layer.

Nf is calculated for the different scenarios in this thesis and is provided in Table 18. The results indicate longer expected service life for the pavement sections using FG-LWA.

Furthermore, the densities of each material used in pavement design structure as indicated in Table 19 were used and the amount of materials needed for a unit pavement section of one meter by one meter (length by width) was calculated and provided in Table 20. For this purpose, the layer thicknesses and the corresponding material densities were taken into account. An approximate cost of construction for each scenario was then calculated using the results from Table 20.

Table 18: Number of load repetition to failure

Million	**Standard1**	**Standard2**	**Scenario1**	**Scenario2**	**Scenario3**	**Scenario4**
Nf	73.6	110	82.4	97	93.4	93.4

Using the work by Schneider's (2016) the unit cost for materials used in the scenarios are as follows:

- The unit cost of EPS: 110.67 $/m3
- The unit cost of Foam glass: 76.47 $/m3
- The unit cost of HMA: 258.50 $/m3
- The unit cost of Granular A: 42.30 $/m3
- The unit cost of Granular B: 35.25 $/m3
- The unit cost of RCA: 0.0078$/kg (Al-Bayati et al., 2018)

Table 19: Density of the layers

Layer	Density (Kg/m^3)
Surface	2200
Binder	2200
Granular A	1800
Granular B	1550
EPS	50
RCA	2295
Foam Glass	150

Table 20: tonnage per unit pavement section and cost for each scenario

Design	Amount/unit pavement section (t)	Cost ($\$/m^3$)
Standard 1 (EPS)	0.819	260.71
Standard 2 (Foam glass)	1.17	193.00
Scenario 1	0.906	191.17
Scenario 2	0.996	195.53
Scenario 3	0.849	197.95
Scenario 4	1.16	190.71

It is estimated from the calculation above that scenario 3 would be the most economically feasible scenario with respect to both the unit weight of the pavement and the unit price per cubic meter.

5.4 Summary

In this chapter, the potential impacts of replacing the traditionally used EPS with the proposed FG-LWA materials were evaluated with respect to the mechanistic pavement response. A case study was conducted using an existing pavement section completed by MTO. First, it was shown that the critical strains as well as pavement deflection will be moderated when FG-LWA is used in the pavement structures as compared to the EPS. Then, four different pavement sections were evaluated using KenPave program to determine whether using FG-LWA can help reduce the HMA layer thickness and granular base thickness in the original design. Finally, the materials densities along with the layers thicknesses were used to calculate the unit price of constructing 1m by 1m of the different pavement design scenarios. It was concluded that using FG-LWA would be a promising alternative to replace the conventional lightweight fill materials for pavement application.

Chapter 6: Assessment of Environmental Impact of FG-LWA compared to EPS

This chapter of thesis focuses on the Life Cycle Assessment (LCA) as a tool for strategic planning by assessing the environmental aspects of using different materials in the pavement structure. Two types of road paving technologies based on the use of two different mixtures containing innovative FFG-LWA and EPS are discussed in this chapter. LCA has been found to be a useful tool when comparing various products.

6.1 Life Cycle Assessment of Pavement Designs:

Nowadays, stakeholders in pavement projects have an interest in evaluating environmental burdens by considering different life cycle stages of roads. Figure 20 illustrates FHWA's description of the Life Cycle Assessment stages for pavement design. According to the figure the pavement life cycle includes the material production, design, construction (new construction as well as preservation, maintenance and rehabilitation activities), and use and end-of-life stages associated with the pavement structure.

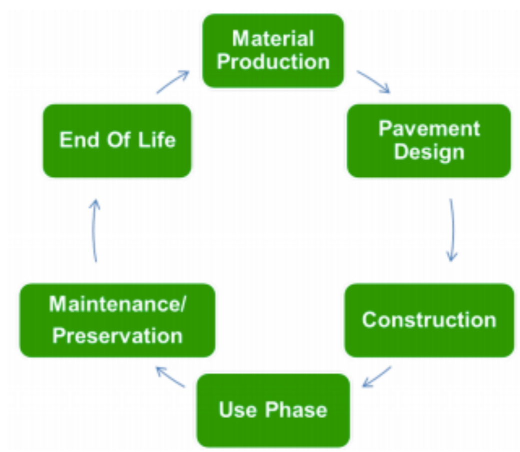


Figure 20: Pavement life cycle (FHWA)

LCA is the appropriate tool that can help the project stakeholders to deal with environmental aspects of their pavements to reach the objective of sustainable pavement construction. Indeed, LCA helps to quantify, analyze, and compare environmental impacts of different types of pavements from the material extraction to their end of life. For pavement design, therefore, the life cycle is typically defined as the phases of extraction and production, construction, use, maintenance and rehabilitation

(M&R) and End of Life (EOL). Each of these steps is affected by the design of the pavement, where the choice of structural pavement layers and materials is made to achieve the expected pavement performance for a given traffic, climate and native soil.

The parameters to be considered for the environmental impact assessment of using of EPS versus FG-LWA on the roads are:

- Global warming potential,
- Carbon dioxide emission,
- Depletion potential of the stratospheric ozone layer,
- Acidification potential of land and water,
- Depletion of recourses, and
- Toxicological stress on human health and ecosystem,

6.2 Methodology

6.2.1 Goal and Scope of the LCA study

The goal and scope definition phase is the first step in a LCA study. In this phase, the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study.

The objective of this study is to undertake a detailed review of Canada's road construction designs for specific roads that needs more insulation material to prevent the damages occurring due to the humidity and weather conditions. In this case, the comparison between the most commonly used insulation material, called Expanded Polystyrene (EPS), and a new product called FG-LWA is being made to identify whether to transfer the new foam glass technologies into Canada's road instead of using other non-environmentally friendly materials. Due to its long service life, the disposal of the EPS and foam glass cannot yet be quantified and is thus not included.

There are concerns from the environmental sustainability point of view for using waste glass as raw material for the production of FG-LWA. However, such process not only turns waste into treasure and reduces resource consumption, but also protects the environment. The challenges that have emerged by increasing the amount of municipal waste glasses that is sent to the landfill made it an urgent matter to find a solution. Hence, this research has proposed an innovative solution to address such concern as well as improving the durability of pavements.

6.2.2 Functional Unit

As we discussed before, the aim of this study is to review the environmental aspects of Canada's road construction pavement designs for specific roads that needs more insulation material in order to reach the objective of sustainable pavement construction. It is assumed that both systems cover the criteria for driving safely and smoothly on the road. It is also assumed that the traffic and other design life aspects are the same for all the systems. The intended audiences for this study will be municipalities and ministries, as well as potential investors. The thesis also focuses on the region of Kitchener-Ontario, Canada with moderate to low temperature during winters and hot weather during summers.

In this study, the functional unit is defined as one lane-km of driving pavement. Width and thicknesses of each section with different materials are based on the specific design for each material.

6.2.3 Reference Flow

In order to better understand the reference flow, the research explains the amount of material to be used to fulfill the functional unit for both products. Therefore, the materials needed to get to produce one lane-km of service for each pavement design is clearly defined. In this chapter, the same pavement design is used to compare the LCA of using foam glass LWA with EPS in road construction for the application of lightweight fill material and protection against environmental condition.

In conventional flexible pavements, material layers are usually arranged in the order of descending load-bearing capacity with the highest load bearing capacity material on the top and the lowest load-bearing capacity material at the bottom. This section describes the typical flexible pavement structure consisting of:

1. Surface course: This is the top layer and the layer that comes in contact with traffic. It may be composed of single or multiple lifts of HMA.
2. Base course: This is the layer directly below the surface course and generally consists of aggregate.
3. Sub-base course: This is the layer (or layers) under the base layer.

Based on each pavement design, the thickness of each layer will be different. According to OPSS 310, Construction Specification for HMA, and assuming that the materials are all transported to the construction site and the segments excavated and ready to be paved, different types of machineries are used for placing the pavement layers. For both EPS and FG-LWA, it is assumed that the materials would be transported from a distance of maximum 200 km to the construction job site. FG-LWA layers will be placed and distributed using crawler mounted excavator. EPS is usually handled by workforce, therefore in the placement of EPS, there is much more worker needed.

Following Schneider's (2016) research on Life Cycle Cost Assessment (LCCA) of using EPS and foam glass in pavement applications, the systems consist of an HMA layer underlain by an unbound granular base layer, an unbound granular sub-base fill layer, and finally either foam glass or EPS acting as the sub-grade. Assumptions are that three different lifetime design 80-kN equivalent single axle load (ESAL) levels were examined; corresponding to low (1 x 10^6 over 20 years), intermediate (10 x 10^6 over 20 years) and high (60 x 10^6 over 30 years) highway traffic. In this thesis, the low highway traffic is assumed.

In his LCCA assessment, Schneider presented each design case with the application of hypothetical roadway section of one km length. A total structure height of 6 meters was assumed for all cases, whereby the HMA, granular base and granular sub-base layer thicknesses are as specified in Table 21 and the remainder of the depth is made up of artificial lightweight fill material in the form of either FG-LWA or EPS geo-foam, depending on the specific design case. The roadway width was assumed to be 3.75 meters in all cases. Also, the minimum thickness of the HMA layer in all cases was assumed to be 3.0 in (76.2 mm) for the low traffic under AASHTO 1993 pavement design method. The densities of FG-LWA as well as EPS used in the study are mentioned in Table 21. Table 22 provides the depths and volumes of the layers.

Table 21: Density of the material used in the design

The density of foam glass (kg/m^3)	The density of Aggregate (kg/m^3)	The density of HMA (kg/m^3)	The density of EPS (kg/m^3)
150	2430	2350	30

Table 22: Thicknesses of the layers for pavement structure of foam glass and EPS (Schneider, 2016)

Design Artificial Subgrade	LWA	EPS	Unit
Design Lifetime ESALs	$1x10^6$	$1x10^6$	
Depth Hot Mix Asphalt	127.0	317.5	mm
Depth Granular Base	152.4	152.4	mm
Depth Granular Subbase	152.4	152.4	mm
Depth Lightweight Fill	5568.2	5377.7	mm
Road Length	1000	1000	m
Road Width	15	15	m
Volume Hot Mix Asphalt	1905.0	4762.5	**m^3**
Volume Granular Base	2286.0	2286.0	**m^3**
Volume Granular subbase	2286.0	2286.0	**m^3**
Volume Lightweight Fill (m3)	83523.0	80665.5	**m^3**

6.2.4 System Boundaries

In this thesis, it is assumed that the two pavement designs have the same design life, traffic and maintenance, and repair program. The overall system boundary for the LCA of pavement design using both Foam glass and EPS is shown below. Based on the design method that is used in this study, the use cycle as well as the maintenance and repair life are not considered as we assume that the road is built for the same function with the same design life and the same serviceability and maintenance. Therefore, the same design method is used to assume that all the two pavement designs are equivalent. (Figure 21)

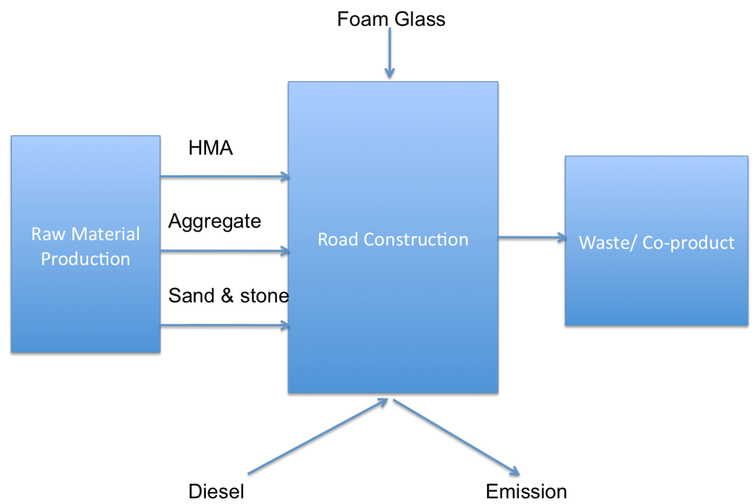


Figure 21: system boundaries for pavement structure using foam glass

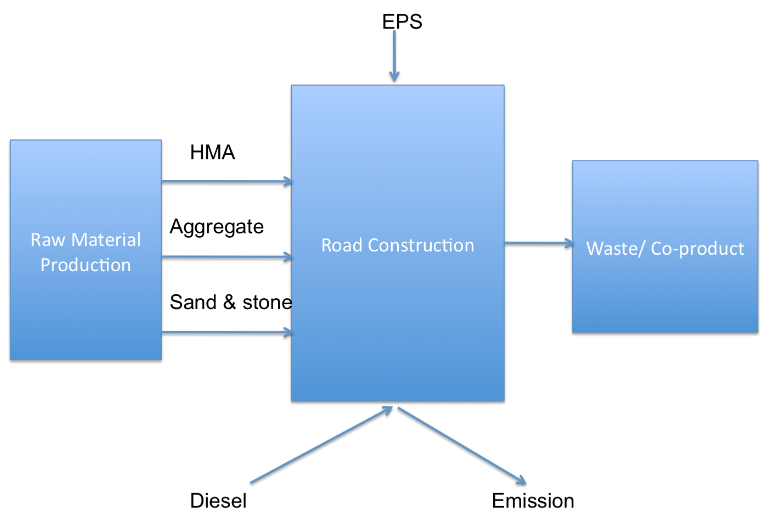


Figure 22: system boundaries for the pavement structure using EPS

Following the system boundaries of FG-LWA as well as EPS an HMA are described.

6.2.4.1 FG-LWA System Boundaries:

For better understanding the system boundaries of FG-LWA, the raw material as well as production steps of the material are discussed. Figure 24 details the system boundary of the LCA for foam glass manufacturing.

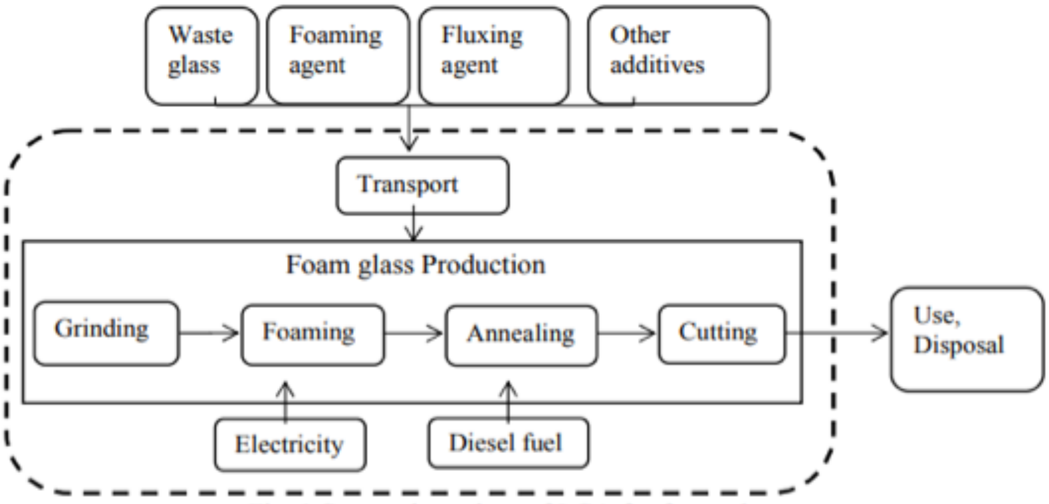


Figure 23: system boundaries for the production of foam glass (James, 2003)

6.2.4.2 EPS System Boundaries:

The primary purpose of the Life Cycle Assessment of the EPS is to provide updated environmental impacts associated with the material. Figure 24 details the system boundary of the LCA for the production of Expanded Polystyrene. The use and Disposal parts are not discussed in this thesis.

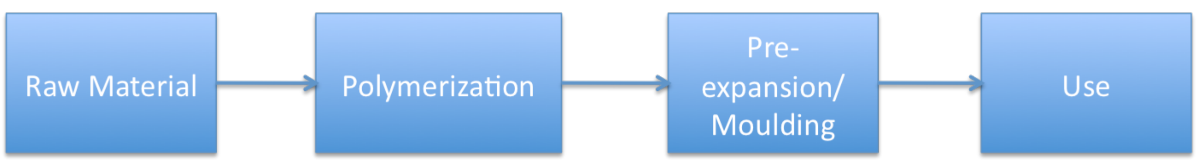


Figure 24: system boundaries for the production of EPS

6.2.4.3 HMA System Boundaries:

As explained previously, we have defined the Hot Mix Asphalt in the software program based on the definitions of Natural Resources Canada and Ambaiowei (2014) work. The system boundary of the production of HMA is illustrated by Figure 25.

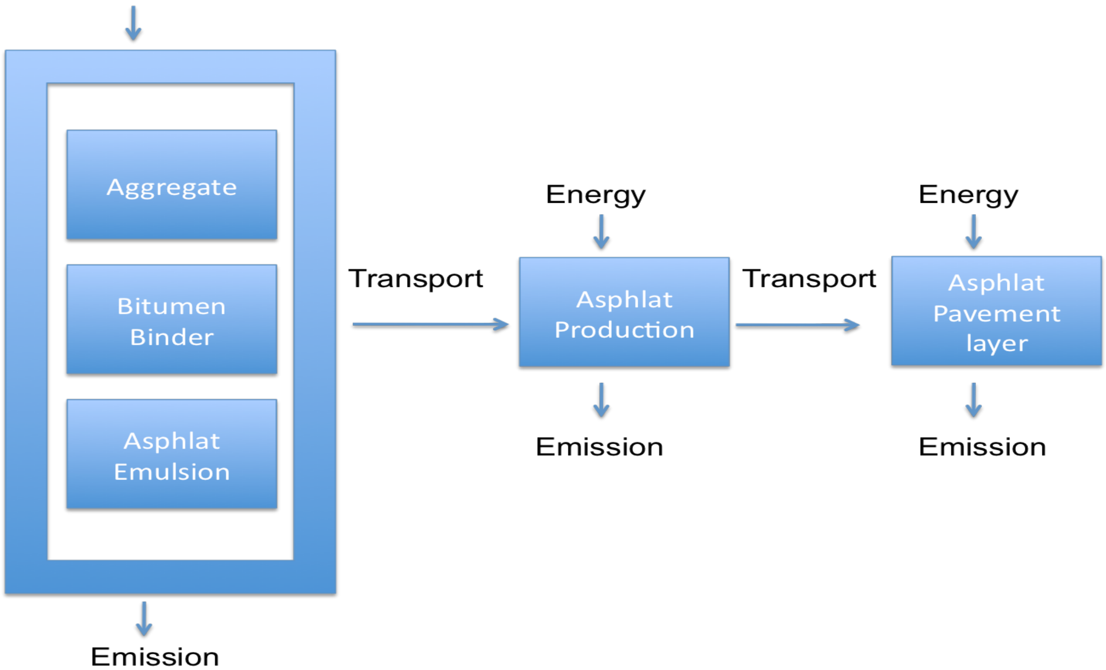


Figure 25: system boundaries for the production of HMA

6.2.5 Life Cycle Inventory Analysis

6.2.5.1 Data Collection

SimaPro 8.04 LCA software program was used in this thesis to model the systems of interests. All the new processes must be defined based on the system boundaries of the project. The new processes included FG-LWA material and the manufacturing processes; HMA material and manufacturing processes, Expanded Polystyrene material and manufacturing processes as well as granular materials for the sub-base and base layesr. In order to define all the energies consumed based on the Ontario's Electricity Energy Grid, the 2016 Ontario electricity grid mix has been defined as presented by Table 23.

Placement and construction consist of all activities required to install the materials. Energy consumption for asphalt binder production includes crude oil extraction, transport, and refining energy. Energy consumption for asphalt binders has been determined to be 4.900 MJ/kg. For asphalt emulsions, energy consumption is 3490 MJ/t. The energy consumption for aggregate production is defined to be 0.0305 MJ/kg (chehovits et al., 2010). Also, the highest energy consuming process for placement is hot-in-place with 0.456 MJ/kg.

Table 23: Ontario electricity grid (2016)

Name	Amount	Unit	Distribution	SD^2 or 2*SD Min
Electricity/heat				
Electricity, hydropower, at reservoir power plant/FI U	0.233	KWh	Lognormal	1.17
Electricity, nuclear, at power plant/US U	0.585	KWh	Lognormal	1.13
Electricity, natural gas, at power plant/US U	0.082	KWh	Lognormal	1.13
Electricity, hard coal, at power plant/US U	0	KWh	Lognormal	1.14
Electricity, at wind power plant 2MW, offshore/OCE U	0.068	KWh	Lognormal	1.13
Electricity, biomass, at power plant/US	0.005	KWh	Lognormal	1.35
Electricity, production mix photovoltaic, at plant/US U	0.022	KWh	Lognormal	1.14
Electricity from waste, at municipal waste incineration plant/CH S	0.004	KWh	Lognormal	1.38

On the other hand, Chehovits et al. (2010) discusses that the produced construction materials must be transported to the job site. Transport energy has been reported as 0.0009 MJ/kmt. The density of HMA was assumed to be 2350 kg/m3, and the density of the aggregates used was chosen to be 2430 kg/m3. According to the study of Arulrajah et al. (2015) the total energy consumption related to the use of foam glass as a construction material is Zero. We assume that the placement of EPS has also zero energy consumption. In this thesis the highest hot-in-place energy of 0.456 MJ/kg would be used for pavement design for both Foam glass and EPS.

According to Table 5, the energy consumption is for the HMA placement with the weight of 911.26 tonnes. Therefore, the energy is equal to 1394750 MJ/kg. Table 24 summarized the energy consumption for different materials in the pavement structure.

Based on the system process for producing Hot Mix Asphalt (Table 4) and using Ambaiowai (2014), the input (material, fuel) and emission outputs is defined in Table 25. No emission to water or soil is defined in this model.

Table 24: Energy consumption for the production of Asphalt binder, emulsion, aggregate and the placement of HMA

Product	Energy consumption	Unit
HMA-placement	1.39E06	MJ/kg
Asphalt binder production	4.9	MJ/kg
Asphalt emulsion production	3.49E06	MJ/kg
Aggregate production	0.0305	MJ/kg

Table 25: SimaPro model definition of HMA

Materials/fuels	Amount	Unit
Gravel, crushed, at mine/CH with US electricity U	0.95	Kg
Bitumen, at refinery/CH with US electricity U	0.05	Kg
Electricity/heat		
Process water, ion exchange, production mix, at plant, from surface water RER S	424	Kg
Propane	0.26	Kg
Heavy fuel oil	0.64	Kg
Diesel	1.05	Kg
Residual fuel oil	2.95	L
Natural gas combustion in industrial equipment	4.66	M3
Diesel	4.9	MJ
Diesel	3490000	MJ

Diesel	1394750	MJ
New Ontario electricity grid mix	2.12	Kwh
Emissions to air		
Carbon monoxide	263	kg
Carbon dioxide	70	mg
Nitrogen oxides	718	kg
Particulates, < 10 um	244	kg
Sulfur dioxide	9467	kg
Mercury	1.72	g
Lead	83	g

It is needed to define the FG-LWA since the material is new and the software does not include it. Based on the manufacturer datasheet the material is consist of 95% of weight from the mixed glass, from the public collection, 2% silicon carbide; as a foaming agent and 3% Kaolin. According to the manufacturer's technical data energy consumption demand for the production of 1m^3 foam glass is as follows:

- 30 KWh/m^3 for processing and preparation of raw materials
- 70 KWh/m^3 for heating foam glass

The total amount of 100 KWh/m^3 is needed for the production of 1m^3 foam glass. Water demand is 200 Kg/m3. The energy requirement for aggregate crushing is 3.36 KWh/m^3.

Using the 2016 Ontario Mix grid, the Foam Glass manufacturing process is defined as Table 26.

Table 26: Simapro model definition for Foam Glass Aggregate

Materials/fuels	**Amount**	**Unit**
Glass, from public collection, unsorted/RER U	0.95	Kg
Kaolin, at plant/RER with US electricity U	0.03	Kg
Silicon carbide, at plant/RER with US electricity U	0.02	Kg

Electricity/heat		
New- 2016 Ontario electricity grid mix	0.67	kWh
New- 2016 Ontario electricity grid mix	0.023	kWh
Process water, ion exchange, production mix, at plant	0.005	kg

The EPS is defined based on three different models; one the EPS defined in the OpenLCA software database (Appendix A), with all the inputs and outputs, one the EPS defined in Simapro by adding the blow molding process (Table 29) and finally EPS based on the work of Khoo et al. (Khoo et al., 2005). (Table 28) The same thicknesses of the layers for all the pavement models using any of the EPS models are defined.

Table 27: Simapro model definition for EPS (khoo et al., 2005)

Materials/fuels	Amount	Unit
Bauxite, at mine/GLO US-EI U	1.11	g
Hard coal mix, at regional storage/UCTE US-EI U	87.41	g
Crude oil E	2.150	g
Lignite, at mine/US- US-EI U	22.14	g
Nitrogen, liquid, at plant/US- US-EI U	30.88	g
Natural gas, unprocessed, at extraction/RNA US-EI U	1.75	M^3
Emissions to air		
Carbon monoxide	1381.12	mg
Carbon dioxide	608974	mg
Methane	4122.37	mg
Nitrogen oxides	11072.26	mg
Sulfur oxides	6905.59	mg
Hydrogen sulfide	0.59	mg

Hydrocarbons, unspecified	3997.66	mg
Metals, unspecified	5.83	mg
Hydrogen	81.59	mg
Emissions to water		
COD, Chemical Oxygen Demand	670.16	mg
BOD5, Biological Oxygen Demand	139.86	mg
Suspended solids, unspecified	710.95	mg
Hydrocarbons, unspecified	69.93	mg
Ammonium, ion	11.07	mg
Phenol	1.165	mg
Aluminium	44.87	mg
Calcium, ion	1.16	mg
Copper, ion	1.16	mg
Mercury	0.58	mg
Sodium, ion	699.3	mg
Nickel, ion	0.99	mg
Lead, ion	0.58	mg
Zinc, ion	0.012	mg
Sulfur dioxide	23.89	mg
Carbonate	157.34	mg
Nitrate	4.08	mg
Phosphate	5.24	mg

Table 28: SimaPro model definition for EPS adding the blow molding process

Materials/fuels	Amount	Unit
Polystyrene, expandable, at plant/RER with US electricity U	1	Kg
Blow molding/US- US-EI U - hydro electricity	1	Kg

Tables 30, 31, 32 and 33 provide details of the SimaPro models for pavement designs based on information provided above using both EPS and FG-LWA has been as follows:

Table 29: SimaPro pavement structure design using foam glass

Materials/fuels	Amount	Unit
Granular base/subbase	1388745	Kg
Granular base/subbase	1388745	Kg
Hot Mix Asphalt	1119187.5	Kg
Foam Glass aggregate	3132112.5	Kg
Electricity/heat		
New- 2016 Ontario electricity grid mix	780518.34	KWh

Table 30: SimaPro pavement structure design using EPS model adding blow moudling process

Materials/fuels	Amount	Unit
Granular base/subbase	1388745	Kg
Granular base/subbase	1388745	Kg
Hot Mix Asphalt	2797968.8	Kg
EPS- material and processing-hydro power	604991.5	Kg
Electricity/heat		

New- 2016 Ontario electricity grid mix	780518.34	KWh

Table 31: SimaPro pavement structure design using the new EPS model

Materials/fuels	**Amount**	**Unit**
Granular base/subbase	1388745	Kg
Granular base/subbase	1388745	Kg
Hot Mix Asphalt	2797968.8	Kg
EPS-new study	604991.25	Kg
Electricity/heat		
New- 2016 Ontario electricity grid mix	780518.34	KWh

Table 32: SimaPro pavement structure design using EPS OpenLCA model

Materials/fuels	**Amount**	**Unit**
Granular base/subbase	1388745	kg
Granular base/subbase	1388745	kg
Hot Mix Asphalt	2797968.8	kg
Expandable Polystyrene- OpenLCA EPS removed	604991.25	kg
Electricity/heat		
New- 2016 Ontario electricity grid mix	780518.34	kWh

6.2.6 Life Cycle Impact Assessment

Baumann et al. (2004) describes that the aim of the life cycle impact assessment is to describe the environmental loads from the inventory results into environmental impacts, such as acidification, ozone depletion, global warming etc. in order to make the results more environmentally relevant, comprehensible and easier to communicate. Ayer et al. (2018) explain that the LCIA includes the grouping and characterization of resource use and emission from the Life cycle impacts into environmental impact category.

On the other hand, this study presents the characterization of the environmental impact category. According to Baumann et al. (2004) characterization is a quantitative step in which the extents of the environmental impacts are calculated per category using equivalency factor defined while modeling the cause-effect chain.

There are two impact assessments calculated in this paper using the TRACI 2.1 (version 1.00) methods. The first assessment is to calculate the environmental impacts of the production of foam glass compared to the production of each of the EPS models. (Table 34) The second assessment is to calculate the environmental impacts of the road construction models with foam glass LWA compared to the road construction models with ESP. (Table 35)

In Table 34 the impact categories from the production of one-kilogram foam glass aggregate using the Ontario electricity is compared to the production of three different models for the EPS defined in the software. EPS1 is defined as Expanded Polystyrene using the OpenLCA software model data; EPS2 is the defined EPS using Expanded Polystyrene using the Simapro software model data by adding the process of blow molding. This process contains the auxiliaries and energy demand for the mentioned conversion process of plastic. The EPS3 is the defined as expanded polystyrene based on the khoo et al. (2005) model.

Table 33: Life Cycle Assessment for the production of FG-LWA with different models of EPS

Impact category	Unit	Foam Glass aggregate	EPS1	EPS2	EPS3
Ozone depletion	Kg CFC-11 eq	5.51E-08	8.58E-08	1.15E-07	3.14E-09
Global warming	Kg CO2 eq	0.26	3.97	4.8	1.19
Smog	Kg O3 eq	0.014	0.166	0.187	0.279
Acidification	Kg SO2 eq	0.002	0.013	0.020	0.009
Eutrophication	Kg N eq	1.33E-04	6.25E-03	5.46E-03	1.9E-03

Carcinogenics	CTUh	3.12E-09	2.74E-08	1.62E-07	2.85E-08
Non-carcinogenics	CTUh	2.86E-08	3.41E-07	1.78E-07	2.22E-07
Respiratory effects	Kg PM2.5 eq	1.16E-04	9.17E-04	1.41E-03	1.62E-04
Ecotoxicity	CTUe	0.122	0.608	5.41	2.89
Fossil fuel depletion	MJ surplus	2.04E-03	12.5	1.25	9.37

As seen in Figure 26, contribution of FG-LWA production to almost all of the environmental impact categories (i.e. Fossil Fuel Depletion, Exotoxicity, Respiratory effect, Non-carcinogenic, Carcinogenic, Eutrophcation, Acidification, Smog and Global warming) is smaller than EPS production. The only exception is Ozone depletion where the EPS defined based on the Khoo et al. (2005) model resulted in less contribution. The manufacturing of foam glass produces 5.51E-08 kg CFC-11 eq of Ozone depletion but the EPS3 produces 3.14E-09 kg CFC-11 eq.

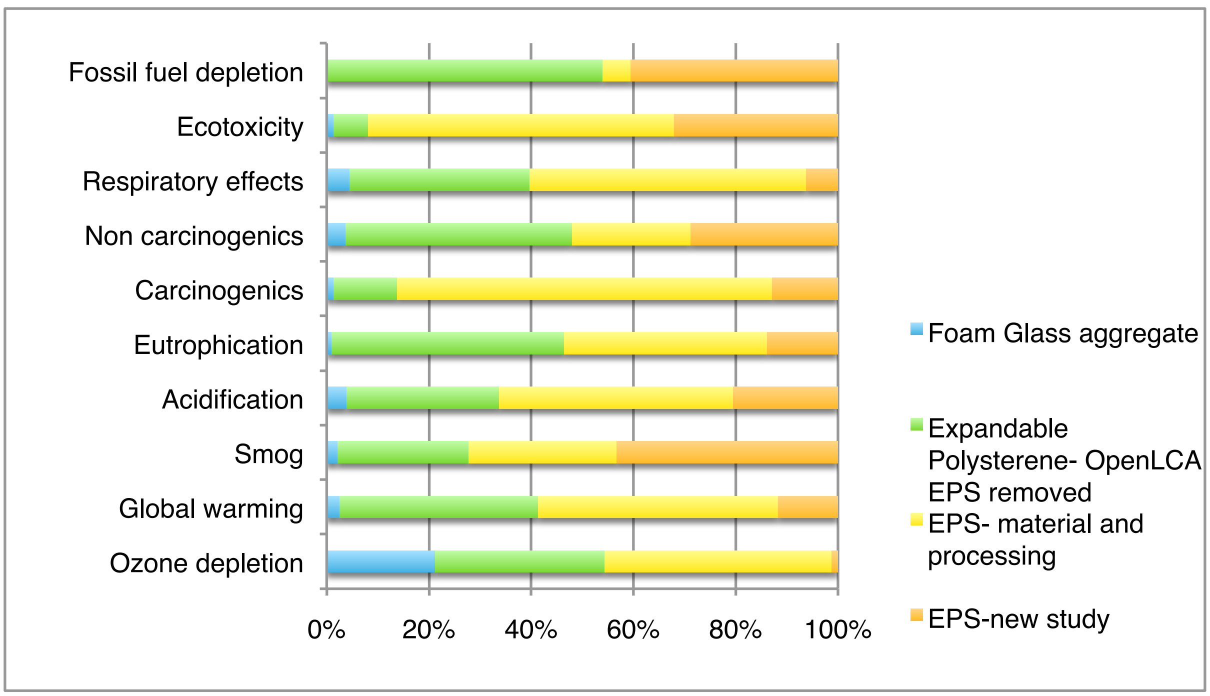


Figure 26: Environmental Impact categories for the production of foam glass versus EPS

In order to compare the road construction models based on the application of Foam Glass or EPS the TRACI 2.1 (version 1.00) method is used in SimaPro software program to estimate the environmental category impacts of each model. As indicates in Table 35 and Figure 27, the lowest contributions to all the environmental impact categories (Fossil Fuel Depletion, Exotoxicity, Respiratory effect, non-carcinogenic, Carcinogenic, Eutrophcation, Acidification, Smog and Global warming) is related to the road design incorporating the FG-LWA as compared to all other three models of EPS.

Table 34: life cycle assessment of road construction using foam glass compared to different models of EPS

Impact category	Unit	LWA Road	EPS1	EPS2	EPS3
Ozone depletion	kg CFC-11 eq	8E4	2E5	2E5	2E5
Global warming	kg CO2 eq	4.72E11	1.18E12	1.18E12	1.18E12
Smog	kg O3 eq	1.64E11	4.1E11	4.1E11	4.1E11
Acidification	kg SO2 eq	1.59E10	3.99E10	3.99E10	3.99E10
Eutrophication	kg N eq	5.3E8	1.33E9	1.33E9	1.33E9
Carcinogenics	CTUh	622	1.56E3	1.56E3	1.56E3
Non carcinogenics	CTUh	8.04E3	2.01E4	2.01E4	2.01E4
Respiratory effects	kg PM2.5 eq	1.28E9	3.19E9	3.19E9	3.19E9
Ecotoxicity	CTUe	3.33E10	8.33E10	8.33E10	8.33E10
Fossil fuel depletion	MJ surplus	9.37E11	2.34E12	2.34E12	2.34E12

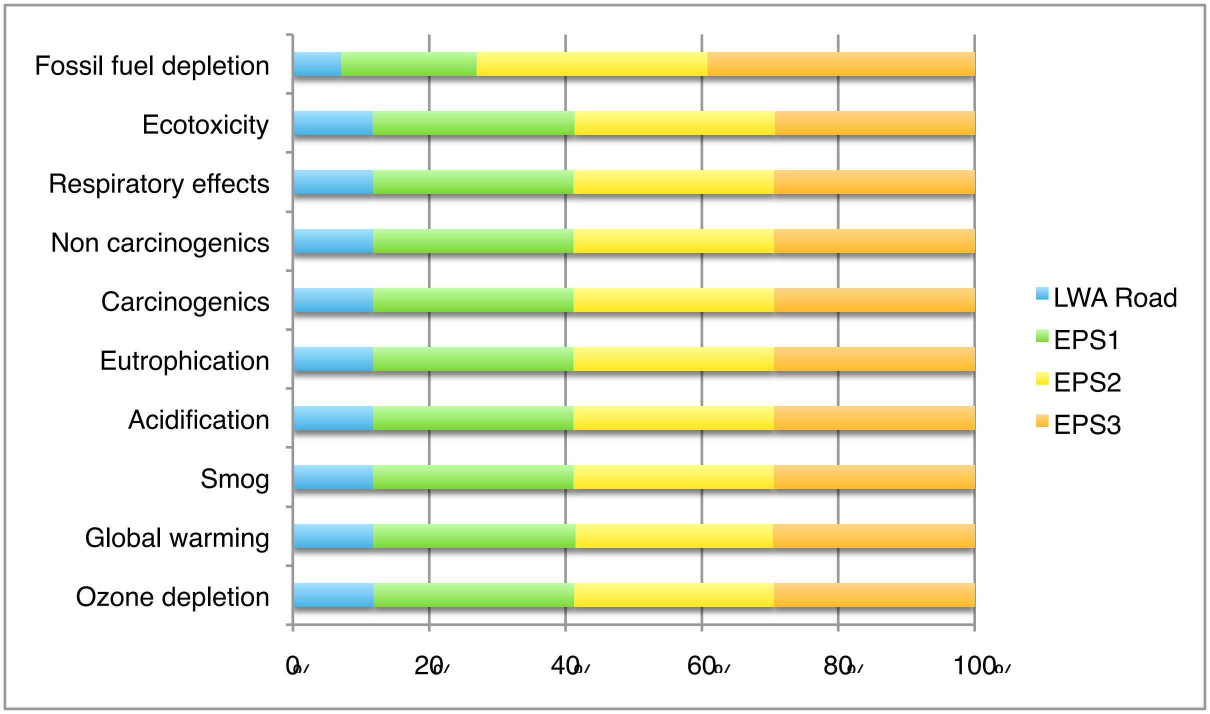


Figure 27: Environmental impact categories for road design based on foam glass versus EPS

6.3 Alternative Production Energy

The main motivation behind this part of the study was to evaluate and compare the environmental impacts of pavement designs using EPS and FG-LWA when different sources of energy are used to produce the lightweight aggregates. In order to analyze different scenarios, the sensitivity analysis in this paper focused on the outputs of the FG-LWA production when natural gas is used instead of Electricity in Canada. The production process for EPS would remain the same in this analysis.

Also the natural gas composition for the Ontario has been defined in the software using 2017 Gas Composition & Higher Heating Value (HHV) data provided by Embridge gas distribution Inc to the Ministry of Environment and Climate change. This information is provided under Ontario Regulation 143/16 under Climate Change mitigation and Low-Carbon Economy Act. The composition of Ontario typical gas is as Table 35:

Table 35: Natural gas composition for Ontario (2017)

Material	Mole %	Molecular Weight (g/mol)	Kg
Methane	94.65	16.04	0.01581
Ethane	3.79	30.07	0.113
Propane	0.20	44.1	0.008
Butane	0.03	58.12	0.0017
Nitrogen	0.85	28.14	0.023
Carbon Dioxide	0.48	44.01	0.021

According to the information mentioned above, the production of foam glass consumes 0.3 (9.8 MJ) of natural gas as per information provided by the manufacturer. Table 36 presents the energy consumption for production of $1m^3$ of foam glass using natural gas.

The comparison between the impacts of the two foam glass production processes indicates that the best model of manufacturing foam glass with less environmental impact is the model using electricity. Table 38 indicates that all environmental impact categories of producing the foam glass by the use of electricity is lower that the foam glass produced by industrial gas in Ontario.

Table 36: Energy consumption for the production of 1m3 foam glass using natural gas

Energy	Unit	Amount
Natural gas-Ontario	M^3	0.3
Electrical energy for connected load	KWh	1.27
Compressed air-6 bar	M^3	0.36
Water	Kg	0.005
Electricity for processing and preparation of raw material	KWh	0.2
Electricity for aggregate crushing	KWh	0.023

Table 37: comparing the impact category of the production of foam glass produced by electricity and the one produced by natural gas

Impact category	Unit	FG	FG by natural gas
Ozone depletion	Kg CFC-11 eq	5.51E-08	9.92E-08
Global warming	Kg CO2 eq	2.5E-1	4.5E-01
Smog	Kg O3 eq	1.3E-02	2.4E-02
Acidification	Kg SO2 eq	1.7E-03	3.2E-03
Eutrophication	Kg N eq	1.3E-04	9.11E-04
Carcinogenics	CTUh	3.12E-09	9.63E-09
Non carcinogenics	CTUh	2.86E-08	2.60E-07
Respiratory effects	Kg PM2.5 eq	1.1E-04	2.24E-04
Ecotoxicity	CTUe	1.2E-01	6.3E-01
Fossil fuel depletion	MJ surplus	2.03E-03	3.97

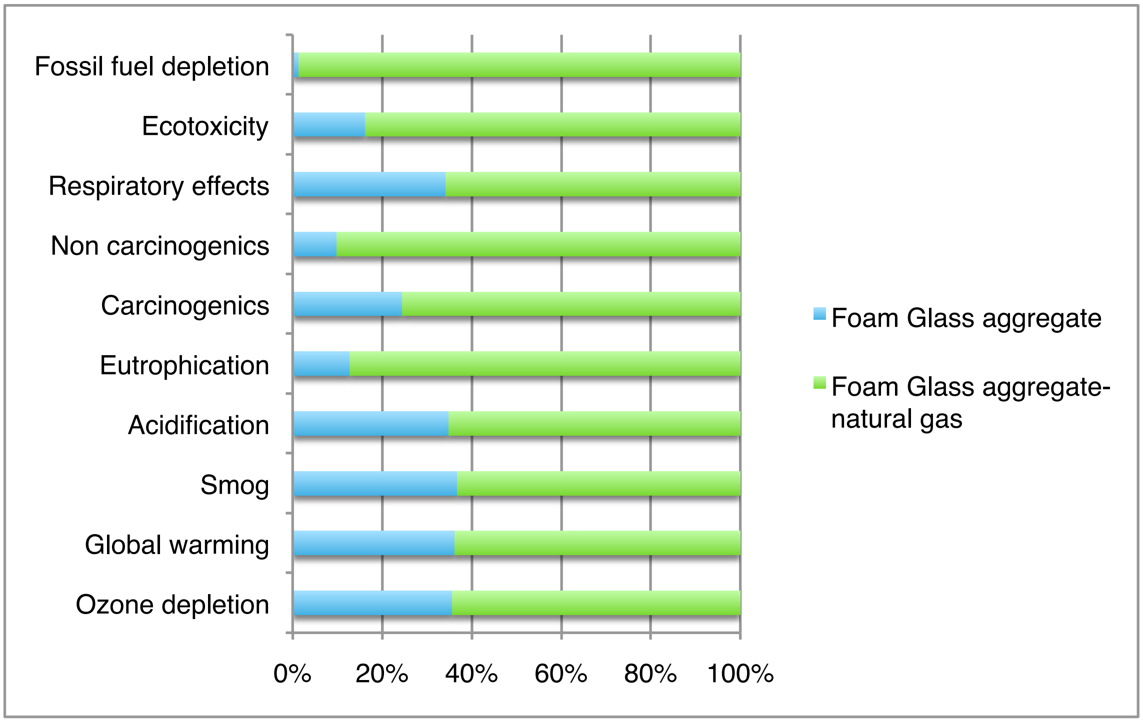


Figure 28: Environmental impact categories of FG-LWA produced by electricity and FG-LWA produced by gas

On the other hand in order to compare the proposed foam glass in Canada with products already used in the European market, four impact categories of ozone depletion, global warming, acidification and fossil fuel of the foam glass manufactured by the electricity in Ontario and the foam glass manufactured by the Misapor manufacturing company will be compared which includes promising results for the Foam glass manufactured in Ontario using electricity.

Table 38: comparison of foam glass produced in Ontario and the European produced sample

Impact category	Unit	FG-Ontario	FG-Misapor
Ozone depletion	Kg CFC-11 eq	5.51E-08	2.11E-06
Global warming	Kg CO2 eq	2.5E-01	1.52E+1
Acidification	Kg SO2 eq	1.73E-03	7.17E-2
Fossil fuel depletion	MJ surplus	2.03E-03	1.94E+2

Chapter 7: Conclusions and Suggested Future Work

7.1 Conclusions

The research presented in this thesis was a part of a bigger research project aiming to evaluate the feasibility of using Foam Glass Lightweight Aggregate (FG-LWA) in construction projects, and particularly as a lightweight fill material in pavement application. The main goal of the research was to produce an innovative construction material that can address a growing concern with the abundance of the municipal waste glass deposits and at the same time help with durability of pavements in Canada.

The results of physical, mechanical and chemical properties of the FG-LWA indicate that the material is suitable to be used as aggregate in pavements and it conforms to the requirements of the OPSS 1010 for granular A, M, O, S and B. Also, as a part of the environmental assessment of the FG-LWA, chemical properties of the material were evaluated at Golder & Associates labs. The Toxicity Characteristics Leaching Procedures (TCLP) results for samples tested identified arsenic and lead exceedances of their respective ODWS. This indicated that the FG-LWA would fall within the "Restricted Level 1" and "Restricted Level 2" categories based on arsenic and lead levels. However, in consideration of the greatest exceedance, the TCLP leachate generated results in Restricted – Level 2 category. Therefore, the use of FG-LWA should be restricted for applications where it would be placed greater than 2 m above the nominal groundwater level, greater than 100m away from potable water wells and greater than 30m away from water bodies.

Furthermore, in order to improve the FG-LWA features, research was expanded to evaluate the effects of changing the formulation, foaming agent type and content, manufacturing temperatures, and sources of the raw materials. The application of other glassy and glass-ceramic raw materials with a controlled microstructure, modifications in shapes and sizes of the pores and the application of ceramic colors in foams were also explored. The effect of the aforementioned factors on the microstructure of the end product was also studied through the use of Scanning Electron Microscopy (SEM). It was concluded that a homogenous microstructure and enhanced properties can be achieved by using waste of ceramic frits and glazes under a firing condition of 800°C and 30 minutes of firing cycle.

In order to evaluate the potential of using FG-LWA as an alternative lightweight fill material, mechanistic pavement design and conceptual Life Cycle Assessment (LCA) approaches were used.

An existing pavement construction project completed by the Ministry of Transportation (MTO), was re-evaluated, where EPS was used in the original design. The design evaluation was completed in two phases. Under phase one, the same pavement structure proposed by MTO was adopted and only the FG-LWA material was used instead of existing EPS. The second phase included the evaluation of four scenarios with different structural layers and thicknesses, where FG-LWA was used as an alternative to the EPS with the objective of achieving equal or lower values for the critical stresses and strains at the bottom of the asphalt layer and on the top of the subgrade layer. To this end, Kenpave program was used to conduct a mechanistic design evaluation of the pavements using FG-LWA. The results indicated that a longer service life can be expected when using FG-LWA is used instead of the EPS.

Finally, Life Cycle Analysis approach was used as a means for strategic planning, analysis and quantification of the environmental impacts of using two different materials in pavement structure (FG-LWA versus EPS). The Simapro software program was used to collect, analyze and monitor the sustainability performance of products and services. Two flexible pavement structures, designed for a specific set of traffic and climatic conditions, were used in the LCA study. The first pavement structure used Expanded Polystyrene (EPS) as lightweight fill material and was considered as the baseline scenario, while in the second one the EPS was replaced by FG-LWA. The thicknesses of all other pavement layers (asphalt and granular layers) were determined using the AASHTO 93 Pavement Design Approach to ensure the equivalency and comparability of the two pavement structures. The environmental impact categories considered for the two pavements included the Ozone Depletion Potential, Global Warming Potential, Acidification Potential, Eutrophication Potential, Carcinogens, Noncarcinogens, Smog Potential, Respiratory Effects, Ecotoxicity, and Fossil Fuel Depletion. The impacts were calculated using the characterization factors from the TRACI 2.1 LCIA model.

In order to identify whether to transfer the new FG-LWA technologies into Canada's road instead of using other non-environmentally friendly materials, the effect of using different sources of energies for manufacturing purposes was also studied. The outcome of all assessments shows lower environmental impact and emission when the FG-LWA is used instead of EPS in pavement application, especially if electricity is used for production rather than natural gas.

In conclusion, the Foam Glass Lightweight Aggregate was found to be an innovative material that uses recycled waste glass to produce high quality aggregates with superior properties for pavement application. The produced aggregates have a density between 120 to 150 kg/m3, which is 15 to 20 times lighter than natural aggregates. The results confirm that the FG-LWA could be used as lightweight fill materials to replace other industrial alternative, such as EPS which is a petroleum-based product. Consequently, this can lead to a longer life pavement with significantly lower environmental impacts.

7.2 Suggested Future Work

There are still areas of further research and development on the material in order to improve its physical, mechanical and chemical properties. The areas of future advancements proposed in this thesis for future research are as follows:

1. Research on production of red and other colored FG-LWA to be used in construction of bus and bicycle lanes and runways.
2. Investigation of nano-coating of interconnected type microstructure of foam glass materials for developing new activated aggregates with the capability of filtering water.
3. Modifying the formulation of the FG-LWA and finding the best manufacturing processes in order to alleviate the traces of Arsenic and Lead, which were found to exceed the specifications requirements in this research.

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A. SimaPro model for EPS from OpenLCA database

Materials/fuels		
Anhydrite floor, at plant/CH U	8.42E-06	kg
Barite, at plant/RER U	0.000001291	kg
Limestone, at mine/US* US-EI U	0.00039	kg
Chromium, at regional storage/RER U	2.33E-08	kg
Aluminium product manufacturing, average metal working/RER with US electricity U	0.00018	kg
108 Waste treatment, Incineration of waste, Oil/Hazardous waste, EU27	-0.01549	kg
Bentonite, at mine/DE with US electricity U	0.000082878	kg
Clay, at mine/CH with US electricity U	1.15E-07	kg
Coal FAL	0.1463	kg
Copper, primary, at refinery/US- US-EI U	0.00019	kg
Dolomite, at plant/RER with US electricity U	4.26E-06	kg
Electricity, biomass, at power plant/US	0.19339	MJ
Electricity, hydropower, at reservoir power plant/BR with US electricity U	0.22674	MJ
Fluorspar, 97%, at plant/GLO with US electricity U	0.000014954	kg
Natural gas (m3)	0.90765	m3
Natural stone plate, grounded, at regional storage/US* US-EI U	4.94E-13	kg
Gravel, unspecified, at mine/CH with US electricity U	1.28E-06	kg

108 Waste treatment, Incineration of waste, Oil/Hazardous waste, EU27	-0.0003	kg
108 Waste treatment, Incineration of waste, Oil/Hazardous waste, EU27	-0.01166	kg
Iron ore, 46% Fe, at mine/GLO with US electricity U	0.00035	kg
Lead, primary, at plant/GLO with US electricity U	5.62E-07	kg
Manganese, at regional storage/RER with US electricity U	4.48E-07	kg
Dummy_Disposal, solid waste, unspecified, to unspecified treatment/kg/US	-0.02695	kg
Nickel, 99.5%, at plant/GLO with US electricity U	0.000027335	kg
Crude oil E	1.0429	kg
Peat, at mine/NORDEL with US electricity U	0.00085	kg
Phosphorus, white, liquid, at plant/RER with US electricity U	1.56E-11	kg
Sand, at mine/CH with US electricity U	0.00056	kg
Sodium chloride, at plant NREL/RNA U	0.00227	kg
Sulfur, at plant/kg NREL/RNA U	0.0002	kg
Uranium from mine S	6.54E-06	kg
118 Waste treatment, Landfill of waste, Plastic, EU27	-0.00012	kg
118 Waste treatment, Landfill of waste, Plastic, EU27	-0.00178	kg
126 Waste treatment, Landfill of waste, Wood, EU27	-3.41E-06	kg
126 Waste treatment, Landfill of waste, Wood, EU27	-0.00012	kg
Washing, cold water/US	0.16509	m3
Tap water, at user/CH with US electricity U	2.78E-10	kg

Zinc sulphide, ZnS, at plant/US- US-EI U	0.00002573	kg
Emissions to air		
Aldehydes, unspecified	1.08E-13	kg
Ammonia	7.35E-09	kg
Antimony	3.33E-11	kg
Arsenic	1.02E-08	kg
Benzene	0.000018257	kg
Benzene, (chloromethyl) ethenyl-	5.30E-06	kg
Cadmium	1.16E-09	kg
Carbon dioxide, biogenic	0.00509	kg
Carbon dioxide, fossil	2.5405	kg
Carbon disulfide	4.25E-09	kg
Carbon monoxide, biogenic	7.54E-06	kg
Carbon monoxide, fossil	0.00377	kg
Chlorine	9.82E-07	kg
Chromium	2.83E-06	kg
Copper	6.87E-08	kg
Dinitrogen monoxide	2.15E-08	kg
Ethane, 1,2-dichloro-	1.57E-09	kg
Ethene	6.66E-06	kg
Ethene, chloro-	7.59E-10	kg
Fluorine	3.59E-08	kg
Hydrocarbons, aliphatic, alkanes, cyclic	5.59E-06	kg

Hydrocarbons, aromatic	0.000028169	kg
Hydrocarbons, chlorinated	6.82E-07	kg
Hydrogen	0.000060023	kg
Hydrogen chloride	0.000059488	kg
Hydrogen fluoride	2.20E-06	kg
Hydrogen sulfide	1.19E-08	kg
Lead	2.75E-07	kg
Methane, biogenic	0.00006252	kg
Mercury	1.84E-09	kg
Methane, chlorodifluoro-, HCFC-22	0.000001124	kg
Methane, dichloro-, HCC-30	3.01E-09	kg
Methane, fossil	0.03123	kg
Nickel	5.15E-06	kg
Nitrogen oxides	0.00484	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	0.00517	kg
Particulates, < 2.5 um	0.00022	kg
Particulates, > 10 um	0.00028	kg
Particulates, > 2.5 um, and < 10um	0.00038	kg
Propene	0.000004934	kg
Selenium	3.54E-11	kg
Silver	1.02E-09	kg
Styrene	0.000045081	kg

Sulfate	7.51E-15	kg
Sulfur dioxide	0.007	kg
Toluene	0.000002536	kg
Water	65.18522	kg
Xylene	1.06E-06	kg
Zinc	3.24E-08	kg
Emissions to water		
Acidity, unspecified	7.82E-06	kg
Aluminium	1.17E-06	kg
Ammonium, ion	0.000029316	kg
AOX, Adsorbable Organic Halogen as Cl	6.05E-08	kg
Arsenic, ion	8.29E-10	kg
Benzene	1.63E-06	kg
BOD5, Biological Oxygen Demand	0.00027	kg
Bromate	3.28E-09	kg
Cadmium, ion	2.92E-11	kg
Calcium, ion	0.00001633	kg
Carbonate	0.00011	kg
Chlorate	6.09E-07	kg
Chloride	0.00057	kg
Chlorinated solvents, unspecified	3.36E-08	kg
Chlorine	2.14E-08	kg
Chromium, ion	8.71E-12	kg

COD, Chemical Oxygen Demand	0.00192	kg
Copper, ion	1.85E-07	kg
Cyanide	3.29E-11	kg
DOC, Dissolved Organic Carbon	0.000038165	kg
Ethane, 1,2-dichloro-	2.46E-11	kg
Ethene, chloro-	1.72E-11	kg
Fluoride	3.77E-07	kg
Hydrocarbons, unspecified	0.00016	kg
Iron, ion	4.34E-08	kg
Lead	2.05E-09	kg
Magnesium	5.22E-09	kg
Manganese	2.63E-10	kg
Mercury	1.95E-10	kg
Molybdenum	7.24E-09	kg
Nickel, ion	1.29E-07	kg
Nitrate	8.27E-06	kg
Nitrogen	3.20E-06	kg
Oils, unspecified	0.000036982	kg
Phenol	4.10E-07	kg
Phosphorus	0.0000629	kg
Potassium, ion	2.03E-07	kg
Sodium, ion	0.00028	kg
Strontium	5.05E-11	kg

Sulfate	0.0004	kg
Sulfide	1.83E-07	kg
Sulfite	6.40E-09	kg
Suspended solids, unspecified	0.00175	kg
Tin, ion	4.40E-14	kg
TOC, Total Organic Carbon	0.000038165	kg
Water	0.10582	kg
Zinc, ion	3.78E-08	kg

B. KenPave Program results for stresses and strains of the layers

MATERIAL	Depth Z	Vertical Deflection D_z	Vertical Stress s_z	Major P. Stress s_1	Minor P. Stress s_3	Intermediate P. Stress s_2	Vertical Strain e_z	Major P. Strain e_1	Minor P. Strain e_3	Shear Stress e_3	Shear Strain e_3
EPS	0	0.13605	580.0	492.6	492.6	0.0	-5.9E-05	1.1E-04	1.1E-04	0	0.000E+00
EPS	6	0.1429	375.4	141.4	141.4	0.0	9.8E-05	3.9E-06	3.9E-06	0	0.000E+00
EPS	12	0.14211	104.3	-941.7	-941.7	0.0	1.9E-04	-2.4E-04	-2.4E-04	0	0.000E+00
EPS	12.01	0.14211	104.2	-9.7	-9.7	0.0	5.8E-04	-2.4E-04	-2.4E-04	0	0.000E+00
EPS	27	0.13579	24.9	-56.4	-56.4	0.0	3.5E-04	-2.3E-04	-2.3E-04	0	0.000E+00
EPS	39	0.13104	6.9	-75.0	-75.0	0.0	4.6E-04	-3.3E-04	-3.3E-04	0	0.000E+00
EPS	237	0.06768	0.7	-0.5	-0.5	0.0	1.1E-04	-7.1E-05	-7.1E-05	0	0.000E+00
EPS	237.01	0.06768	0.7	0.0	0.0	0.0	1.6E-04	-7.1E-05	-7.1E-05	0	0.000E+00
FG	0	0.06326	580.0	310.2	310.2	0.0	-3.0E-05	7.0E-05	7.0E-05	0	0.000E+00
FG	6	0.06989	379.2	105.8	105.8	0.0	1.1E-04	-5.0E-06	-5.0E-06	0	0.000E+00

FG	12	0.06913	113.8	-824.6	-824.6	0.0	1.7E-04	-2.1E-04	-2.1E-04	0	0.000E+00
FG	12.01	0.06312	113.8	4.8	4.8	0.0	5.7E-04	-2.1E-04	-2.1E-04	0	0.000E+00
FG	27	0.06313	41.8	-21.8	-21.8	0.0	3.0E-04	-1.5E-04	-1.5E-04	0	0.000E+00
FG	39	0.0596	23.3	-21.9	-21.9	0.0	2.8E-04	-1.6E-04	-1.6E-04	0	0.000E+00
FG	237	0.04057	0.4	-3.9	-3.9	0.0	6.6E-05	-3.5E-05	-3.5E-05	0	0.000E+00
FG	237.01	0.04057	0.4	0.0	0.0	0.0	8.0E-05	-3.5E-05	-3.5E-05	0	0.000E+00

KenPave Program results for stresses and strains of the layers-Scenario1 & 2 FOR POINT 1

Depth z	Vertical Deflection D_z	Vertical Stress s_z	Major P. Stress s_1	Minor P. Stress s_3	Intermediate P. Stress s_2	Vertical Strain e_z	Major P. Strain e_1	Minor P. Strain e_3	Shear stress	Shear strain
0	0.06446	580.0	315.1	315.1	0.0	-3.1E-05	7.1E-05	7.1E-05	0	0.000E+00
5	0.07219	414.4	209.6	209.6	0.0	1.0E-04	1.7E-05	1.7E-05	0	0.000E+00
11	0.0714	129.9	-900.2	-900.2	0.0	1.9E-04	-2.3E-04	-2.3E-04	0	0.000E+00
11.01	0.0714	129.9	8.5	8.5	0.0	6.4E-04	-2.3E-04	-2.3E-04	0	0.000E+00
26	0.06469	46.7	-23.6	23.6	0.0	3.4E-04	-1.7E-04	-1.7E-04	0	0.000E+00
38	0.06081	25.5	-24.0	-24.0	0.0	3.1E-04	-1.7E-04	-1.7E-04	0	0.000E+00
237	0.04081	0.4	-3.9	-3.9	0.0	6.0E-05	-3.5E-05	-3.5E-05	0	0.000E+00
237.01	0.04081	0.4	0.0	0.0	0.0	8.0E-05	-3.5E-05	-3.5E-05	0	0.000E+00
0	0.06518	580.0	331.5	331.5	0.0	-3.3E-05	7.5E-05	7.5E-05	0	0.000E+00
6	0.07201	376.3	104.2	104.2	0.0	1.0E-04	-5.1E-06	-5.1E-06	0	0.000E+00
12	0.07124	107.5	-862.1	-862.1	0.0	1.7E-04	-2.2E-04	-2.2E-04	0	0.000E+00
12.01	0.07124	107.4	-1.8	-1.8	0.0	5.6E-04	-2.2E-04	-2.2E-01	0	0.000E+00
22	0.06681	51.4	-26.4	-26.4	0.0	3.7E-04	-1.9E-04	-1.9E-04	0	0.000E+00
32	0.06316	29.9	-26.5	-26.5	0.0	3.5E-04	-1.9E-04	-1.9E-04	0	0.000E+00
237	0.04092	0.4	-4.0	-4.0	0.0	6.2E-05	-3.6E-05	-3.6E-05	0	0.000E+00
237.01	0.04092	0.4	0.0	0.0	0.0	8.2E-05	-3.6E-05	-3.6E-05	0	0.000E+00

KenPave Program results for stresses and strains of the layers-Scenario 3 & 4 FOR POINT 1

D z	Vertical Deflection D_z	Vertical Stress s_z	Major P. Stress s_1	Minor P. Stress s_3	Intermediate P. Stress s_2	Vertical Strain e_z	Major P. Strain e_1	Minor P Strain e_3
0	0.06591	580.0	339.5	339.5	0.0	-3.5E-05	7.7E-05	7.7E-05
6	0.07278	375.6	104.2	104.2	0.0	1.0E-04	-5.1E-06	-5.1E-06
12	0.07201	105.9	-873.1	-873.1	0.0	1.8E-04	-2.2E-04	-2.2E-04
12.01	0.07201	105.8	-3.6	-3.6	0.0	5.6E-04	-2.2E-04	-2.2E-04
27	0.06582	36.0	-47.2	-47.2	0.0	3.7E-04	-2.2E-04	-2.2E-04
237	0.04108	0.4	-4.0	-4.0	0.0	6.2E-05	-3.6E-05	-3.6E-05
237.01	0.04108	0.4	0.0	0.0	0.0	8.3E-05	-3.6E-05	-3.6E-05

0	0.6615	580.0	339.6	339.6	0.0	-3.5E-05	7.7E-05	7.7E-05
6	0.07302	375.6	104.2	104.2	0.0	1.0E-04	-5.1E-06	-5.1E-06
12	0.7225	105.9	-873.1	-873.1	0.0	1.8E-04	-2.2E-04	-2.2E-04
12.01	0.07225	105.8	-3.6	-3.6	0.0	5.6E-04	-2.2E-04	-2.2E-04
27	0.06607	36.0	-47.2	-47.2	0.0	3.7E-04	-2.2E-04	-2.2E-04
225	0.04197	0.4	-3.6	-3.6	0.0	5.7E-05	-3.3E-05	-3.3E-05
237	0.04148	0.4	-3.3	-3.3	0.0	4.4E-05	-3.7E-05	-3.7E-05
237.01	0.04148	0.4	0.0	0.0	0.0	8.5E-05	-3.7E-05	-3.7E-05