Development of a New and Innovative Concrete Paver

by

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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.

I understand that my thesis may be made electronically available to the public.

Abstract

Interlocking Concrete pavers (ICPs) have become increasingly common in North America. These pavements consist of impermeable concrete paving units and permeable joints that allow water to freely enter the surface. The impermeable paving units are placed on a bedding layer of impermeable aggregates. The base and subbase layer store water and allow it to run into the underlying soil subgrade. ICPs contribute to reducing or eliminating runoff, and they are adaptable to various environmental conditions. In addition, they are designed to be resistant freeze-thaw cycles and de-icing chemicals, and are suitable for winter weather in Canada. These pavements are commonly used in low-traffic areas such as parking lots and sidewalks, and the focus of this study is development and placement of new innovative sustainable pavers and high-traffic urban areas.

Using innovative materials in the concrete mix design has a direct impact on the long-term durability of ICPs. The research was directed at reducing cement content in the concrete mix design by replacing cementitious materials such as glass pozzolan and slag to reduce carbon dioxide emissions. Besides, using recycled aggregates instead of natural aggregates in the mix design can lead to more environmentally friendly pavers.

Increasing traffic loads and environmental factors can lead to higher stress are build up in pavement structure. To predict the magnitude of applied stresses, ABAQUS software was utilized in this study. One of the biggest benefits of using ABAQUS software is to visualize the results. The visualization module in ABAQUS provides a graphical display of finite element models and results. It is easy to detect the problematic areas and take an action to solve the problem.

ABAQUS, which is a general-purpose finite element software, was used to model the ICPs under various traffic loadings and different materials and environmental conditions. ICPs were simulated for heavy truck vehicles in high traffic areas. These new ICPs will be implemented in an urban area; this model was designed to be applicable for areas that support heavy truck vehicles such as buses and bus rapid transit (BRT).

In this study, ABAQUS software was utilized to evaluate deflection, principal stress, shear stress, pavement and foundation thickness, and contact pressure of ICPs. The calculated maximum deflection was -2.1 µm and the maximum principal and shear stresses were 3.41 MPa and 1.42 MPa respectively under 827.4 KPa tire pressure. In general, the pavement performed well under the above-mentioned conditions and the level of stress in the pavement structure was found to be much less than the structural strength of conventional Portland cement concrete.

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Special thanks to my husband for his continued and unfailing love, support and understanding during my pursuit of Master degree.

Finally, I would like to thank my family for their endless support and help. Words cannot describe how I am grateful to have them.

Dedication

This is dedicated to the one I love.

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Chapter 1
Introduction

1.1 Background

The growing population and movement of people to urban areas are one of the most important issues to consider in developing urban road infrastructure. The economic development of a city will lead to drastic changes and usually increases traffic volume. The pattern of demand and supply can be managed with careful planning and design of road infrastructures. Urban road infrastructure should be designed in a way to respond to public transportation systems such as bus rapid transit (BRT) and to be able to sustain heavy truck loading. Moreover, designing pavements for urban transportation systems plays a key role in providing services to low-income and vulnerable members of society. Moving heavy loading vehicles leads to designing durable pavements that can respond to the demand properly (Vaitkus and Gražulytė, 2019).

High traffic volumes accelerate the deterioration of pavements, especially asphalt pavement resulting in deformation, rutting, cracks, raveling, potholes, and other distress. Cracking on roadways, when not treated, can expand quickly causing further damage to roadways, which can be hard to repair, resulting in an expensive rehabilitation or reconstruction. To maintain pavements, it is important to provide long-term maintenance throughout the service life (Malek, 2018).

If the pavement deteriorates, repair and rehabilitation are necessary. The most significant concerns in highly traffic roads and urban streets relate to the type of loading, frequency of use and duration (Delatte, 2014). In addition, lane closure due to the maintenance of roadways extends the traffic period to complete repairing tasks resulting in additional financial losses (Murugan and Natarajan, 2016). Consequently, there are two main challenges associate with conventional pavement maintenance:

1) Pavements are exposed to high traffic volume that has negative effects on their performance.
2) Maintenance is time-consuming and costly.

The development of a new type of concrete pavement provides a promising solution over existing Interlocking Concrete pavers (ICPs) to reduce road work since their constructions and installations are time-saving. ICPs, more broadly, have some advantages over conventional pavements such as concrete or asphalt pavements. Since slabs for ICPs are made at industrial and manufacturing facilities, the risk of material segregation and other potential defects due to on site conditions are removed. Besides, ICPs can be constructed during cold or hot weather, thus, there is no limiting constructing season for installing the concrete blocks or pavers. However, there may be challenges if the ground is frozen during construction (Vaitkus and Gražulytė, 2019). Precast concrete blocks are factory made under a controlled environment, which can result in higher quality and durability than cast-in-place pavements. Generally, conventional pavements require curing time to achieve sufficient strength while precast panels and pavers can be transported to the site ready for installation (Delatte, 2014). Asphalt pavements must be properly placed and compacted in order to perform well.

On many urban freeways, the cost of road user delay may exceed $50,000 per day depending on the traffic. To minimize additional costs for construction projects, ICPs come to attention for their time-saving and low frequent rehabilitation and maintenance costs (Delatte, 2014).

ICPs can add vitality to almost any environment as high temperatures, moisture, petrochemicals, or heavy loads do not damage them. Poor soil condition causes unevenly under loads which results in pavement deformations. ICPs can withstand abrasion and have greater resistance to deformation.

1.2 Interlocking Concrete Pavers Installation

The Interlocking Concrete pavers Institute (ICPI) members produce impermeable concrete pavers that typically meet the Canadian Standard Association, CSA-A231.2. ICPI provides certification of the test result to ensure that the products meet applicable ASTM or CSA standards (Smith, 2011).

Since curing time is not required for ICPs they can be ready for traffic immediately after installation. This leads to reducing construction time and restoring access quickly.

ICPs typically consist of bedding sand, aggregate base, soil subgrade, edge restraints, and drainage (Figure 1-1).

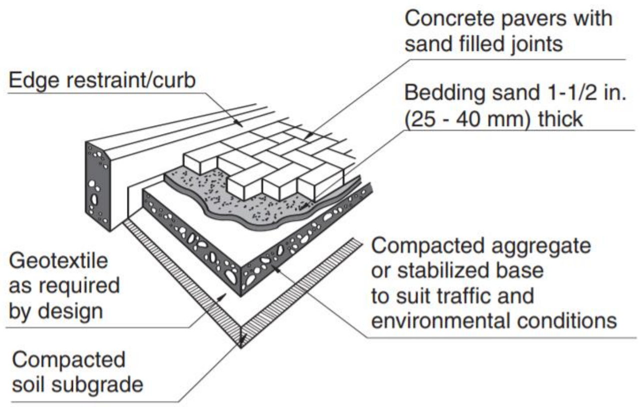


Figure 1-1: Typical component of Interlocking Concrete pavers system (Mujaj and Smith, 2001).

For installing this pavement, it is recommended to have an contractor who holds a certificate from the Concrete Paver Installer Certification Program (ICPI) as these contractors have been instructed and tested on how to properly construct ICPs. The installation procedure may differ from one application to another. For example, the standards for pedestrian applications are different from that of commercial areas with high traffic demand.

Mechanical installation is provided for certain laying patterns. Mechanical installation equipment accelerates the installation process as concrete pavers can be placed in sections rather than one paver at a time (Figure 1-2).

A few weeks after placing the ICPs, a technical meeting with a professional can be held to assess the performance of the pavements under traffic loads as this pavement can be placed and removed easily. Figure1-3 and 1-4 show the construction of ICPs for easy inspection (Larrard and Sedran 2013).

Figure 1-2: Mechanical installation equipment (Larrard and Sedran 2013).

Figure 1-3: A view of trial installation (Larrard and Sedran 2013)

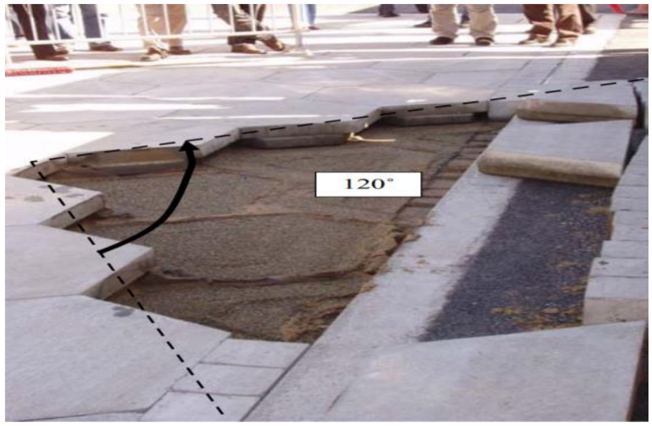


Figure 1-4: Removal of interlocking concrete blocks (Larrard and Sedran 2013).

1.3 Problem Statement

Over the last 30 years, in many countries, including Australia, Canada, England, the Netherlands, South Africa and United State, extensive work has been conducted on the structural design of the ICPs. Consequently, municipal applications such as parking lots, plazas, city streets, and crosswalks have been increased for these types of pavements (Hein and Burak, 2007).If constructed properly, ICPs offer good performance with limited maintenance and decreased future rehabilitation costs. Selecting the proper design and materials for the site traffic and environment can lead to longer service life with little maintenance. On the other hand, poorly selected materials, design and construction errors can compromise the service life of the pavements considerably. In order to minimize potential errors in ICPs design and installation, pavement engineers must have a deep understanding of theoretical frameworks, and be aware of the limitations of the procedures (Delatte, 2014).

To construct durable ICPs, the following need to be considered:

- Materials selection;
- Subgrade soil;
- Mixture proportioning;
- Traffic and environment;
- Pavement performance analysis; and
- Construction techniques.

There are some issues related to the construction of ICPs which need to be carefully considered when designing this type of pavement. One of the common designed details is related to the leveling of the concrete pavers. Further, the foundation level of the ICPs needs to be adjusted based on their applications. If the existing soil at the site contains high amounts of clay, which have higher porosities than sandy soils, and thus retain larger volumes of water, modifications such as cement treatment may be required. If left untreated, the high moisture content may lead to heaving or settlement. ICPs applications require greater site evaluation, construction skills, inspection and design effort in comparison with conventional concrete pavers (Smith, 2006).

Evaluating the performance of these new innovative concrete pavers developed in this research is crucial. There are many methods to evaluate the performance of pavement; among the existing method, finite element analysis (FEA) is a strong tool for assessing the performance of the pavement. ABAQUS is a general-purpose finite element software that can be used to model the pavement under various traffic load scenarios, materials and environments. The program simulates the pavement in a three dimensional (3D) space with many features and options that produce a robust and efficient model (Bugher, 2019).

This research aims to analyze the performance of a new concrete paver, in collaboration with Sidewalk Labs, which can withstand heavy traffic loads in a municipal application. By calculating the stress, deflection and other critical parameters, an optimum paver design was selected to propose a ICP for a reasonable service life and range in environmental conditions.

1.4 Knowledge Gap

The majority of existing applications for concrete pavers are related to areas with low speeds and light traffic loads. There are still some questions regarding ICPs that should be fully understood before they can be integrated into urban roads, especially on collectors and arterials. As explained in the literature review in chapter 2, some studies focused on modelling the pavement with the modelling software to find the optimum dimensions and shapes for concrete blocks, and assess the performance of the pavement. Other studies, considered sustainable materials such as waste materials and admixtures to develop durable concrete mixes and to enhance the mechanical properties of ICPs. It is noteworthy that the concrete pavers developed in this research are designed for urban areas, as such, they need to be larger than typical pavers. They are designed to be structurally sound, functional, people-centric, and aesthetically pleasing.

This study consists of two stages. First, it aims to evaluate the new materials, and design by conducting laboratory tests that characterize performance. Second, to predict performance and assess the stress, deformation and other parameters for this pavement under different loads using ABAQUS software. As a result of the combination of both stages that are contained in this work, a strong and durable pavement system was developed to respond to traffic loads at the designed speed, ability to drain and reduce stormwater, reduce carbon dioxide emissions, and provide a low maintenance cost pavement.

1.5 Research Objectives

As it was mentioned before, over the last 30 years or so, ICPs were mostly implemented in the areas with low traffic loadings such as sidewalks and parking lots. Using ICPs in high traffic demand areas such as urban highways requires deep understanding of selecting proper materials, laboratory testing, and construction techniques and strategies to fabricate durable pavements meeting high traffic demands and environmental conditions.

This research project aims to develop a new and innovative type of concrete paver using FEA to evaluate the overall performance of the pavement under high traffic demand. The objectives for this research project are as follows:

1) Utilize a finite-element model to simulate field conditions with ABAQUS software in order to evaluate the overall performance of ICPs under heavy loads and assess stress, deflection and related parameters of the pavement.
2) Recommend the optimum foundation and pavement's thicknesses.
3) Design a sustainable impermeable paver that contains recycled and innovative materials that reduces greenhouse gases (GHG).

1.6 Research Methodology

Figure 1-5 shows the summary of the research methodology. Each step is fully explained in the following chapters of this thesis.

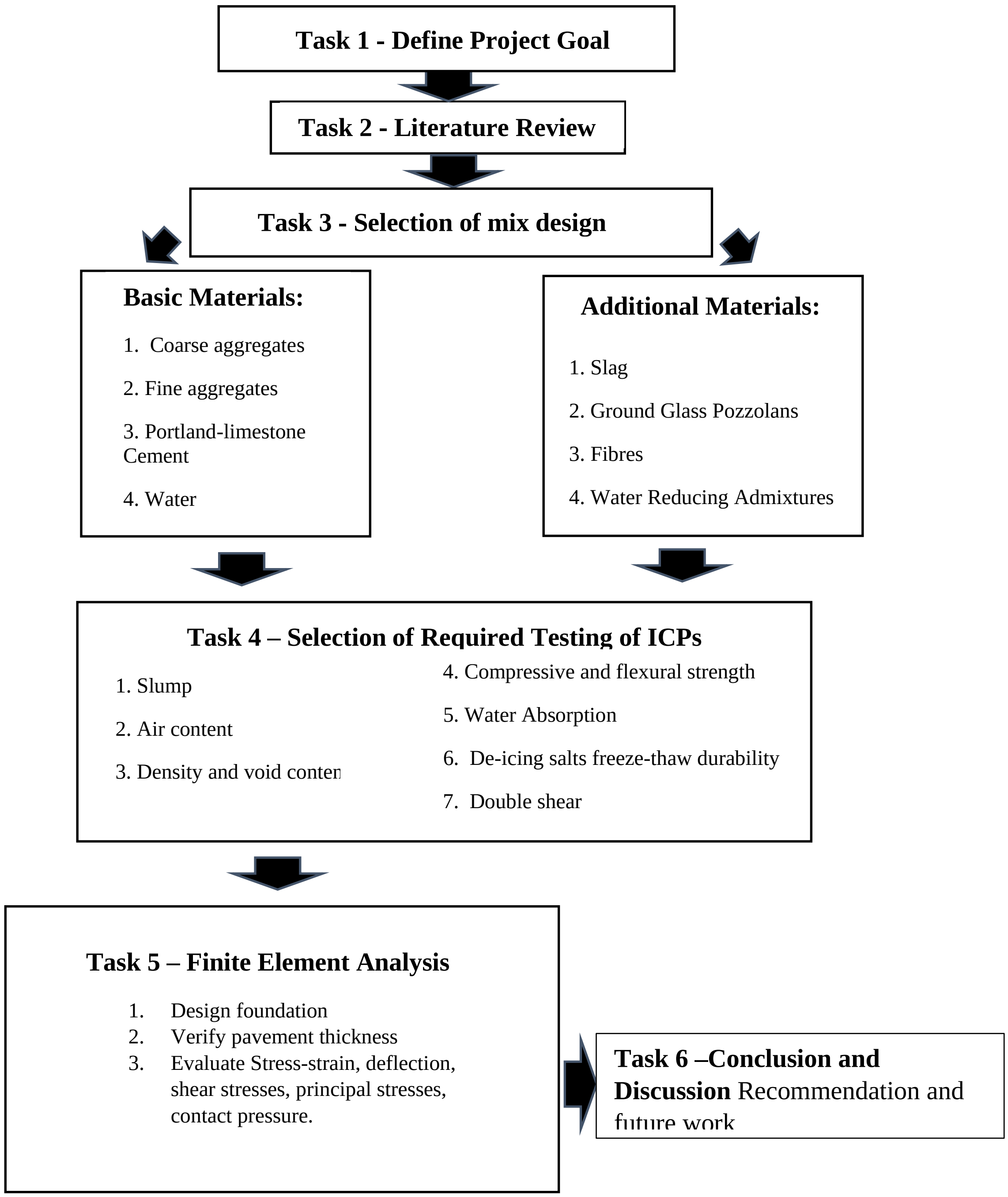


Figure 1-5: Research methodology.

1.7 Thesis Organization

This thesis consists of six chapters:

Chapter 1 provides and introduction to the research project and includes some background on Interlocking Concrete Pavers. Chapter 2 is the literature review, focusing on modelling method and process, pavement sustainability, materials needed for ICPS mix design, concrete testing. Chapter 3 focuses on the aspect of the concrete pavers modelling analysis and summary of the ICPs, as well as the principal components of Interlocking Concrete Paver Systems. Chapter 4 outlines the finite element method and step-by-step modelling process. Chapter 5 discusses the results from ABAQUS software and describes the current behavior of the pavement under traffic loadings. Chapter 6 concluded the project, recommendation and future work.

Chapter 2
Literature Review

2.1 Introduction

The concept of interlocking concrete pavers (ICPs) was introduced in the Roman Empire. In that era, interlocking stone blocks formed the upper layer of the road, and the mechanical and physical characteristics of the bottom layers were similar to those of today's (Mascio and Moretti, 2019). Today, although ICPs are produced using advanced materials and technology, the basic design has remained the same.

It is worth noting that most of the urban areas are covered with conventional impermeable pavements. Impermeable pavements can cause run-off from storm water instead of redirecting it to groundwater (Li and Harvey 2013). When impermeable pavements are used, infiltration into the subsurface is reduced. In addition, water pollutant associated with storm water run-off is increased (Brattebo, 2003). In fact, Permeable Interlocking Concrete Pavement (PICP) consists of rigid concrete paving units with permeable joints that allow water to penetrate through the entire surface freely. However, porous asphalt and pervious concrete are also classified as permeable pavements.

There is a reasonable amount of research regarding ICPs, which was conducted over the years (Barber and Knapton, 1980, Knapton, 1976, Lin and Ryu, 2016, Lin and Cho, 2016, Mampearachchi and Gunarathna, 2010, Mampearachchi and Senadeera, 2010, Mampearachchi and Senadeera, 2014). Today, ICPs are widely used for specific applications. Some of these applications are sidewalks, cycle path, residential driveways, parking lots and industrial spaces, but much research has been done to apply this pavement in areas under high traffic volume conditions such as highways (Mascio and Moretti, 2019).

Another environmental concern related to pavements' surface and atmospheric heat resulting in producing pavements is the Urban Heat Island (UHI) (Li and Harvey, 2013, Golden and Kaloush, 2006). Pavement material type has a significant impact in regards to UHI. For example, solar radiation is absorbed more easily by dark surfaces like black asphalt or dark sealed coated pavements especially during the summer (Solecki and Rosenzweig, 2004). However, the adverse effects of urban heat island (UHI) can be reduced by choosing designs that retain water in conventional pavements and other innovative methods (Qin and He, 2018). Recently, with the use of Portland cement, environmental contamination resulting from the cement production process commensurate with significant growth has increased dramatically. The cement content for ICPs mix design can be reduced by replacing cementitious materials such as glass pozzolans and slag without compromising the mechanical properties and durability of pavements. Additionally, replacing recycled materials in ICP mixtures can save natural resources and reduce the amount of carbon dioxide in the atmosphere (Shi and Mukhopadhyay, 2019). Other advantages of using ICPs include: low maintenance cost, easy installation and replacement, good durable with less life cycle cost, design flexibility, applicable for both vehicular and pedestrian needs.

2.2 Modelling Method and Process

Analyzing the stress and deformation of roadways under vehicle traffic loads is one of the essential subjects in designing pavements in order to assess the long-term performance of the pavements (Zheng and Hai-lin, 2012). In the early 1950s, Seddon used the method of integral transform to determine the distribution of stress when the surface of the pavements is subjected to pressure forces (Sneddon, 1952). Many studies such as Kenney in 1954 and Mathews in 1958 and 1959 used analytical methods to assess stress and deformation of road structures under different loadings. However, due to the increment in traffic and loads, the empirical models are insufficient to assess the behavior of the pavement (Kenney, 1954, Mathews, 1958 and 1959).

The finite element method (FEM) is suitable for analyzing the behavior of pavements. Researchers use different criteria and concepts for designing interlocking concrete pavers. For example, they evaluated criteria based on ICPs' performances on-field or stress-strain variation in base and sub-base materials (Gunatilake and Mampearachchi, 2019). In 2016, Lin et al. developed a deflection prediction model for concrete block pavement based on surface structure, block shapes, and structural patterns with the use of FEM analysis and dynamic loading (Lin and Cho, 2016).

Some of the earlier studies investigated the behavior of interlocking concrete pavement under loading repetition. They mainly focused on modelling the jointed concrete pavement to calculate stress, strain, and deflection of concrete blocks. As a result, the behavior of pavement under a certain number of repetitions of loads was analyzed (Molenaar, 1965, Tabatabaie, 1978, Tayabji and Colley, 1983, Nishizawa and Matsuno, 1984).

Interlocking concrete pavers have different characteristics that depend on the materials used in the pavements, sub-layers and sub-based layers, the shape of the blocks, and the technology, so modelling is essential to develop sustainable pavements. One of the approaches to develop a Finite Element Method is to determine the pavements dimensions such that they have better performances on the field.

In 2014, Mampearachchi et al., focused on finding suitable block shapes and paving patterns with the Finite Element Model (FEM). They considered different block shapes and patterns under low to medium traffic but for heavy trucks and buses. As a result, the best combination of pattern and block shapes is considered as an optimum design. Stretcher and herring patterns with an angle of zero or 90 degrees and uni-style block shape are regarded as optimum designs (Mampearachchi and Senadeera, 2014).

In addition, in 2017, Dhanushika et al., developed FEM to determine the optimum dimension of concrete blocks and to assess the deflections and stresses in pavements in road applications. The results show that the shape and dimension are optimal and achieve the lowest stress and deflection (Dhanushika and Peiris, 2017).

Finally, in 2019, Di Mascio et al., analyzed the stress-strain, rutting and fatigue performances of concrete blocks in urban and local roads. They analyzed the interlocking concert block pavements when subjected to three-wheel positions, five-block patterns (it appears in Figure 2-1), three bedding sand thicknesses. Rectangular concrete blocks with plane-side surfaces were chosen which the blocks set down on the bedding sand layer, a cement-treated base layer, and a granular unbound foundation (Mascio and Moretti, 2019). For this research, the hexagonal interlocking concrete paver was chosen (see Figure 2-2).

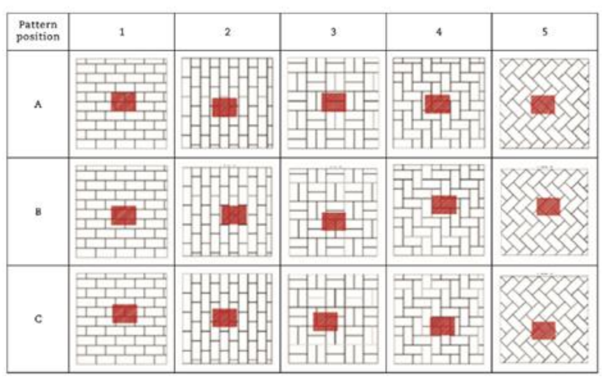


Figure 2-1: Concrete blocks and patterns (Mascio and Moretti, 2019).

Figure 2-2: Hexagonal interlocking concrete pavers (Larrard and Sedran, 2013).

In 2019, Larrard et al., impermeable equilateral hexagon concrete pavers have been exposed to traffic loads for almost a year, and ICPs exhibited satisfactory behavior with very little cracking under heavy truck loads. One of the main advantages of using an equilateral hexagon design in this research is to reduce the risk of angle failure as these innovative concrete pavers are exposed to heavy truck loads and they experience high traffic volume in urban areas.

In addition, these concrete pavers in comparison with other conventional pavements produced little noise according to the Larrard study. As the human and environmental aspect of these pavers are important to this research, the shape of concrete pavers was chosen in a way that reduces noise emissions and faster construction process that lead to reduce traffic congestion in urban areas (Larrard and Sedran, 2013).

The following points are considered to choose the shape of Interlocking Concrete Pavers (Larrard and Sedran, 2013):

- Reduction of nuisances caused by maintenance works for both users and neighbors,
- Performance of the concrete pavers under heavy truck and traffic loads,
- Possibility of repairing or modifying pavement functions,
- Ability to reduce noise,
- Ease of access to underground networks,
- Easy and fast maintenance.

2.3 Pavement Sustainability

The term "sustainability" encompasses three different aspects: social, environmental and economic that demonstrated in Figure 2-3. According to the World Commission of Environment and Development (WCED), "sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

Figure 2-3: Sustainability triple-bottom-line (WCED, 1987).

The goal of designing sustainable pavements is to respond to social needs and demand, and to consider environmental and economic aspects. Taking advantage of new technologies and innovative materials combined with field investigation can lead to the development of infrastructures with a long life cycle. Some of the critical parameters that come to attention in social and economic aspects of designing the pavement include public safety, cost of construction and vehicle operation, comfortable to walk or drive on, cost of maintenance and pavement durability; for environmental aspects: energy consumption, GHG emissions, stormwater run-off, and air quality (Van Dam and Harvey, 2015).

The use of concrete pavers can be useful as the existing pavement is preserved and less materials are used. Construction cost is much lower compared to conventional pavements. Concrete pavements have a longer life and require minimal maintenance and service to people for years before they need to be rehabilitated (TAC, 2013).

In 2013, Li et al. investigated the two environmental issues such as heat island and stormwater runoff that can be improved by reflective and permeable pavement like interlocking concrete pavement. The goal of this paper was to demonstrate the feasibility of using permeable pavement as a practice solution to address the abovementioned issues. They compared six permeable and three non-permeable pavements under different tests performed by the University of California Research Center (UCPRC) in California. The results showed that reflective pavements cause less absorption of solar radiation and less emission of heat during critical times of the day, while permeable pavements reduce stormwater runoff by permitting water to drain into the pavement and water evaporation (Li and Harvey, 2013).

2.4 Materials

Annually, a significant amount of non-renewable materials such as aggregates, bitumen, cement, and lime were consumed during the building and maintenance of the pavement system, which has adverse effects on the environment and cost industries large amounts of money. On the contrary, recycled materials such as recycled glass and concrete can replace with virgin aggregates in both flexible and concrete pavers to reduce the cost of construction and prevent depletion of natural resources (Gautam, et al., 2018).

2.4.1 Glass Pozzolan

Glass Pozzolan is a recycled material that has a low environmental impact, and it can be used as aggregate or Pozzolan in cement and concrete (Soroushian, 2012). In 2000, the effect of ground glass on the strength of concrete that has 30% cement replaced by the ground glass was examined. In this study, the size of glass Pozzolan powders plays a significant role in reactivity with the cement during hydration, and the glass particle size smaller than 38 μm had a better performance in improving the compressive strength of concrete (Shao, et al., 2000). In another study, laboratory tests were conducted to determine the compressive strength, workability, and split tensile of the concrete with different amounts of cement replaced with ground waste glass powder. The results indicated that cement containing 21% ground glass increases the compressive strength of concrete above 75% (Figure 2-4 shows strength activity index) and, increasing glass content reduces the workability and split tensile of the concrete (Olofinnade, et al., 2017). In addition, the effect of ground glass as the natural sand replacement in concrete mixtures is examined. The results show that the compressive strength and durability of concrete have improved significantly (Oliveira, et al., 2008).

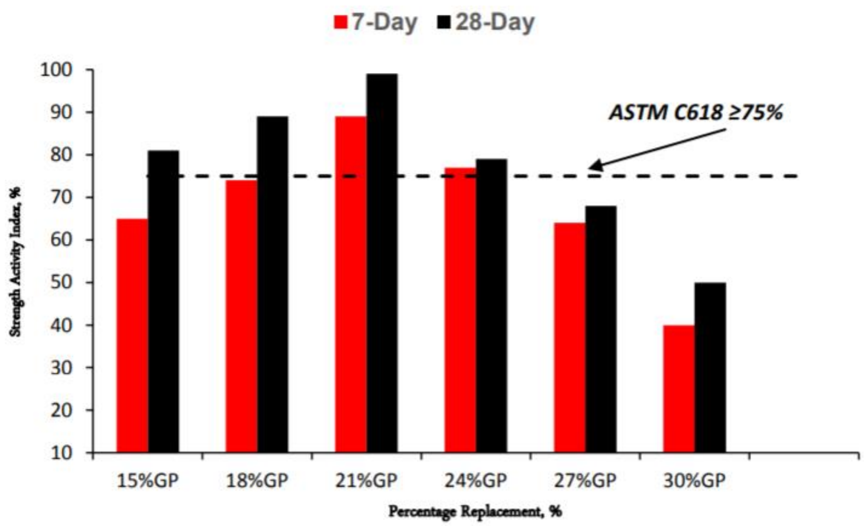


Figure 2-4: Strength activity index for concrete containing glass powder concrete (Olofinnade, et al., 2017).

2.4.2 Water Reducing Admixture

Water reducing admixtures are chemical admixtures for concrete, which are added in order to reduce water content in a mixture and increase the workability of mixes without adversely affecting the properties of concrete. They also reduce the volume of voids in concrete and improve the mechanical property of concrete (Barbudo, et al., 2013). A few studies revealed that water-reducing admixture is more effective when combined with recycled aggregate. The mechanical performance of concrete made with recycled aggregate and water reducing admixture shows better workability and strength for concrete (Barbudo, et al., 2013).

2.4.3 Fibre

Fibre is a small piece of reinforcing materials that have specific properties and characteristics. Fibres used in concrete mixes can be glass, synthetic or natural. Polypropylene as an example of synthetic fibres is commonly used in concrete overlays, Figure 2-5. Fibre-Reinforcement Concrete (FRC) has lower deflection than unreinforced concrete and reduces construction by preventing laying down mesh or other reinforcement (Wafa, 2018).

Figure 2-5: Polypropylene fibres (Wafa, 2018).

Fibres are usually used in concrete to increase concrete structural integrity; for example, controlling plastic shrinkage cracking and drying shrinkage cracking and increasing tensile strength. Many researchers investigated different aspects of fibre and their effects on concrete mixtures' performance. In 2002, a study was conducted to analyze the importance of the distribution of fibre on improving spalling resistance of concrete when it is exposed to elevated temperature. The obtained results showed that fibres that are distributed uniformly through the concrete have better performance (Bayasi, et al., 2002).

Some experimental studies compared different fibres when they are subjected to impact loading. The results obtained have shown that the overall concrete’s resistance has improved 3-18 times in comparison with none-fibre samples. Some fibres play anti-cracking roles and improve toughness in concrete while others enhance flexural strength in concrete (Ramakrishna, et al., 2005 and Bei-Xing, et al., 2004).

The other role of fibre is to delay and control the tensile cracking of the composite materials. The ability of steel fibre to resist crack propagation that highly depends on the bond between concrete and fibres as well as the distribution of fibres in concrete (Elsaigh, et al., 2005). Besides, fibre reinforcement is appropriate for areas that concrete is exposed to sulfate attacks because fibres contribute to reducing the permeability of concrete.

2.4.4 Slag

The use of slag in concrete mixtures contributes to the reduction of cement consumption and carbon dioxide emissions (Parron-Rubio, et al., 2019). Many studies have been completed to examine concrete that uses different types of slag as a part of cement material in concrete mixtures. In 2018, different types of slag as a substitution of 25% cement content were investigated (Parron-Rubio, et al., 2018). The goal of this study was to evaluate the advantages and drawbacks of each mix. The results reveal that the mix with Stainless steel slag reduces the water content without significantly decreasing the strength of concrete. Besides, ground granulated blast furnace slag used in mixes had better performance than reference samples (no slag) (Parron-Rubio, et al., 2018).

There are also some studies that examined the use of ground granulated blast furnace slag (GGBFS) as a substitution of cement (Çelik, et al., 2013 and Öner, et al., 2007). In some studies, a high percentage of cement replaced with GGBFS. The results demonstrate that the compressive strength of concrete replacing 80% of slag in cement content decreased while the better results were achieved when we had substitutions up to 60% (Khatib, et al., 2005).

2.5 Concrete Testing

2.5.1 Fresh Concrete Testing

Slump, void content, and density are three important fresh concrete testing for ICPs that play an important role when we are assessing the workability of construction of Interlocking Concrete pavers. In addition, the abovementioned testing is required for other kinds of pavements such as conventional concrete pavers.

2.5.1.1 Slump Test

The concrete slump test measures the consistency of fresh concrete before it sets with the conventional test method (CSA A23.2-5C, 2009). The slump test analyzes the workability of fresh concrete to ensure the uniformity of concrete under field conditions. Zero slump concrete is used for the production of paver blocks that result in very dry mixes with low impact resistance and fracture toughness, but these can be offset with fibre reinforcement (Reinhardt, 1999). The quality of paver produced will depend on various parameters such as air voids, grade of cement used, water content, and the quality of aggregates.

2.5.1.2 Void Content for Fresh Mix

It is crucial to measure the consistency of fresh mix before the concrete sets. There are several methods for measuring the air content of the concrete mix such as the pressure method, volumetric method, and gravimetric method. Among those methods, the pressure method is more common for measuring air content using (CSA A23.2-4C) standard. The pressure method should not apply to concrete with lightweight aggregates or aggregates with high porosity. The sample should not be taken from the first or last portion of the batch as the consistency of samples is important to maintain adequate control. It is essential to keep the air in the mixes between 6-8% as too much air decrease the workability of fresh mixes.

2.5.2 Structural Performance Test

There are various types of structural tests for ICPs. In this project, four important tests are selected to confirm the structural performance of ICPs. The structural testings are compressive strength, double shear strength, water absorption, and freeze-thaw.

2.5.2.1 Compressive Strength Test

A compressive strength test is used to ensure that the concrete mixtures are strong and meet the specified strength. CSA A23.2-10C describes the preparation for concrete samples. Three to six samples with a dimension of 100mm X 200mm cylinder are suitable for this test. The strength results from the cast cylinder may be used for some purposes such as quality control, estimating the strength in structure, or evaluating the adequacy of curing.

2.5.2.2 Double Shear Strength Test

The goal of conducting the double shear test is to find the shear strength of concrete before failure occurs. In the present experimental research plan, to find out the shear strength of concrete pavers, two specimens with a dimension of 150 mm X 150 mm X 450 mm are considered, Figure 2-6. For this test, the specimens are cast in the laboratory by using mold that was fabricated at the University of Waterloo shown in Figure 2-7 (Swamy, 1989; Kalwane, 2016).

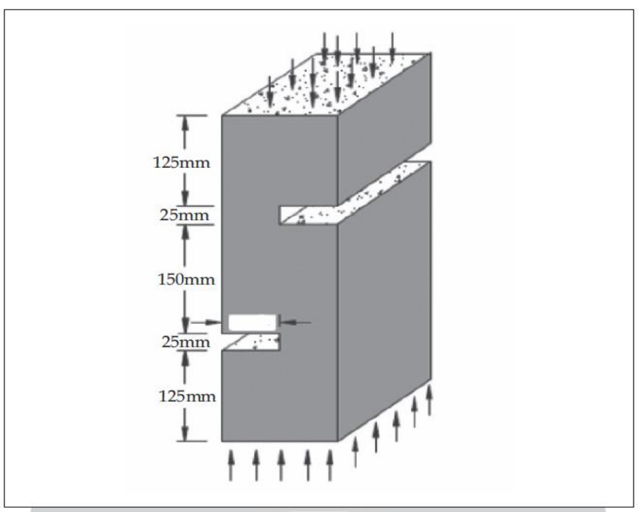


Figure 2-6: Geometry of double shear specimen (Kalwane, 2016).

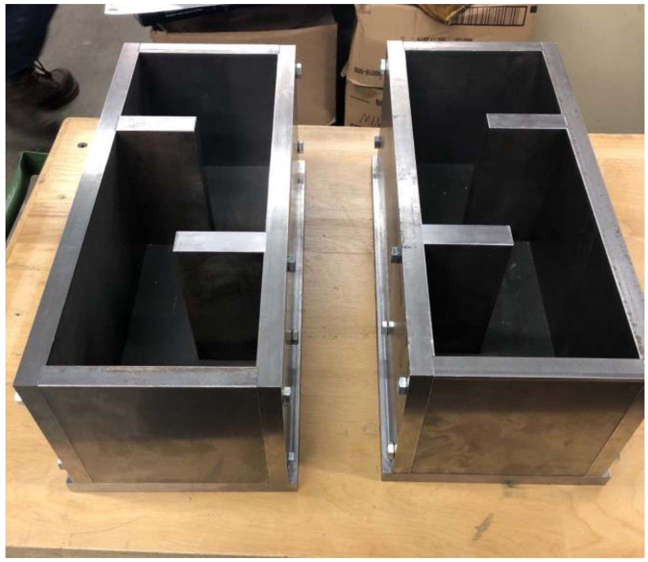


Figure 2-7: Shear mold for double shear test.

For the double shear test, the shear load is applied continuously by compressive strength testing machine shown in Figure 2-8. Depending on the ability of compressive strength testing machine, displacement of the specimen as well as shear strength of specimen can be calculated. With using compressive strength testing machine, the double shear testing process is accelerated (Kalwane, 2016).

Figure 2-8: Specimen under the double shear test (Kalwane, 2016).

2.5.2.3 Water Absorption Test

The susceptibility of unsaturated concrete when the water penetrates through the surface and interior concrete is intended to be determined by the water absorption test. The water content, density, absorption, and voids in hardened concrete or mortar can be calculated from this test. CSA A23.2-11C standard is used for preparing the sample and test. A minimum of three (3) samples are considered for this test. The average absorption of the test set should not be greater than 5% and no individual paver should be greater than 7%, and the volume of the test specimen should not be less than 350 cm3 (0.35 L).

2.5.2.4 Freeze-Thaw Durability Test

When the water in moist concrete freezes, it produces pressure in pores concrete and causes cracking, scaling, and crumbling of the concrete. In order to reduce the adverse effects of expanding water in concrete, the freeze-thaw test is conducted for this study. The sample preparation and test method are covered by CSA A.231.2-7.3 and TS 3.80 - 05.07 standard, respectively. It is worth paying attention to the average weight loss of a set of concrete pavers subjected to 50 freeze-thaw cycles, and immersion of NaCl solution shall be less or equal to 1%. Air entraining additives develop the proper pore structure to accommodate the hydraulic pore pressures associated with freezing and benefit the freeze-thaw durability of mortar. Air entraining additives provide a place for freezing expanding, which relieves the pressure and thereby prevents cracking (Tate and Thomson, 2001).

2.6 Principal Components of Interlocking Concrete Paver Systems

The principal components of Interlocking Concrete pavers are (Figure 2-9):

- Impermeable concrete pavers
- Bedding sand
- Jointing sand
- Sealer
- Drainage
- Geotextile fabric
- Edge restraints

Concrete pavers are usually placed on high-quality bedding sand (25 to 40 mm (1 to 1.5 inches)). High-quality sand is used to fill joints between concrete pavers and allows the pavements to be joined together and act as a structurally durable layer.

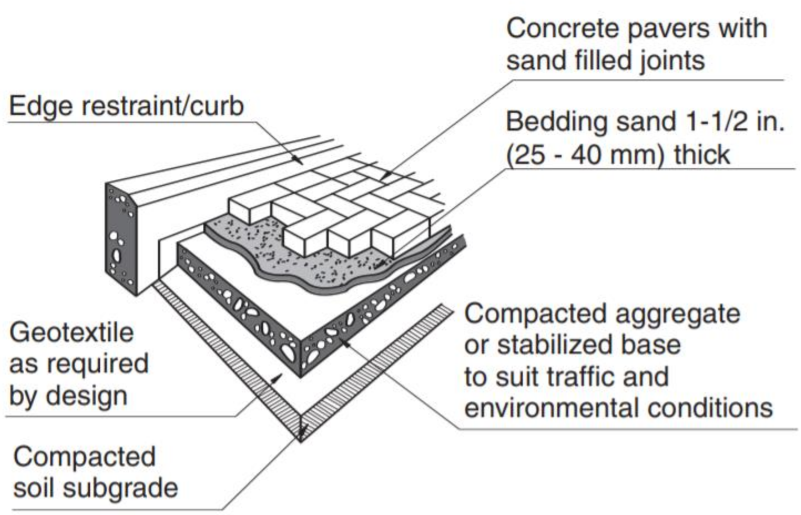


Figure 2-9: Typical component of Interlocking Concrete pavers system (Mujaj and Smith, 2001).

2.6.1 Impermeable Concrete Pavers

Production of high-quality concrete structures includes Portland cement composition, coarse and fine aggregates and sufficient water to produce ICPs with zero slumps. This concrete is molded with special equipment under vibration and intense pressure. Admixtures can be used to enhance various engineering properties (resistance and density) and to reduce water absorption. Normally, paver units are made with spaced bars to ensure uniform joints to prevent crushing. Pavers are manufactured to specifications specified in ASTM C 936, Standard Specification for Interlocking Concrete Paving Units. This standard requires average concrete pavers of 55 MPa, a minimum of 50 MPa, average absorption of 5% and maximum absorption of 7 %, and resistance to 50 freeze-thaw cycles.

2.6.2 Bedding Sand

Bedding sand is placed to withstand the compressive forces associated with loads and tire pressures. High-quality manufactured or natural sand is required for setting ICPs. Degrading testing and gradation analysis are necessary for verification requirements. Concrete sand quality should meet the ASTM C 33 standard. Some older specifications allow using finer sand which is not appropriate, especially under traffic pavements. The screening process should be done cautiously as sand may contain too many particles passing the 75-μm sieve size with flat or elongated shapes. These kinds of particles are not suitable enough for typical paver installation; however, they may be used in some applications.

2.6.3 Jointing Sand

For filling the joints, finer graded (100 percent passing the 1.18 mm sieve size) is required for filling the joints (typically 5 to 6 mm) between the pavers, and it is essential to meet the requirement of ASTM C 144. Jointing sand transfers the loads to surrounding blocks by shear forces and plays a significant role among the individual paver units. This enables the pavement to act as a distinct layer allowing the distribution of load to be distributed evenly through the pavement.

Polymeric Jointing Sand would be an alternative for the filling of narrow or wide joints between pavers. It can be ideal for stabilizing horizontal or sloped installations. This type of sand prevents loss of jointing when the pavement has some movements and withstand erosion caused by rain, frost, etc.

2.6.4 Edge Restraints

Edge restraints are an essential component of Interlocking Concrete pavers. They hold pavers tightly together and enable pavement to be consistent throughout the entire system. They prevent the pavement from breaking apart under horizontal traffic forces and freeze-thaw cycles (ICPI, 2012).

If there is a possibility of losing bedding sand, placing geotextile should be necessary to prevent this migration. Exposed concrete should be 1/8 in. (3 mm) radius edge to reduce the chance of crushing. Besides, when some changes occur in pavements materials, laying patterns or slopes, edge restrains should be placed to act as a restraint (Figures 2-10 and 2-11).

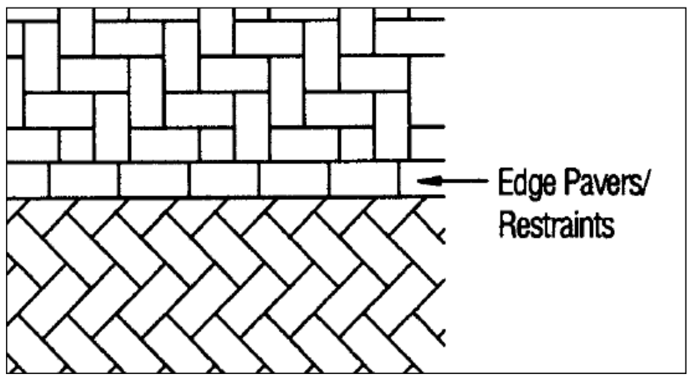


Figure 2-10: Change in laying pattern direction (ICPI Tech, 2005).

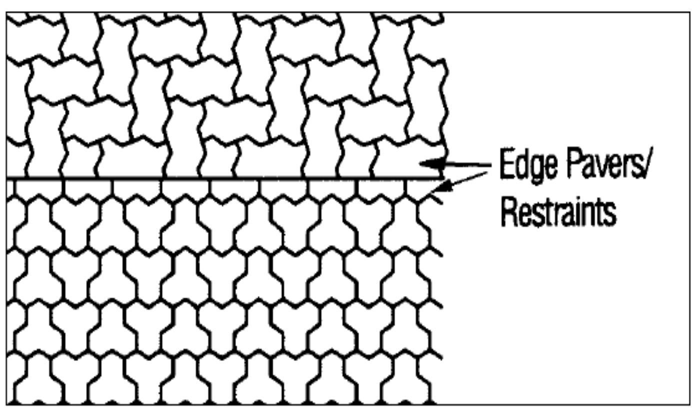


Figure 2-11: Change in paver shape (ICPI Tech, 2005).

2.6.5 Sealer

Sealer is essential on some applications such as airports and highways to prevent loss of the joint sand from the effect of repeated loads; however, it is not normally required to increase the surface durability of the pavement. Sealer is useful as it can prevent water and oil from penetrating through jointing sand into the bedding sand. There are several types of sealers in markets, and choosing a suitable sealer depends on the applications and climate (ICPI, 2012).

2.6.6 Drainage

Drainage pipes should be installed perpendicular to the lowest road surface and before building the base layer. Pipes can be covered with geotextile to prevent the loss of bedding sand materials. If bedding sand materials have a high percentage of fines, continuous rainfall transports finer sieve fractions in the sand into the drain holes and block the pipes. The gradation is an important factor in drainage. To avoid a potential problem, it is recommended that bedding sand materials have 0% to 1% passing the No. 200 (0.075 mm). The purpose is to remove excess water from the base coarse (ICPI, 2012).

2.6.7 Geotextile Fabric

Geotextile is usually required for a cement-treated base to prevent the migration of bedding sand through cracks. Woven geotextile fabric is commonly used in the cement-treated base; however, it is unnecessary to use geotextile when we have aggregate or hot mix asphalt base.

It is recommended to use geotextile fabric to place ICPs over existing asphalt or concrete surfaces. In order to prevent the migration of sand from the joint into edge restrains or structures, it is recommended to place the geotextile fabric against edge restraints or structures (ICPI, 2012).

2.7 Summary of Test Methods

Table 2-1 provides a summary of the structural test methods outlined in this research.

Table 2-1: Summary of Interlocking Concrete Pavers (ICPs) test methods.

S/N	Test	Specification Name	Specification Code	Requirements	Standard
1	Compressive Strength Test	Precast concrete pavers Compressive strength of cylindrical concrete specimens	CSA A231.2-14 : Clause 6.1.1; Clause 7.2 CSA A23.2-9C	Sets of Five (5) Samples Cored cylinders where the thickness and diameter are equal. Thickness/Diameter - 1:1 Or: saw-cut cubes where the height, length, and thickness are equal	*"Compressive strength of not less than 50 MPa and the average of the 5 units shall not be less than 55 MPa "* *"Generally, the concrete should not be cut or cored until it has reached a maturity equivalent to at least 7d at 10 °C"*
2	Water Absorption Test	Water content, density, absorption, and voids in hardened concrete, grout, or mortar	CSA A23.2-11C	A minimum of three (3) Samples is enough. Volume of test specimen shall be not less than 350 cm3 (0.35 L). Results of two properly conducted tests by the same operator on the same	"*The average absorption of the test set shall not be greater than 5% and no individual paver shall be greater than 7%."*

				material should not differ by more than: 1. Absorption: 0.5 %; 2. Density: 20 kg/m3; and 3. Volume of permeable pore space: 1%. "	
3	De-icing salts freeze-thaw durability test	-	CSA A.231.2-7.3 TS 3.80 - 05.07	A minimum of Three (3) Samples	"*Average weight loss of a set of concrete pavers subjected to 50 freeze/thaw cycles and immersion 3% NACL solution shall be less or equal to 1%"*
4.	Double Shear Strength test on Concrete	Adopted from a book and a Technical Paper.	CSA CAN3-A23.3-M94	A minimum of two samples	*The shear strength of ICPs should be within the range of 6-17 MPa*

2.8 Summary

The main conclusion drawn from this literature review is that the majority of existing applications for concrete pavers are related to areas with low speeds and light traffic loads. Some studies focused on these low traffic loading conditions, assessed the structural performance of ICPs using modelling software to determine the optimum dimensions and shapes for concrete. Other studies, evaluated sustainable materials such as waste materials and admixtures to develop durable concrete mixes and to enhance the mechanical properties of ICPs. The major contribution of this research is to develop innovative interlocking concrete pavers to address the challenges associated with urban city businesses and residences related to both design requirement, durability and sustainability.

From the literature review, to develop innovative ICPs that perform well in urban areas, robust experimental work with innovative materials in concrete mixes are needed. In addition, the behavior of this pavement under urban areas should be simulated to prove that ICPs can be performed in urban areas with higher traffic loading. Construction techniques also play a key role to enhance the service life of this innovative concrete paver.

Chapter 3
Paver Design

3.1 Introduction

SideWalk Lab is very committed to developing new and innovative cityscapes. This comes at a time when many cities have residential roadways in poor condition. This research aims to establish higher-quality roadways to improve the quality of life for a diverse population of residents, workers, and visitors yielding a solution that would encompass adaptability, sustainability, people-centric design, and potentially provide sustainable neighborhoods for cities around the world.

For this project, the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo (UW) works in partnership with the SideWalk Lab company in Toronto. Alphabet's Sidewalk Labs, a New York-based sibling company to Google, created the initial proposal and part of the proposal included the development of an urban Interlocking Concrete Pavement to address urban city business and residences' challenges.

Using ICPs is not common for urban roadways, especially for high traffic areas and this project aims to develop this type of pavements to respond these traffic demands to increase service life and reduce the need for regular maintenance. If this pavement's performance were deemed successful, ICPs could be considered as a rational option for rehabilitation in urban areas. Furthermore, other cities can gain the necessary knowledge and insight for integrating ICPs into municipal roadways.

3.2 Project Location

The SideWalk Labs Toronto project was initially directed for use in the Quayside neighborhood, located on the northwest corner of the Port Lands as shown in Figure 3-1. However, after this research began, it was determined that this project would not be pursued by the City of Toronto, but the research continued with the idea that this concept could be applied to other areas in cities around the world. The proposed pavement needs to be designed for different traffic modes such as personal vehicles, heavy trucks and public transportation vehicles. The resulting infrastructure should be designed in a way that provides pedestrian accessibility and safety during construction while removing construction limitations associated with other pavement types.

Figure 3-1: Location of Quayside, Toronto, Ontario.

3.3 Background

Interlocking concrete pavers (ICPs) have been identified as a potential paving method for the street and sidewalk areas. ICPs are modular paving elements, which are prefabricated in a production facility and brought to the site once they have cured and hardened. They can take various shapes, though the hexagonal shape, as shown in Figure 3-2, is considered ideal for this application.

Figure 3-2: Typical hexagonal ICP shape (Larrad, 2013).

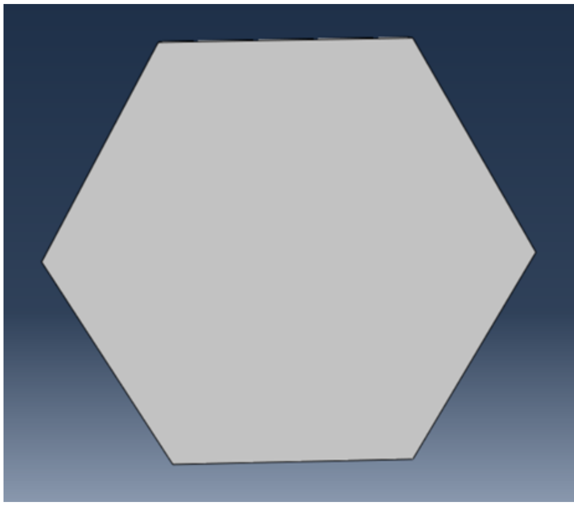
The ICPs are placed on the graded base material that provides vertical support. They are often designed to behave independently but are sometimes designed with shear keys that provide load transfer between adjacent ICPs. The ICPs can be placed by hand if they are small enough or by using a vacuum lifting device.

In an urban context, ICPs provide many benefits. The main benefit of ICPs is that they are highly adaptable to any environmental conditions due to their modular design. Any given element can be removed and replaced by another element with the same dimensions, but with desired characteristics. This adaptability also allows ICPs to address urban city business and residences' challenges. Sustainable design features can also be incorporated into the design of the ICP elements (Qin, 2018).

ICPs are typically permeable by nature, allowing surface water to flow through the unsealed joints between adjacent elements. This permeability can be further increased by incorporating drainage features into the element design. Permeable pavements can reduce the demand for storm water collection infrastructure while providing local flood control and redirecting typical run-off from storm water collection systems to the groundwater system. It can also reduce pooling and splashing under heavy rain events and remove the potential for black ice from standing water. Water-retaining designs can also be used to reduce the urban heat island effect common in other more typical pavements (Qin, 2018).

3.4 The Unique Shape for Concrete Paver

The shape of ICPs should be selected in a way that they can respond to traffic demands as well as be compatible in an urban context. Using common paver shapes, ICPs typically perform well in low-speed and traffic areas. For integrating this kind of pavement into urban areas, careful selection of shape and dimension of ICPs according to their application is crucial. An equilateral hexagon design adopted from IFSTTAR design is selected for this study. The shape of this pavement consists of two parts that act as one concrete paver. The first part of this pavement shown in Figure 3-3 is a hexagonal shape and the second part shown in Figure 3-4 is an irregular shape.



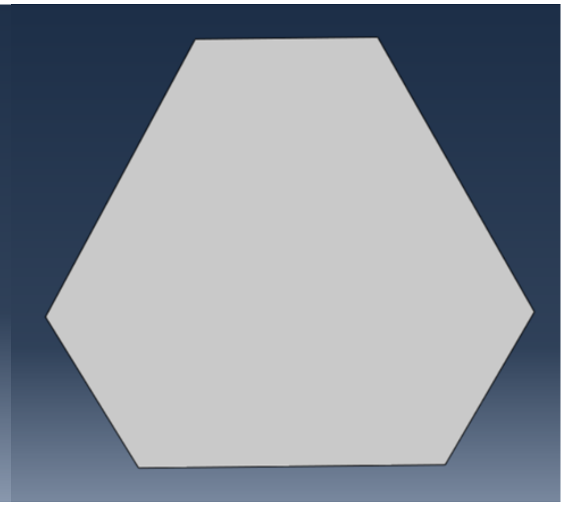


Figure 3-3: Top of the concrete pavers. **Figure 3-4**: Bottom of the concrete pavers

As the top of the concrete paver is a hexagonal shape, the construction pattern that will be performed in urban roads is a honeycomb pattern (Figure 3-5). To better illustrate the overall shape of this pavement, Figure 3-6 and Figure 3-7 are provided. Figure 3-6 shows the concrete paver top view and Figure 3-7 demonstrates the bottom viewpoint of this pavement. This innovative concrete paver was fabricated by SideWalk Labs located in the city of Toronto and Figure 3-8 shows the final shape of ICPs after fabrication.

Figure 3-5: Honeycomb construction pattern [Photograph taken: Jan. 2020].

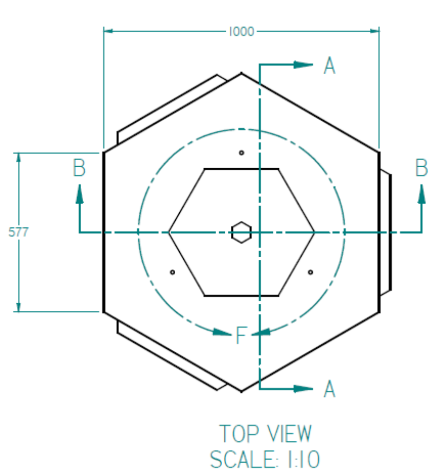


Figure 3-6: Top view of concrete paver.

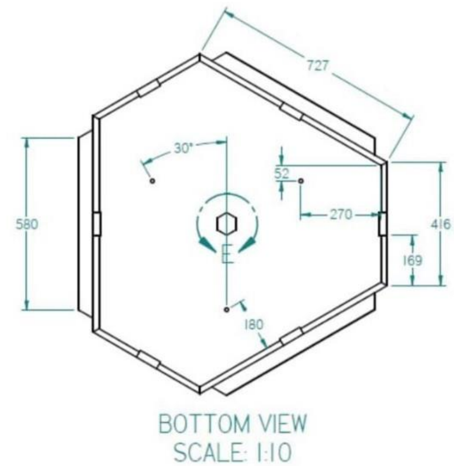


Figure 3-7: Bottom view of concrete paver.

Figure 3-8: Concrete paver fabricated in Sidewalk Lab Toronto [Photograph taken: Jan. 2020].

The thickness of ICPs in high traffic areas such as urban roads should be greater than low traffic areas such as parking lots and sidewalks. Generally, typical shape of ICPs are not applicable for urban areas as the thickness of these pavement are not high enough to withstand in high traffic areas. The overall thickness of this pavement is 200mm and the two-part shape of ICPs helps to reduce the loads and deflections. The selection of thickness is highly important especially in urban areas if we want to have high-quality pavement with long service life.

3.5 Concrete Mix Design

3.5.1 Introduction

This is a preliminary environmental performance assessment of concrete mixes using alternative materials to reduce carbon dioxide emissions and to respond to the environmental aspect of this research. This was completed in partnership with other members of the CPATT research team including Jessica Achebe and Remi Oyediji.

3.5.2 Materials

The environmental performance of business as usual (BAU) concrete mix with 100% General Use Portland Cement (GU) (control mix) was compared to 11 mix designs with different proportions of recycled materials and supplementary cementitious materials. Coarse recycled concrete aggregate (CRCA) was considered as a substitute for natural course aggregate. Portland-Limestone (GUL) Cement, Ground Glass Pozzolans (GP), 10%, Slag and Fly ash (FA) were considered as Portland Cement (GU) substitutes. Primary mix design for this assessment is shown in Table 3-1 below.

Table 3-1: Primary mix design for 1m^3 of concrete mix

# of Mix		GU	Coarse Agg.	Fine Agg. (sand)	Water	Steel Fibre	GUL	GP 10%	Slag 20%	FA 10%	CRCA 25%
1	Control Mix, GU 100%)	417	950	793	188	40	0	0	0	0	0
2	GUL 100%	0	950	793	188	40	417	0	0	0	0
3	90%GU + 10% GP	375.3	950	793	188	40	0	41.7	0	0	0
4	80%GU + 20% slag	333.6	950	793	188	40	0	0	83.4	0	0
5	70%GU +20% slag+10% GP	291.9	950	793	188	40	0	41.7	83.4	0	0
6	80% GU +10%FA+10%GP	333.6	950	793	188	40	0	41.7	0	41.7	0
7	100GU + 75%NA + 25% CRCA	417	712.5	793	188	40	0	0	0	0	237.5
8	90%GUL + 10% GP	0	950	793	188	40	375.3	41.7	0	0	0
9	80%GUL + 20% slag	0	950	793	188	40	333.6		83.4		
10	70%GUL +20% slag+10% GP	0	950	793	188	40	291.9	41.7	83.4	0	0
11	80% GUL +10%FA+10%GP	0	950	793	188	40	333.6	41.7	0	41.7	0
12	100%GUL + 75%NA + 25% CRCA	0	712.5	793	188	40	417	0	0	0	237.5

3.5.3 Impact of Materials (Energy Use)

Figure 3-9 shows the energy use demand for cradle to gate impact of 1km^2 lane pavement section constructed with the mix designs stated in Table 3-1. This shows the sum of energy used for material production, material transportation from plant to construction site, and construction of pavement at the site. Mix 10 seems to provide the best environmental benefit in terms of energy use. All mixes have a lower energy demand compared to the control mix (Mix 1) but Mix 7 performed worse. Energy use benefit of Mix 10 is from the use of high percentage of supplementary cementitious material (30%) and the GUL cement which has less energy demand in material production compared to GU cement. Mix 7 includes recycled materials but the energy required to process the recycled concrete aggregate before using it in the concrete mix make this mix have the worst environmental impact based on energy resource use.

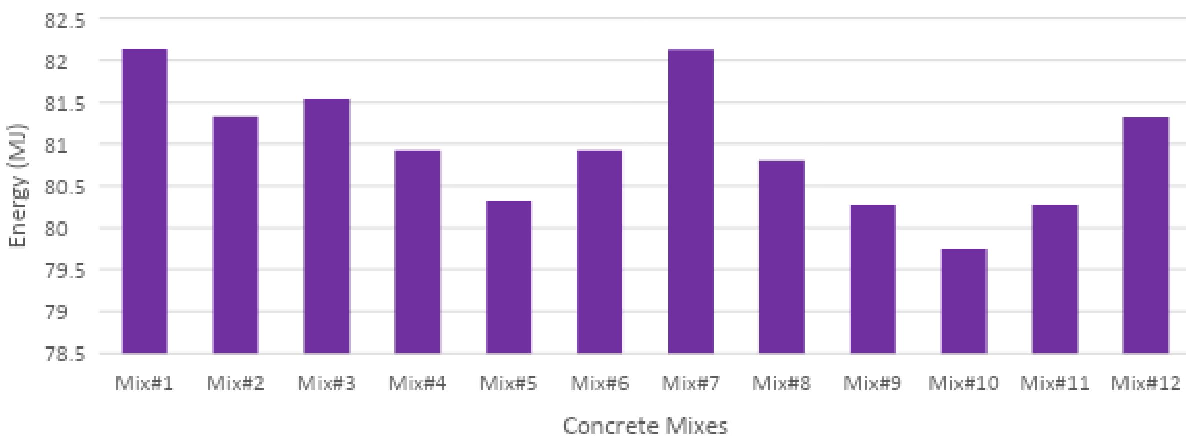


Figure 3-9: Cradle to grave energy use impact for constructing 1km 2lane (3.5m each) pavement section [completed by Jessica Achebe, 2020].

3.6 Summary

In order to improve the quality of residential roadways, innovative solutions are needed to establish high-quality roadways for a diverse population of residents, workers, and visitors. Among existing pavements, ICPs provide many benefits in an urban context. The main benefit of ICPs is that they are highly adaptable to any environmental conditions due to their modular design. Any given concrete pavers can be easily removed and replaced by another paver with the same dimensions, but with desired characteristics. This adaptability also allows ICPs to address urban city business and residences' challenges. Sustainable design features can also be incorporated into the design of the ICP elements. Subsequently, careful selection of shape and dimension of ICPs according to their application is crucial. An equilateral hexagon design adopted from IFSTTAR design is selected for this study. The overall thickness of the proposed pavement is 200 mm and the two-part shape of ICPs helps to reduce the loads and deflections that may arise due to heavier traffic loads. Environmental performance assessment of concrete mixes was assessed using life cycle analysis for mixes using alternative materials to reduce carbon dioxide emissions and to respond to the environmental aspect of this research. Energy use demand for concrete mix design was calculated and mix #7 (composed of GU, natural aggregate and approximately 25% crushed recycled coarse aggregate) showed the worst environmental impact among all 11 mixes. However, it is notable that mix 2-6 and 8-11 also showed promise but mixes 2-6 and 8-11 performed better in comparison to other mixes based on the energy resource use.

Chapter 4

Finite Element Model

4.1 Introduction

The aim of this research is to design a hexagonal concrete paver consisting of a sustainable concrete mix design under heavy traffic loading conditions that meet a typical city's requirement. Evaluating the performance of this new and innovative paver is important as producing sustainable pavements. There are many methods to evaluate the performance of ICPs; among the existing method, finite element analysis (FEA) is a strong tool for assessing the performance of the pavement. FEM can be applied to solve none-leaner and complicated problems by the classical analytical method (Nikishkov, 2004). This method approaches problems numerically and solves general deferential equations in an approximate manner**.** This assumption is assumed in a specific area which can be one, two, or three-dimensional.

4.2 Finite Element Method

This study is based on calculations using the Finite Element Method (FEM). This method breaks down limited areas into a smaller part, called finite element (Ottosen, 1992). When small elements are connected, they form a large area, called the mesh. This method uses many small elements to find approximate solutions to more complicated problems. FEM allows us to examine the behavior of each element in the main area. This leads to assessing variables over the element whether linear or non-linear over the region.

One of the important aspects of FEM calculation is to specify the degree of freedom (DOF) of each element. This describes the behavior of each element based on a finite number of degrees of freedom. The degree of freedom is described as one or more unknown functions in a set of nodal points. For more accurate approximations, more DOFs should be used (Ottosen, 1992).

For some easy problems, FEM calculations can be done manually. However, to calculate the more complex problems computer software is commonly used.

4.3 ABAQUS

ABAQUS is a general-purpose finite element software for modelling pavements under various traffic loadings, materials, and environments. The program simulates the pavement in 3 dimensions with many features and options that produce a robust and efficient model (Gunatilake and Mampearachchi, 2019).

In this research, ABAQUS/standard solver that uses implicit methods to simulate ICPs and foundations in field conditions are implemented. ABAQUS uses three steps to complete an analysis.

The first step to create a model is pre-processing. In this step, the geometry parameters including loads, materials, and boundary conditions can be defined.

The second step is the processing step. This step is a calculation step when all the defined calculations are done.

The third step is the post-processing step. This step involves visualizing the results that allow us to identify high-risk areas easily. User-defined results may be organized and displayed in different ways such as spreadsheets, graphs, or color visualizations of geometry.

In the following, software modules used for building this model are explained systematically.

4.3.1 Geometry Module

There are various shapes, sizes, and construction patterns for ICPs. Shapes and construction patterns should be selected according to their applications. In this research, the equilateral hexagon design pattern was selected for construction patterns, and the shape of concrete pavers consists of two parts that are acting as one system. The reason for its selection of this project is that it is easier to remove and replace for underground utility maintenance. In addition, it is easier to replace local failure in the pavement (potholes) with a modular design.

Figure 4-1 shows the shape of the top of the concrete pavers that is a honeycomb. Whereas the irregular shape was adopted from IFSTTAR design for the bottom of concrete pavers (Figure 4-2), to design the pavement per North American (Canadian) design standards. These two-parts of concrete pavers were assigned together in geometry module in ABAQUS software. In geometry module, the final shape of the concrete paver is depicted.

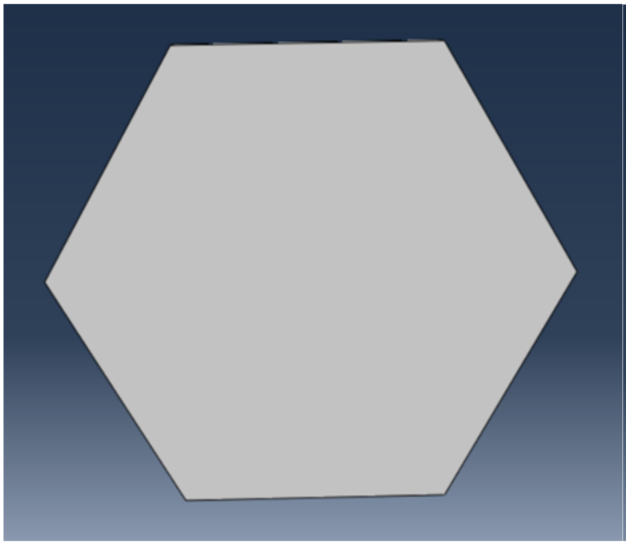


Figure 4-1: Top of the concrete pavers.

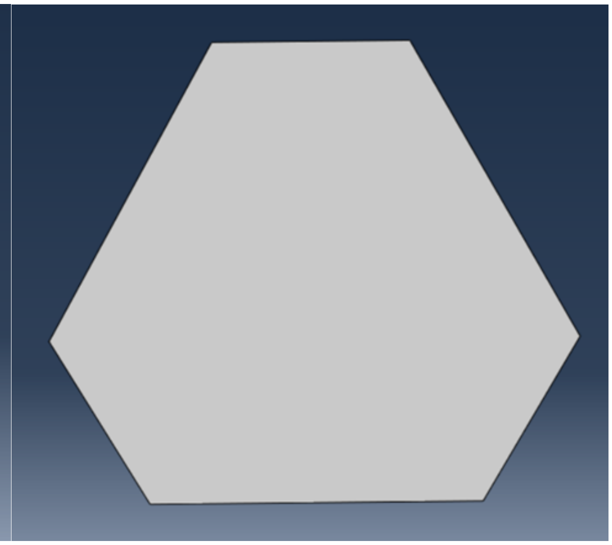


Figure 4-2: Bottom of the concrete pavers.

4.3.2 Part Module

Table 4-1 describes the properties of the systematic structure of the designed pavement used in this research. The material assigned to concrete pavers is intended to be impermeable and material properties in Table 4-1 will be tested in the lab to see if modelling assumptions are accurate. In this model, the structure pavement layers have been connected as a single part to distribute the loads throughout the pavement, and act like asphalt pavements. In construction methods, this kind of pavement can be connected through impermeable joints.

The pavement foundation is partitioned into four regions representing each layer with specific mechanical properties. By applying this structural element strategy, there is no need for defining additional interactions between the layers as they have already been connected. Another method is to model each layer as a single part and then assemble them on top of each other and define the node constraint between them. The sketch of the foundation is shown in Figure 4-3. The sketch that is extruded equally with the dimension of three meters shown in Figure 4-4.

In ABAQUS, when utilizing various layers with different properties, the outcomes show the structural layers with different colors indicating the properties' variation. That is clear in Figure (Figure 4-5).

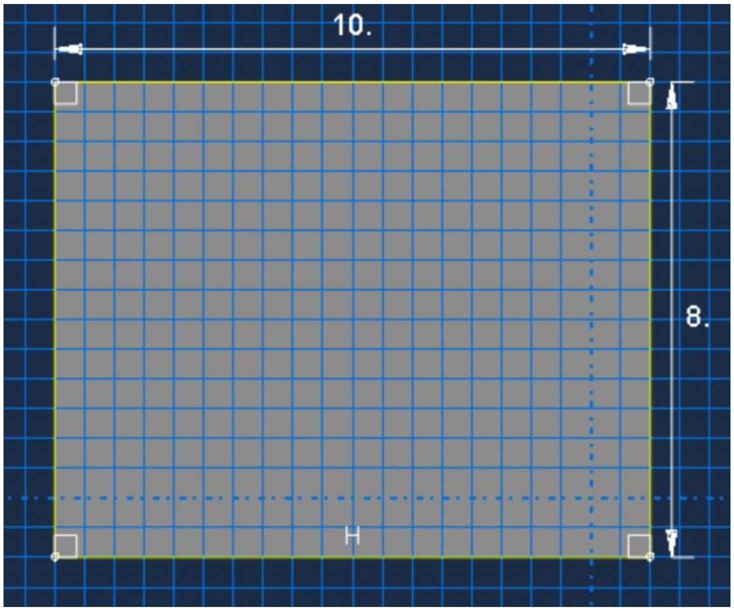


Figure 4-3: Sketch of foundation in ABAQUS software.

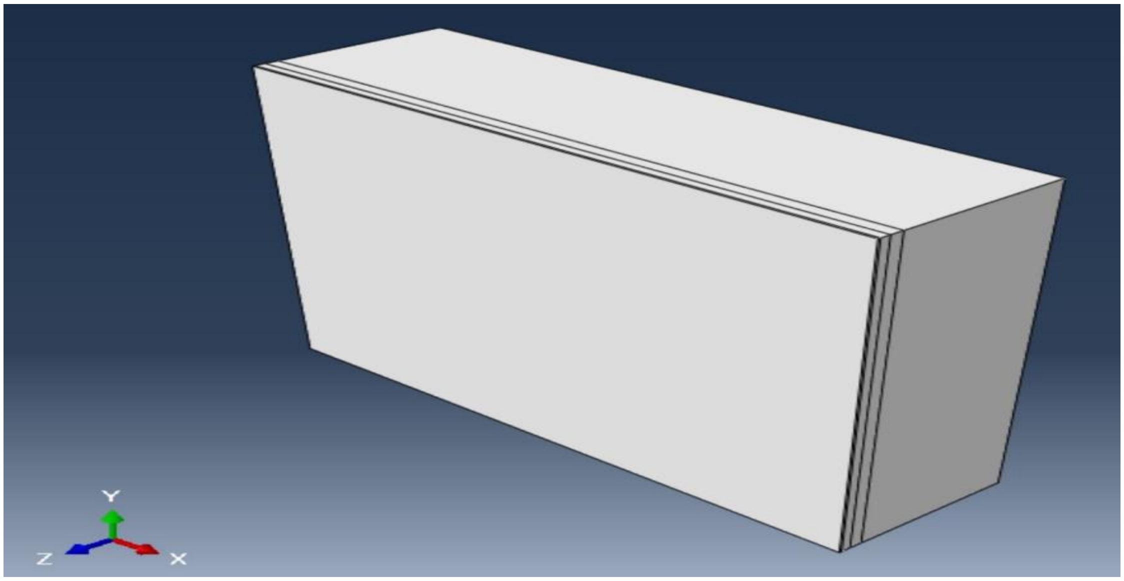


Figure 4-4: Foundation in ABAQUS.

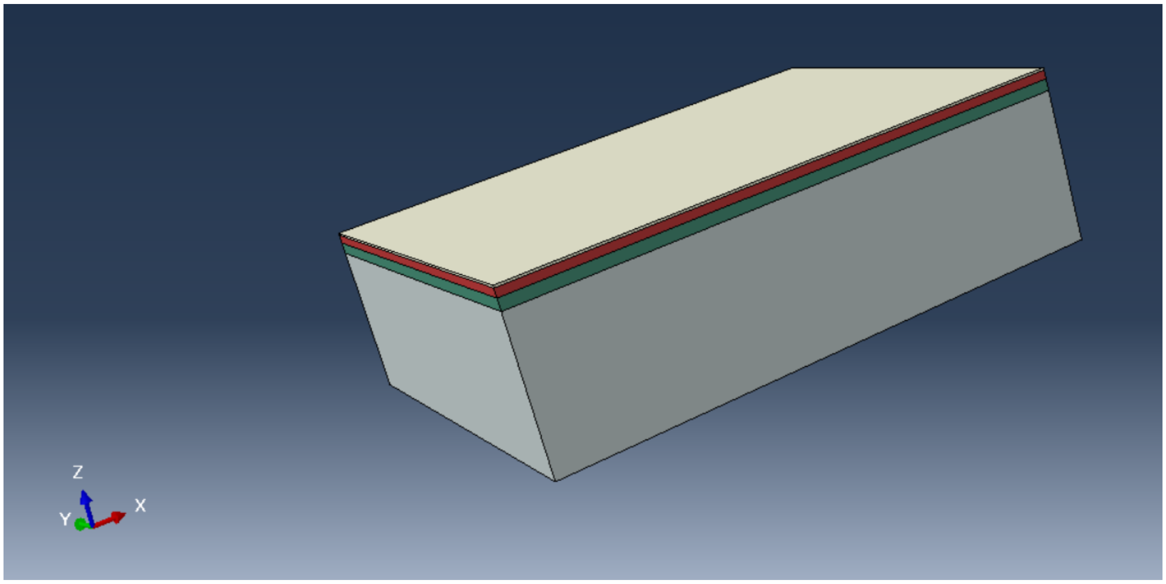


Figure 4-5: Colorful foundation's layers represent the different mechanical properties.

Figure 4-6 shows the thickness of concrete pavers and foundation layers. The thickness of both the concrete paver and foundation is optimized in a way that if the mechanical property of materials and thickness of foundation layers are considered lower than the values shown in Table 4-1 and Figure 4-6, the pavement will fail. By optimizing the pavement thickness, the initial cost can be reduced for this new and innovative paver as the initial cost for this type of pavement is higher than other types. In addition, pavement thickness optimization can reduce life cycle cost significantly.

Figure 4-6 indicated the thickness optimization for pavement base, subbase and subgrade layers for cost performance on urban loads. Different thicknesses and materials properties were considered in the simulation and the optimum thickness was selected for each layer. With this strategy like pavement optimization, the pavement is designed in a way that performs well on roads for the lowest cost.

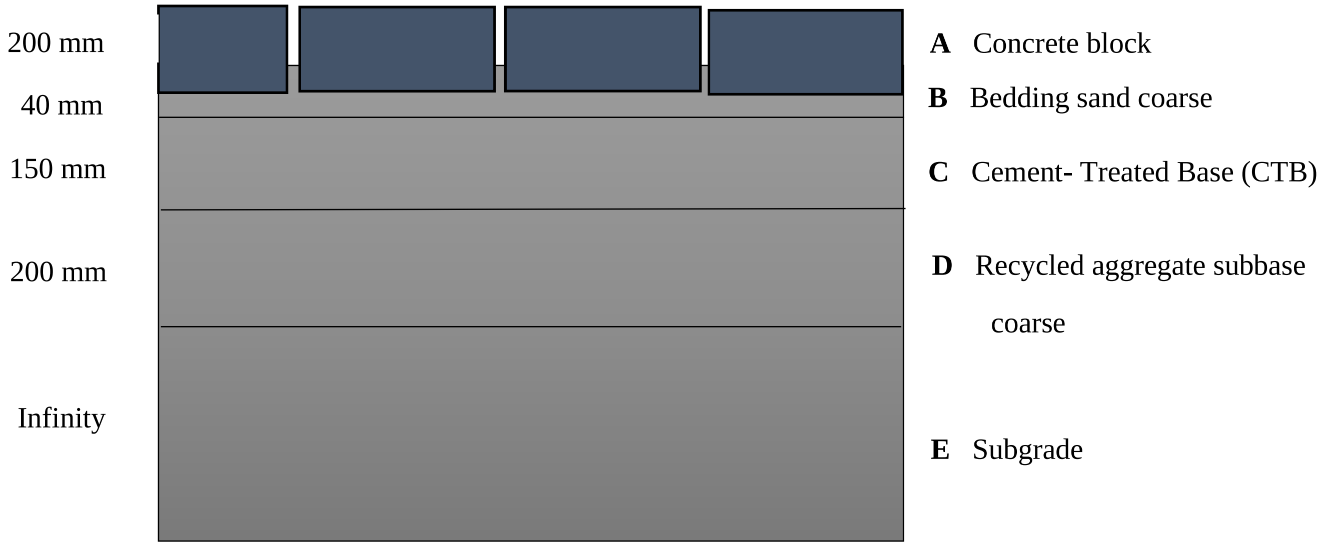


Figure 4-6: Concrete pavers and foundation layer thickness.

4.3.3 Property Module

Material properties can be specified in this module. In this study, five materials have been defined in the property module and have been assigned to the foundation and the equilateral hexagon pattern. As the dynamic implicit step is used, density and elastic behavior have been defined for all of the materials in the model. It contains the specification of Young's Modulus and Poisson's ratio for each layer.

Table 4-1 describes the properties of the systematic structure of the designed pavement used in this research.

Table 4-1: Pavement layer material properties.

Section	Materials	Elastic Modulus (MPa)	Poisson's Ratio
A	Concrete blocks	17,000	0.19
B	Bedding sand coarse	100	0.30
C	Cement-Treated Base (CTB)	5,170	0.20
D	Recycled aggregate subbase coarse	200	0.35
E	Subgrade (sand and gravel)	60	0.40

The selected properties are presented in Table 4-1. For example, the range of elastic modulus for a conventional concrete is within the range of 10-30 GPa, and the selected value for concrete blocks is 17 GPa as shown in Table 4-1. The software calculates how the materials behave when various pressure loads are applied. For instance, if the materials fail under loading, the properties of the material have to be changed in practice so that the material can respond to the loads and ultimately perform well. The use of recycled materials in subbase layer reduces the use of natural aggregate and the cost. In addition, it is true that if high quality materials are used, then it would be expected that they would perform better. However, the higher quality materials may not be economical for this application. The optimization is considered for the pavement materials presented from Table 4-1. The simulation was run repeatedly to determine the materials property of this new and innovative paver such that they can respond to the defined conditions for this research and be optimum at the same time.

4.3.4 Assembly Module

The Assembly Module allows different parts of the pavement to be connected and acting as one system. Concrete pavers consist of two parts (honeycomb top and honeycomb bottom). In an assembly module, the following steps have been taken:

1) Connecting the top and bottom part of the pavement to make one concrete paver.
2) Assemble 10 concrete pavers to make a honeycomb pattern.
3) Assemble the honeycomb pattern to the soil layers.

This is the configuration applied to the model at $time = 0$ before applying the forces. After applying the loads, this configuration will change. The assembly is shown in Figure 4-7.

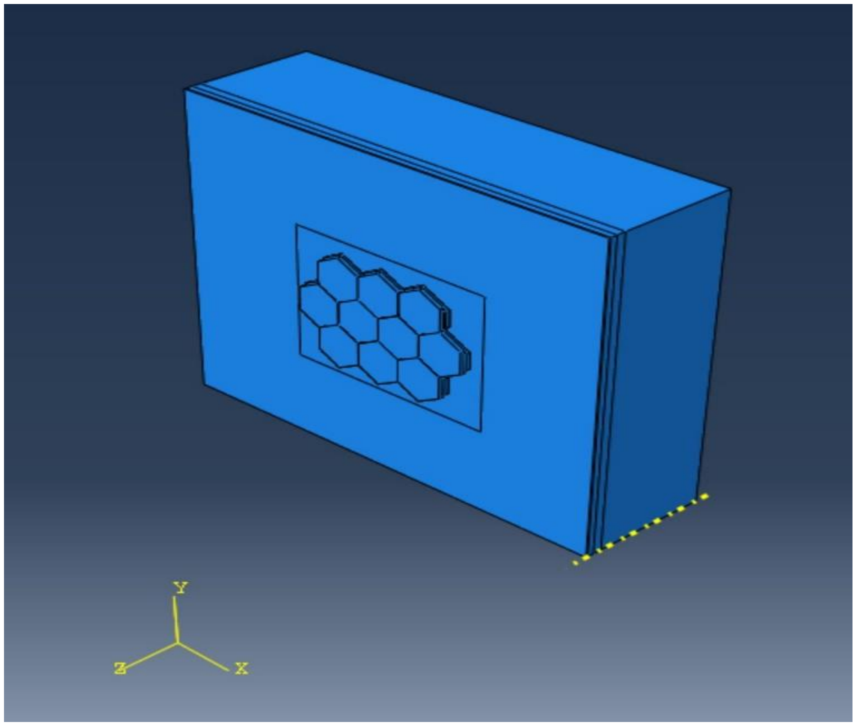


Figure 4-7: Interlocking Concrete Pavement model in assembly module

4.3.5 Step Module

The step module defines the type of analysis to be performed. Even though this problem can be solved statically, the dynamic implicit step is used for better and faster convergence of the problem. Besides, the dynamic implicit step accounts for the inertial forces. The presence of the inertial forces in the nonlinear equations improves the speed of the convergence and each increment will be converged easier. As the problem is static, the step has been set to solve the problem as a quasi-static problem.

As this paver is modeled for heavy truck vehicles and high traffic areas, the large deformation is not far from what would be expected. If it is predicted to have large deformation in the model, the NLgeom is set to be on during the analysis. The NLgeom in the ABAQUS/Explicit option accounts for geometric nonlinearity during the analysis. This increases the accuracy of the simulation but also introduces extra nonlinearity to the problem.

4.3.6 Interaction Module

In the interaction module, the mechanical interaction between the concrete pavers and the foundation should be defined. In this modelling, the tie constraint is defined between the top and bottom of the honeycomb concrete paver. Besides, the tie constraint is specified between the top of the soil and bottom honeycombs; as a result, there will be no relative displacement between their nodes. Settings for interactions are illustrated in Figures 4-8 and 4-9. The goal of defining the interaction between the different regions of pavement is to create a pavement acting as one system; consequently, loads can distribute throughout the entire pavement.

To take into account, general contact is defined between the top and bottom honeycomb layers. The friction coefficient of contact is set to 0.3. By defining general contact, ABAQUS will find all of the contact pairs automatically and there is no need for defining the contact pairs manually.

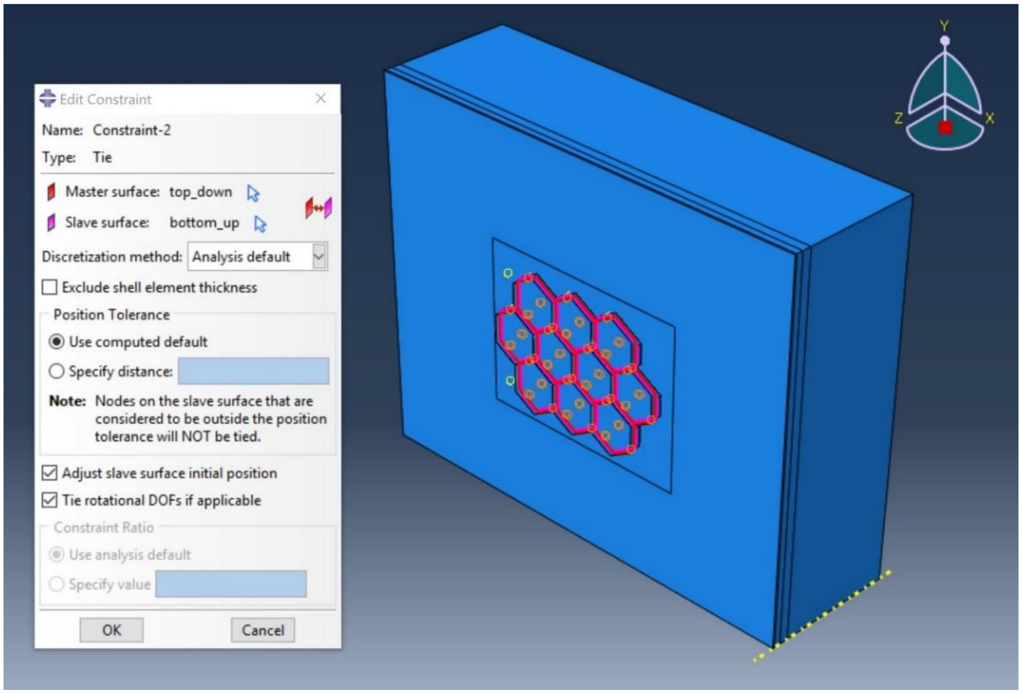


Figure 4-8: Interaction between the top and bottom of the concrete paver.

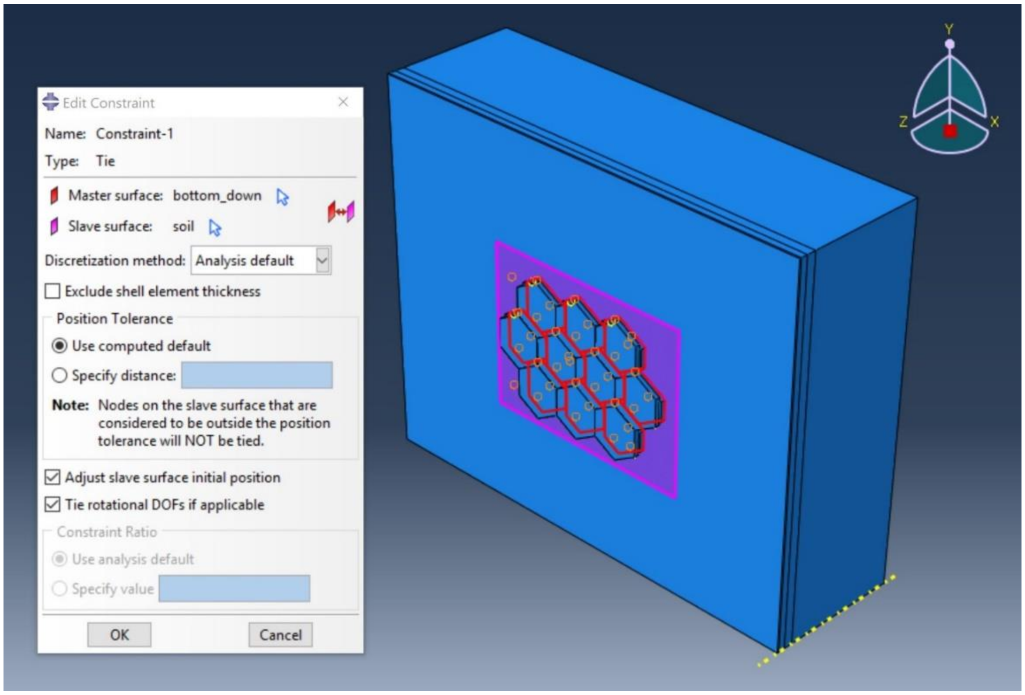


Figure 4-9: Interaction between the bottom of the pavement and top of the foundation.

4.3.7 Load Module

In the ABAQUS software, the pavement and foundation layer can move freely in any direction, unless freedom restrictions are defined.

The designed foundation cannot move in X (U1), Y (U2) and Z (U3) directions as we are not expecting any displacements and rotations for foundation under designed traffic loads (Figure 4-10). All of the active degrees of freedom of the bottom and top of the foundation are restrained to zero (U1= U2=U3 =0).

Concrete pavers should be free in Z (U3) direction as the pavements experience deflection during their lifecycle (Figure 4-11). Consequently, ICPs cannot move in X and Y direction (U1=U2=0) and they are free in Z direction (U3).

When the loads are applied, pavement should be able to distribute the loads throughout the system and the pavement foundation should endure pressure loads without any displacements or rotation.

The traffic design is a typical urban roadway that the range of speed is between 60 to 70 Km/h. This roadway will be under heavy truck vehicles and high traffic volumes (Table 4-2). Double axial load is considered as a load configuration according to Ontario's Default Parameters for AASHTOW are pavement ME design (see Figure 4-12 and 4-13).

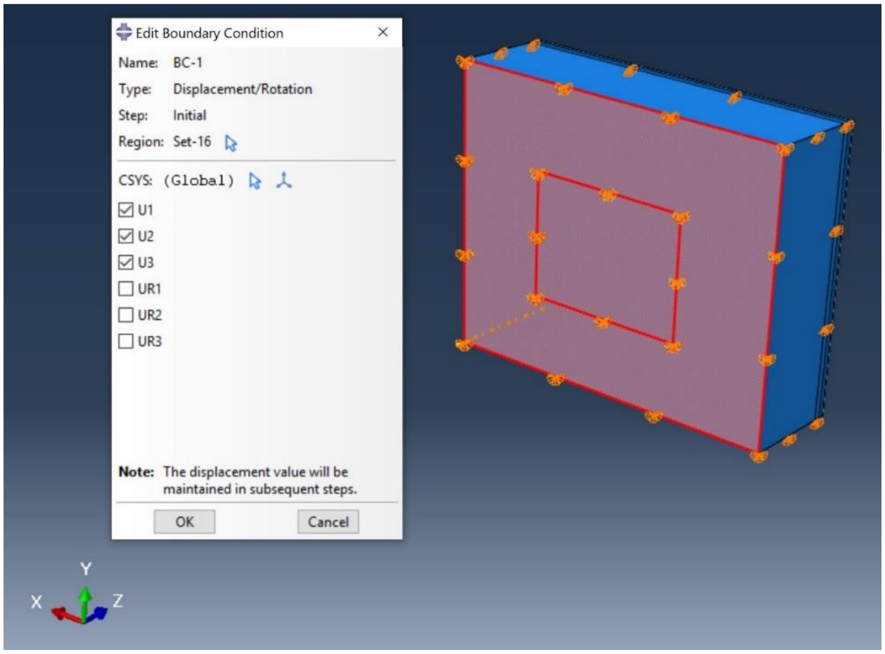


Figure 4-10: Boundy condition for soil layer.

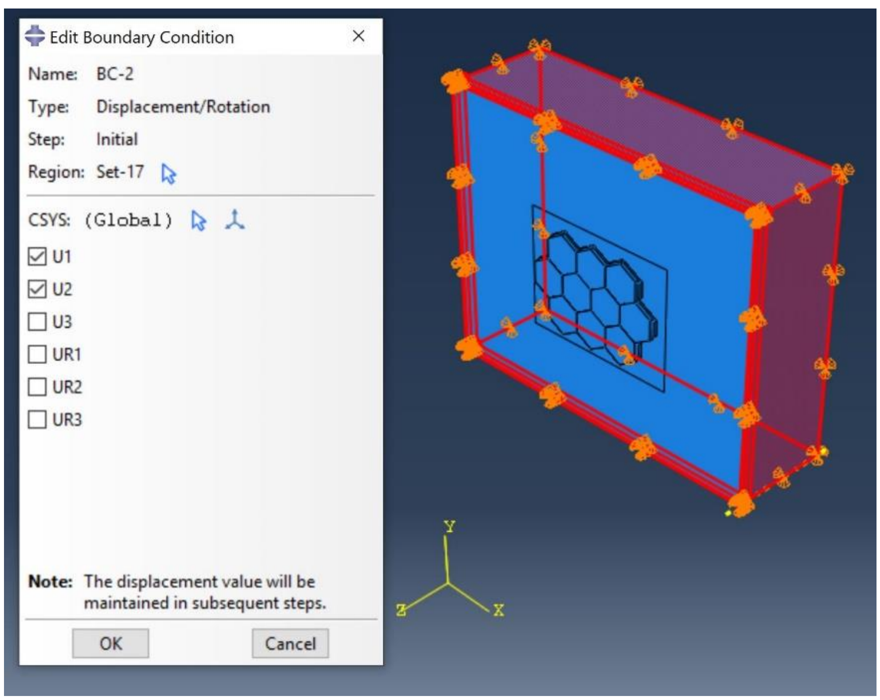


Figure 4-11: Boundy condition for the pavement.

Table 4-2: AASHTOWare Pavement ME Design Defaults Axle Configuration.

Axle Configuration	Default Values
Average axle width (m)	2.59
Dual tire spacing (mm)	305
Tire pressure (kPa)	827.4

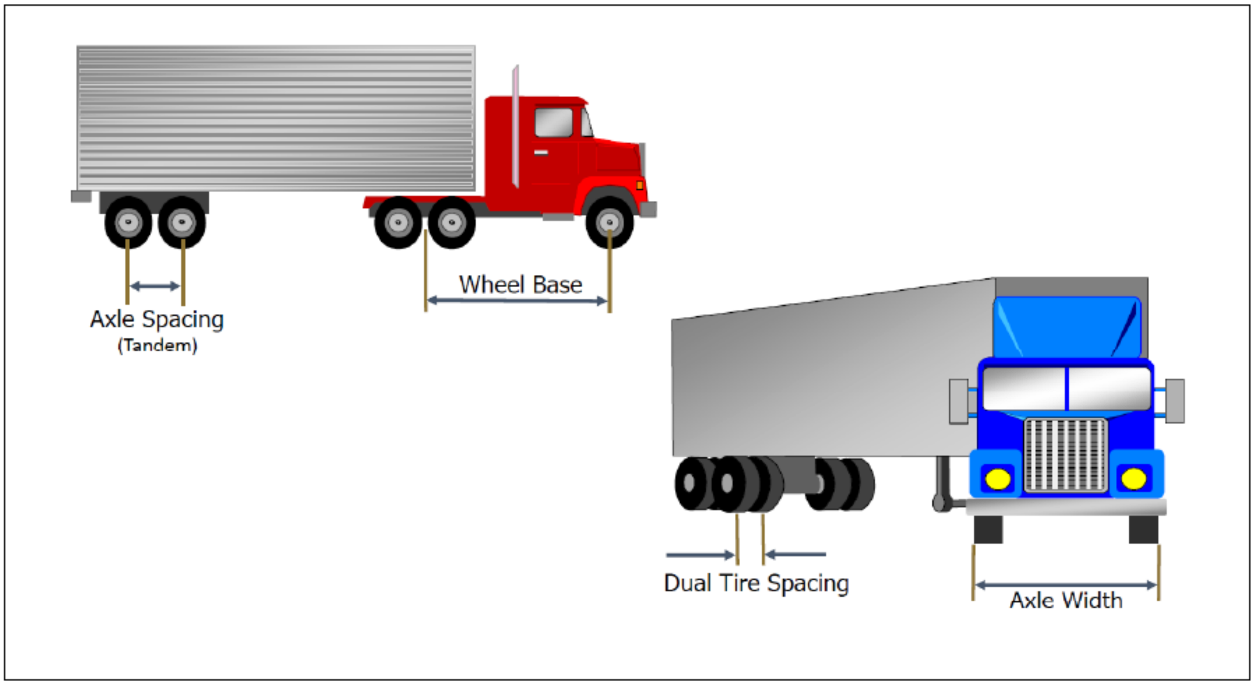


Figure 4-12: Axial configuration (Ontario's Default Parameters for AASHTOWare, 2019).

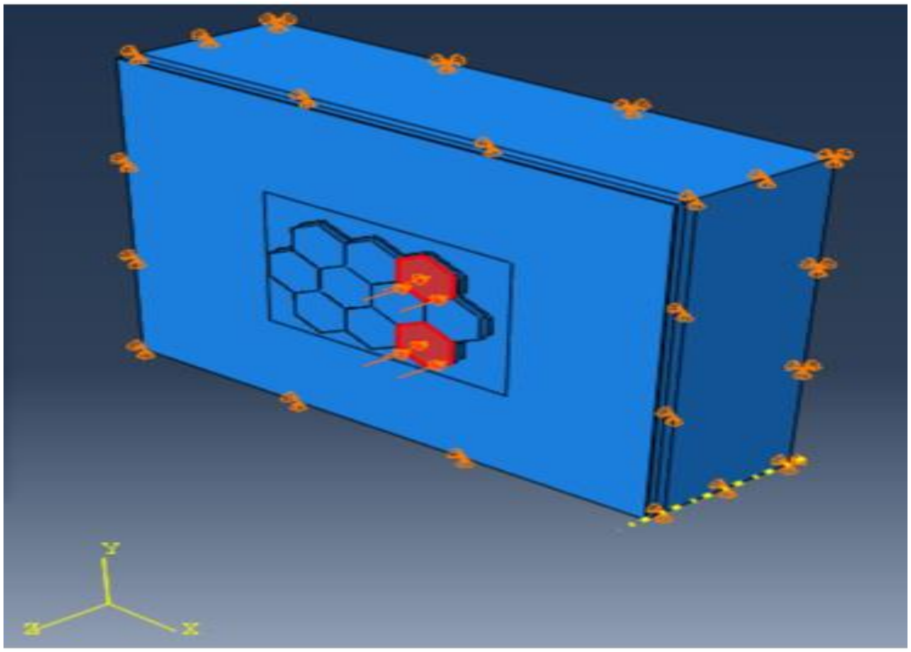


Figure 4-13: Axial load configuration in ABAQUS.

4.3.8 Mesh Module

In this module, the element size is defined for both concrete pavers and foundation layers. ABAQUS software analysis the results based on the defined element number. For example, for an object with 100 elements it results in a higher accuracy in comparison with 50 elements on the same object. However, simulating with higher number of elements is time-consuming and may takes time between hours to days. In this research, the objective is to achieve a simulation that is more efficient and to keep the results with high accuracy.

Concrete pavers and foundation layers are meshed by the C3D8R element. The global size of the elements of top and bottom honeycombs is 0.1. The reason for considering the finer mesh for concrete blocks is to increase the accuracy of the analysis as the loads are applying on the concrete pavers (Figure 4-14).

To achieve an efficient simulation and to speed up the simulation process, the foundation is partitioned into two regions:

- The first region is the interior area that interacts with bottom of the concrete pavers. As the loads apply on this area, the finer mesh (0.1) is needed to increase the accuracy of results (Figure 4-15).
- The second region is the exterior region and the bigger mesh (0.8) was defined for this area.

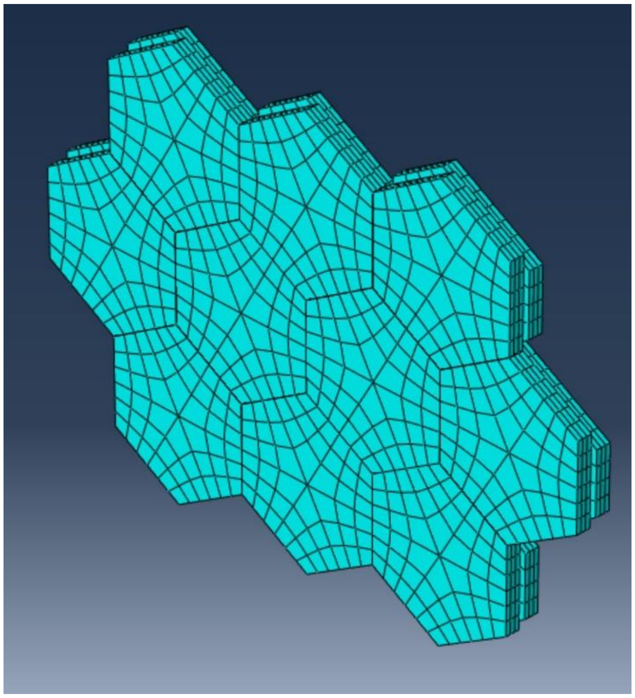


Figure 4-14: The mesh of honeycomb pattern.

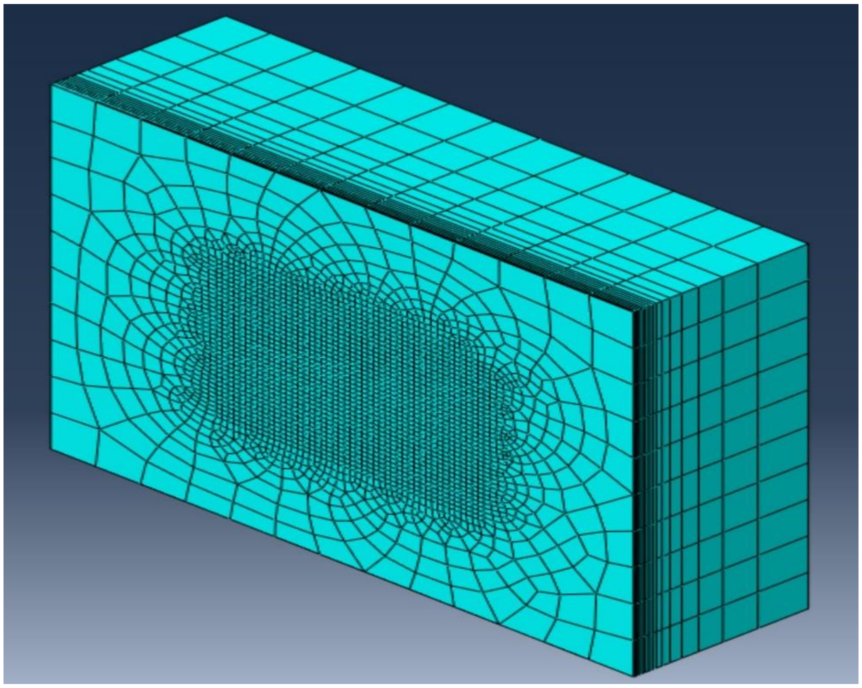


Figure 4-15: The mesh of foundation.

The mesh of the foundation consists of 50122 elements. The mesh of each concrete pavers' bottom is 120 elements. The mesh of the top of the concrete pavers is 162 elements. Therefore, the mesh of the entire assembly consists of 58440 elements. This shows that this model has high accuracy in analysis.

4.5 Summary

Table 4-3 shows the summary of the major findings of the ABAQUS analysis.

Table 4-3: Summary of ABAQUS modules.

Module	Purpose
Geometry	The shape of the concrete paver and foundation layers are depicted; the hexagonal paver was primarily used as the basis of the paver geometry.
Part	The material properties are assigned to concrete pavers and foundation layers. Each layer in the structure has their own defined properties based on material type.
Property	The material property of concrete and foundation layers are defined. The main properties needed for this analysis were the elastic modulus, Poisson's ratio, and the mix design density.
Assembly	Foundation layers and the two-parts of concrete pavers are assembled together to act as one ICPs system.
Step	The type of analysis to be performed is defined; the dynamic implicit step is used for faster convergence of the FEM model.
Interaction	The mechanical interaction between the concrete pavers and the foundation are defined using tie-type constraints.
Load	The magnitude of loads and the freedom of concrete pavers and foundation are defined as related to typical heaving traffic loading in accordance with the AASHTOWare Pavement ME Design guide.
Mesh	The element size for analysis is defined as the size necessary to acquire an accurate model solution. A global element size of 0.1 was used for the honeycomb ICPs structure and an element size of 0.8 was used for the base material.

Chapter 5

Results and Discussions

5.1 Introduction

Pavement assessment is essential to determine the functional and structural conditions of the pavement to meet the needs of a new and innovative design, which will perform well in an urban setting. The pavement design also needs to be accessible, pedestrian friendly, capable of withstanding heavy truckloads and durable under a variety of environmental conditions. Although this research focuses on the FEM analysis for the various designs, there are also complementary laboratory tests that will be completed by other members of the research team. The ABAQUS simulation results have improved over 100 times and each simulation took 12 hours to run.

The results of the FEM analysis of these designs are summarized in the following sections.

5.2 Optimal Pavement Thickness

A properly designed ICP performs well for several geological, traffic, environmental, and operational constraints (Gunatilake and Mampearachchi, 2019). The selection of paver thickness is according to their applications and design needs, such that the thickness of paver in high traffic areas such as urban roads is greater than low traffic areas such as parking lots and sidewalks. Integrating ICPs to high traffic areas requires adequate thickness besides other factors. Choosing the right thickness can increase the resistance of this kind of pavements against traffic loads and reduce deflection (Shafabakhsh and Family, 2014). Different scenarios are considered to determine the optimal thickness, which is an economical choice while not compromising the structural performance of ICPs.

Different thicknesses were considered for this pavement analysis and the FEM results are based on selected thickness shown in Table 5-1. As this new and innovative concrete paver will perform on urban context, the thickness of this paver should be higher than the typical ICPs. Curve fitting was used based on Finite Elements results (see Figure 5-1). It can be seen that as thickness increases, the maximum vertical displacement decreases. According to Figure 1, it can be concluded that the differences between 20 and 21 cm thickness are much less than 19 to 20 cm. Even though 21 and 22 cm thickness have less maximum vertical displacement, it is not an economical choice. The optimum thickness for this modelling is considered 20 cm. This is determined based on the curve fitting exercise which shows that the thickness above 20 cm does not cause a significant change in maximum vertical displacement.

Table 5-1: FEM results for different pavement thickness.

Pavement Thickness (m)	FEM Results (m)
0.16	0.0041
0.17	0.0036
0.18	0.0030
0.19	0.0025
0.20	0.0021
0.21	0.0019
0.22	0.0017

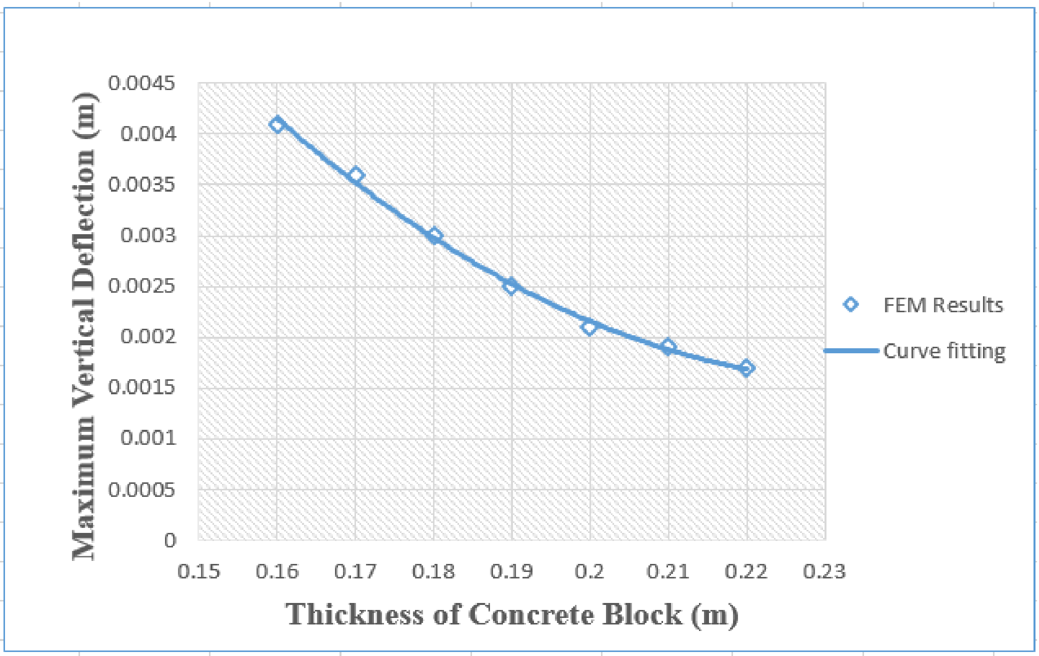


Figure 5-1: Modelling diagram for ICPs.

5.3 Deflection

The structural strength of the ICPs measured by the deflection, shows the structural capacity of the pavement to withstand traffic loads (Pavement Design and Rehabilitation guideline, 2019). The overall strength of the pavement can be indicated by the maximum pavement deflection, such that, the high deflection shows that the overall pavement performance is weak while low deflection shows strong pavement performance. A general guideline indicates that deflection lower than 100µm would represent a good performance for interlocking Concrete pavers. The deformation contour of the foundation along the Z direction is depicted in Figure 5-2.

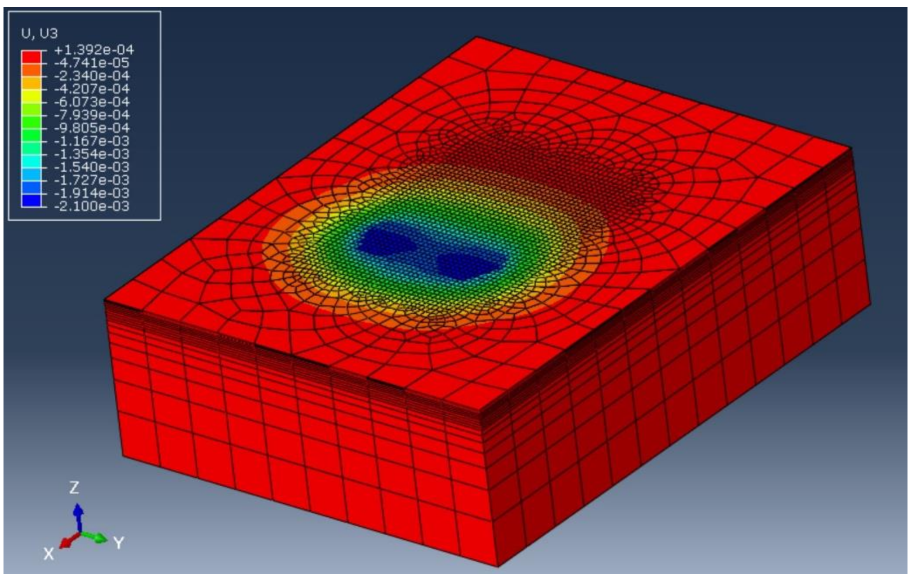


Figure 5-2: The deformation of the foundation in Z direction.

The maximum absolute value of the deformation has occurred at the bottom of the concrete blocks where are loaded. In Figure 5-3 and 5-4 the path for concrete pavers and foundation deformation are shown. Paths are created from the nodes of the top of the foundation and concrete pavers. The path that is thicker than the other paths shows the maximum absolute value of the ICPs deformation. The goal of using this ABAQUS feature is to visualize the problematic path and take steps for improvement.

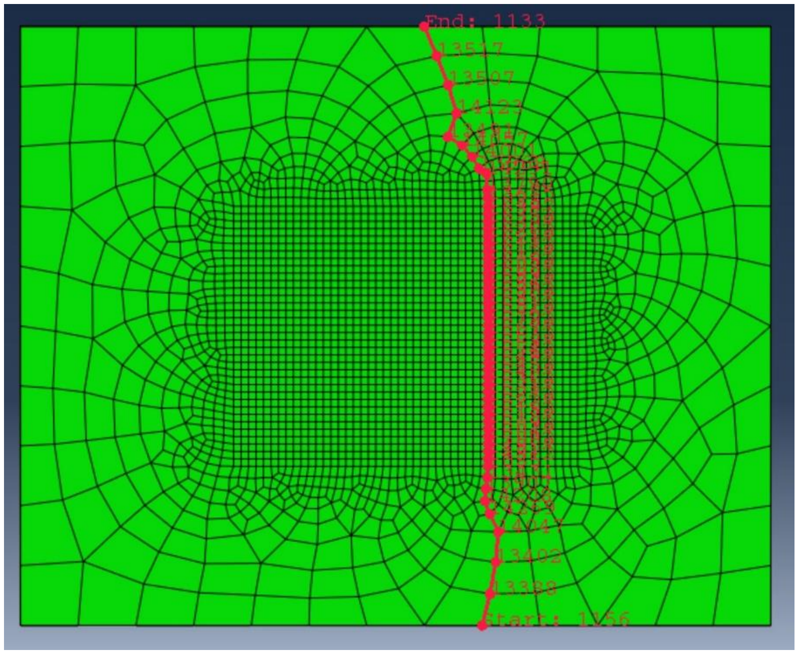


Figure 5-3: Deflection path in foundation.

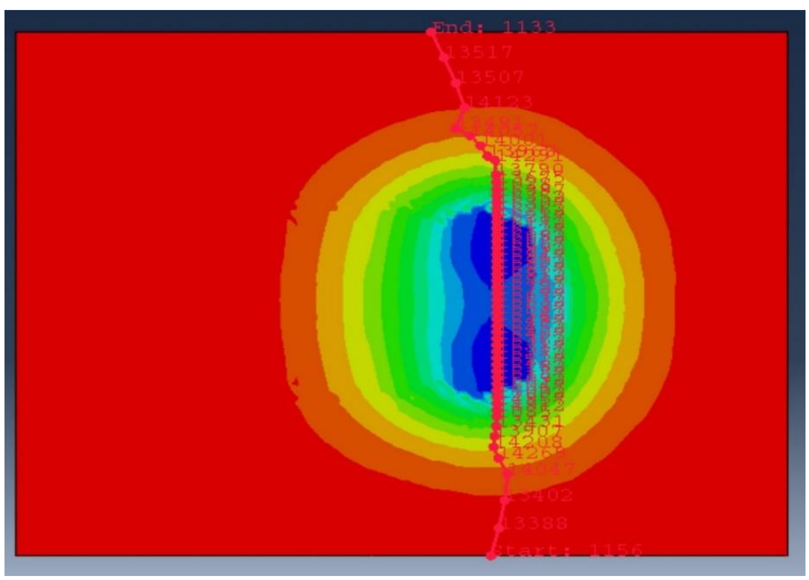


Figure 5-4: Deflection path in concrete pavers.

The maximum allowable deflection for this pavement is 3.8 mm based on traffic data indicated in Asphalt Overlays for Highway and Street Rehabilitation (MS-17) specification. The maximum deformation based on FEM results is 0.0021 mm shown in Figure 5-5. This pavement represents a good performance as the maximum deflection is much lesser than 3.8 mm. This deflection is within allowable ranges of deflection and meets the requirement for the city of Toronto.

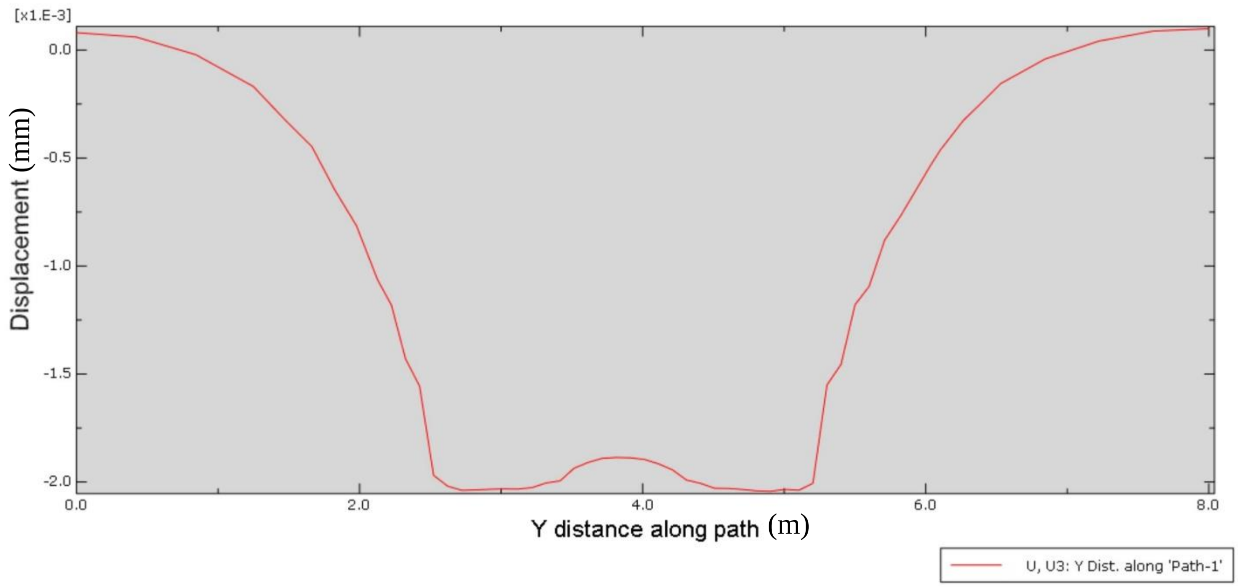


Figure 5-5: The displacement of the nodes of path-1 in the Z-direction.

5.4 CPRESS (Contact Pressure)

The loads applied on concrete pavers transfer through to the base layers, until the loads reach the subgrade layer. The loads are diminished by transferring through the base layers and the subgrade layer does not yield under the loads. This needs to consider the applicable thickness for concrete pavers, and the quality of base materials plays an important role to achieve the proper design. Cement Treated Base materials are considered in the upper layer contact with bedding sand to provide smaller particle size to guarantee that sufficient compaction is obtained. In addition, CTB materials increase the strength of the subbase (Design Considerations for Interlocking Concrete pavers, UNILOCK). When strong materials are selected for base layers, there is no need to increase the thickness of the concrete pavers or deep excavation. This means a more economical design is achieved.

The loading applied simulates double axial loading configurations according to Ontario’s Default Parameters for AASHTOW ME design. The traffic design is for Quayside, Toronto, Ontario. However, it is important to note that this loading would represents many urban areas so the findings of this research would be applicable in other places. This roadway will be under heavy truck vehicles and high traffic volumes. CPRESS (Contact pressure) analysis was used for developing a suitable contact pressure of the tires. Contact pressure is calculated in all of the regions that are initially in contact with each other or will be in contact along with the simulation.

Figure 5-6 shows the contact pressure between concrete blocks. This can show that the pavement is well connected and the pressure of loading is distributed through the pavement.

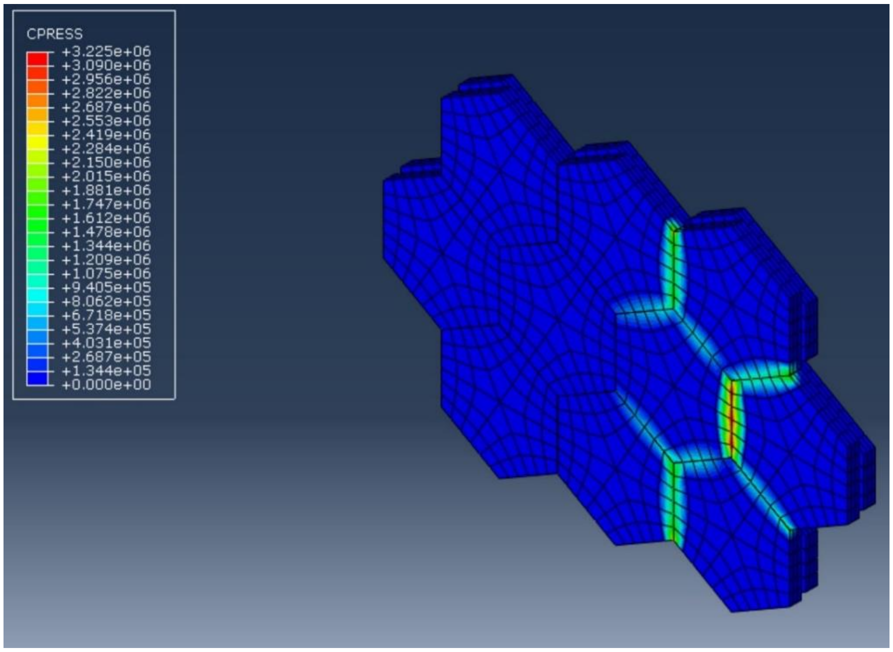


Figure 5-6: Contact pressure between concrete blocks (Pa).

As depicted in Figure 5-7, there is pressure on the regions of foundation that are exactly at the bottom of the under-loading honeycombs, and even there is more pressure near the edges of the honeycombs. Figure 5-8 demonstrates the stresses along the foundation. Because of the difference in Young's Modulus of the layers, the stress contour is not continuous and the stresses remained at the top of the foundation and did not reach the subgrade layer. This justifies the principle that the subgrade layer should not yield. In addition, CBT materials selected for the base layer diminished the applied loadings well and prevent them from reaching the depth in the foundation. The contact stresses depend on the applied loading, but 1.6MPa is typical while 1.426 MPa is calculated for this pavement, and the higher pressure is distributed throughout the pavement (Port and Industrial Pavement Design with Concrete Pavers, second Edition).

In conclusion, the red colors shown in Figure 5-7 and 5-8 did not reach the bottom layers of the foundation. For the well-structured design, this shows the correctness of the simulation as the stresses remain on the top, and base and sub-base layers withstood loading stresses.

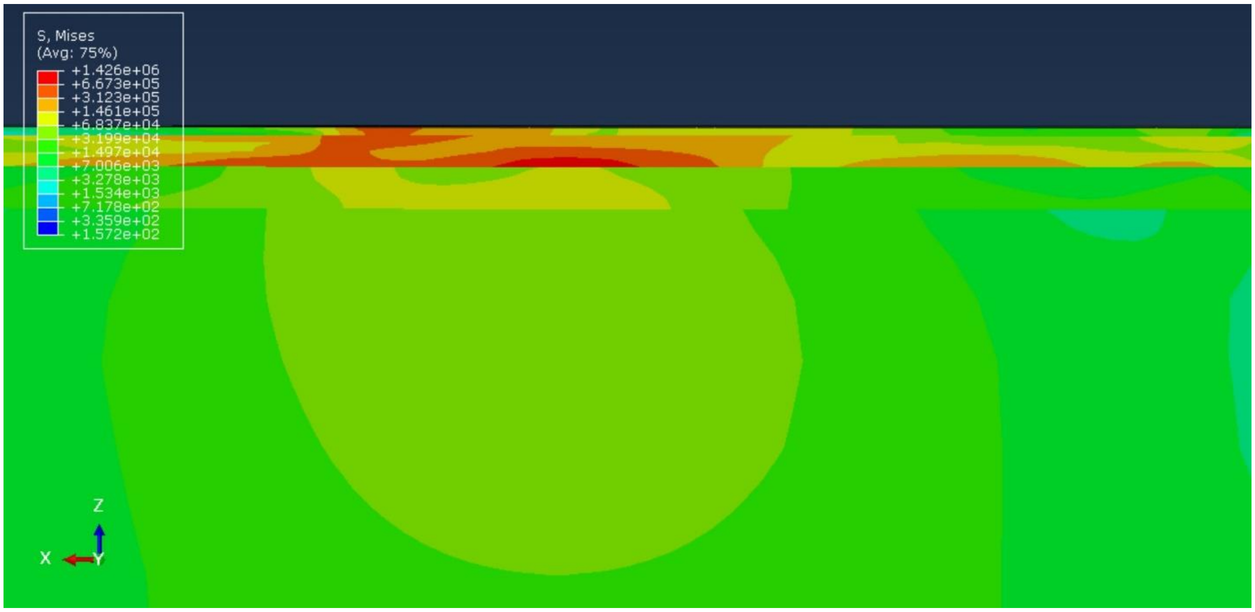


Figure 5-7: The middle plane that is parallel to the XZ plane cuts the foundation (Pa).

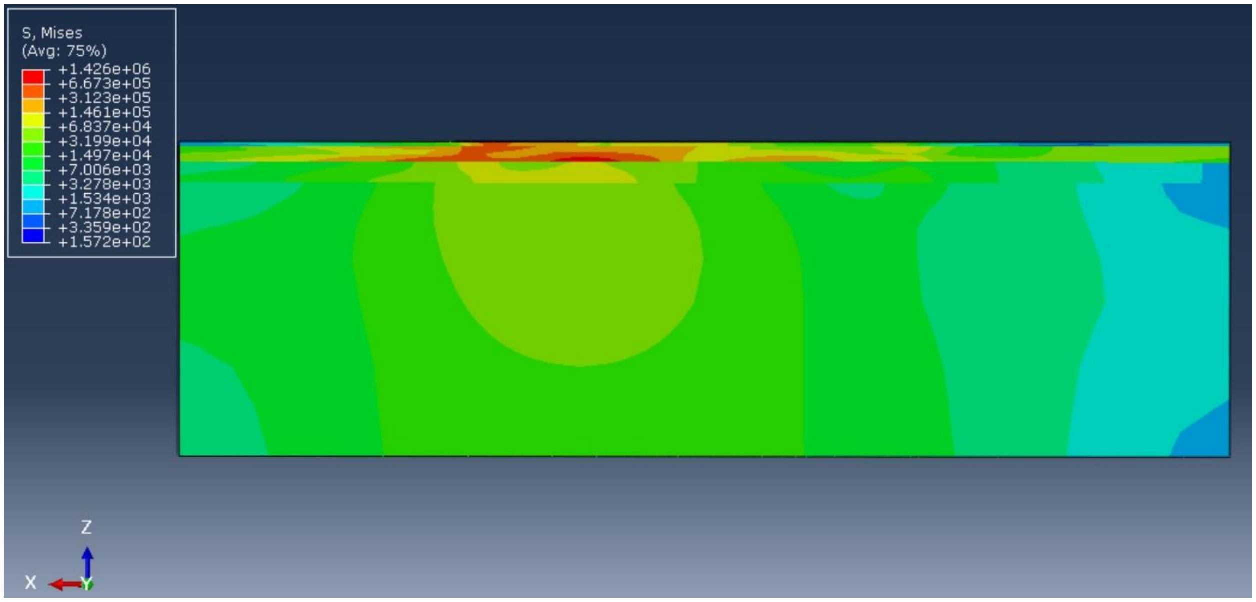


Figure 5-8: Contact stresses in foundation (Pa).

5.5 Von Mises Stress

When identifying problematic areas, the most common stress plot is the Von Mises. Von Mises stress is a value used to determine if a given material will yield or fracture. Von Mises performance criterion is that the material will yield if Von Mises stresses on the material under loading is greater or equal than the yield strength of the same material (Shigley, et al., 1989). A well understanding of the contributing component stresses is essential for a better understanding of what von Mises stress means. The ABAQUS user manual shows three principal stresses in Figure 5-9. By default, ABAQUS / CAE displays the net stress of all major components.

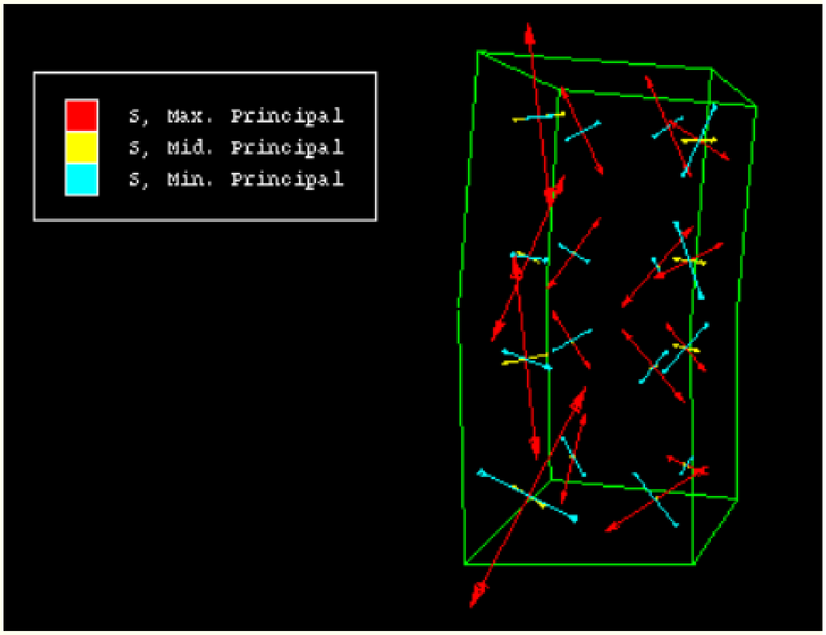


Figure 5-9: Principal stresses in ABAQUS user manual.

How Von Mises stress is calculated for 3D is presented in Equation 5.1:

$$\sigma_{\mathrm{VM}} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2 - \sigma_{xx}\sigma_{yy} - \sigma_{yy}\sigma_{zz} - \sigma_{zz}\sigma_{xx} + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2\right)} \quad \text{Equation 5.1}$$

Where: τ is the shear stress (Pa);

σ is the normal stress (Pa);

Figure 5-10 and 5-11 shows the von Mises stress distribution for the overall component.

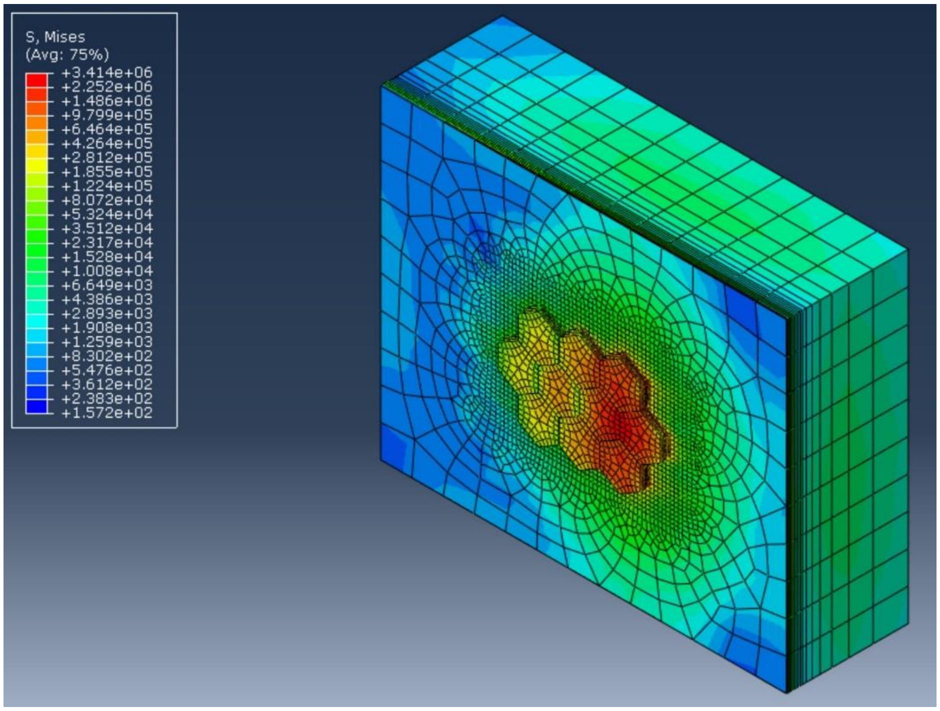


Figure 5-10: Von Mises stress distribution results (Pa).

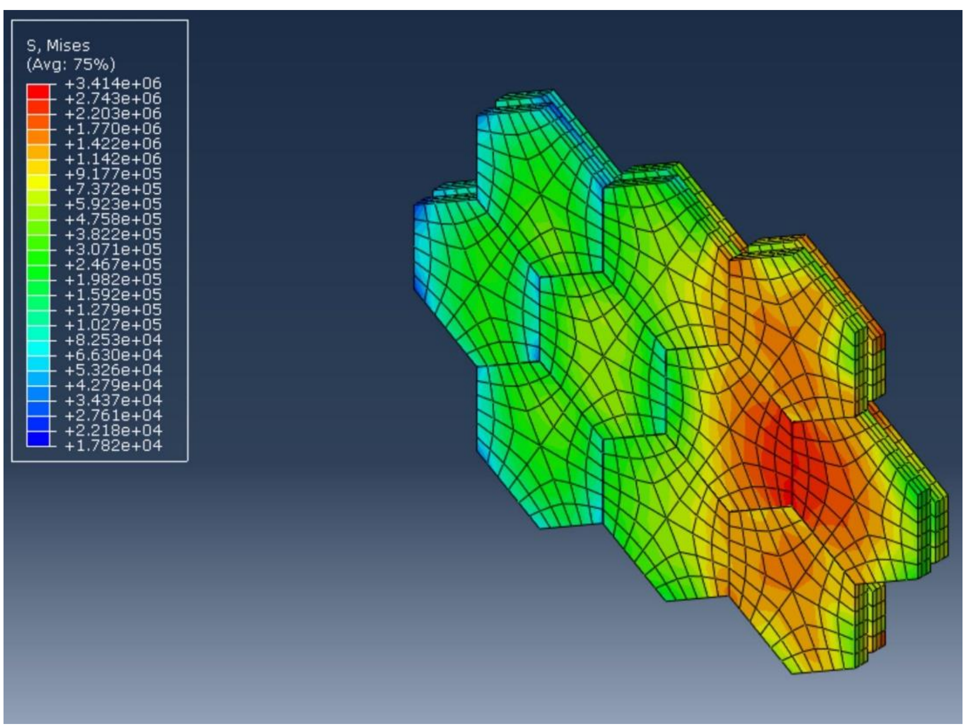


Figure 5-11: Pavement von Mises stress contour (Pa).

In Figure 5-10, there are four regions of high stress. As it is mentioned before, the big advantage of von Mises stress plot is to visualize problematic areas. The maximum stress seen in Figures 5-10 and 5-11 is 3.41 MPa where tire pressures are applied. The compressive strength of conventional Portland cement concrete is within 20 - 40 MPa (3000 - 6000 psi). Even though this pavement is simulated under high traffic volumes and heavy traffic vehicles, 3.41 MPa is within the allowable range of stress for this pavement.

5.6 Shear Stress

Shear stress analysis is crucial to identify the structural performance of the pavement. It is expected to have shear stress when tire pressure applies on the pavement as there is an offset between the upper and lower part of concrete pavers. Figure 5-12 indicates the maximum shear stress in ICPs. It is shown that the vicinity of the loaded area has high shear stress and there is not significant shear stress in most of the concrete pavers. According to the results shown in Figure 5-12, the maximum shear stress that ICPs endure is 1.424 MPa. If we consider the typical property of conventional Portland cement concrete, the shear strength should be within the range of 6-17 MPa. Therefore, as the maximum shear stress in this study is much lower than the shear strength of conventional Portland cement concrete, the maximum shear stress is not critical.

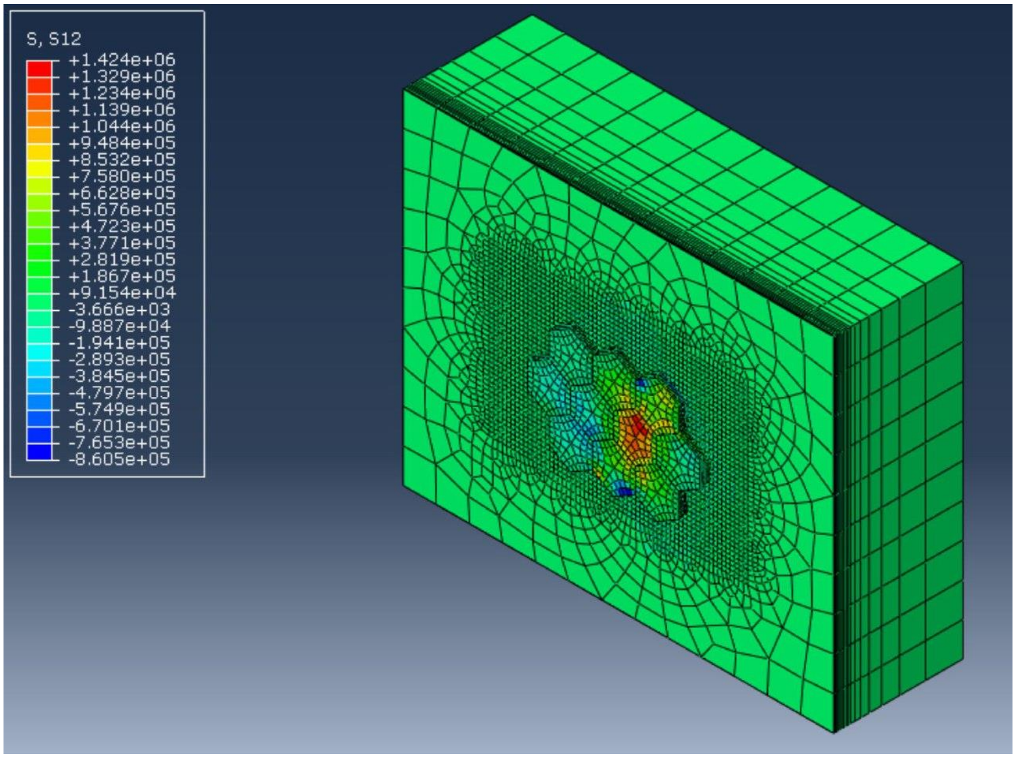


Figure 5-12: Shear stress couture in ABAQUS (Pa).

Figure 5-13 demonstrates the critical area of shear stress in the concrete blocks that are exposed to loadings. The purpose of considering these blocks is to assess finer internal elements to ensure that the blocks under loads are not subjected to shear stress higher than shear capacity of conventional Portland cement concrete. The high shear stress occurs at the edge of these blocks with a maximum value of 0.9 MPa (see Figure 5-13). The shear capacity of conventional Portland cement (6 MPa-17MPa) is much greater then 0.9 MPa. As the maximun shear stress is higher at the edgue of concrete blocks, the joins between blokcs play an important role to transfer stress to adjacent blocks.

To maintain the structural capacity of the pavement, the joints between the blocks should be filled properly with high quality materials to reduce stress on applied loading areas. It is also noteworthy that this should be part of a regular pavament maintance program to ensure the ICP performs well over its life cycle.

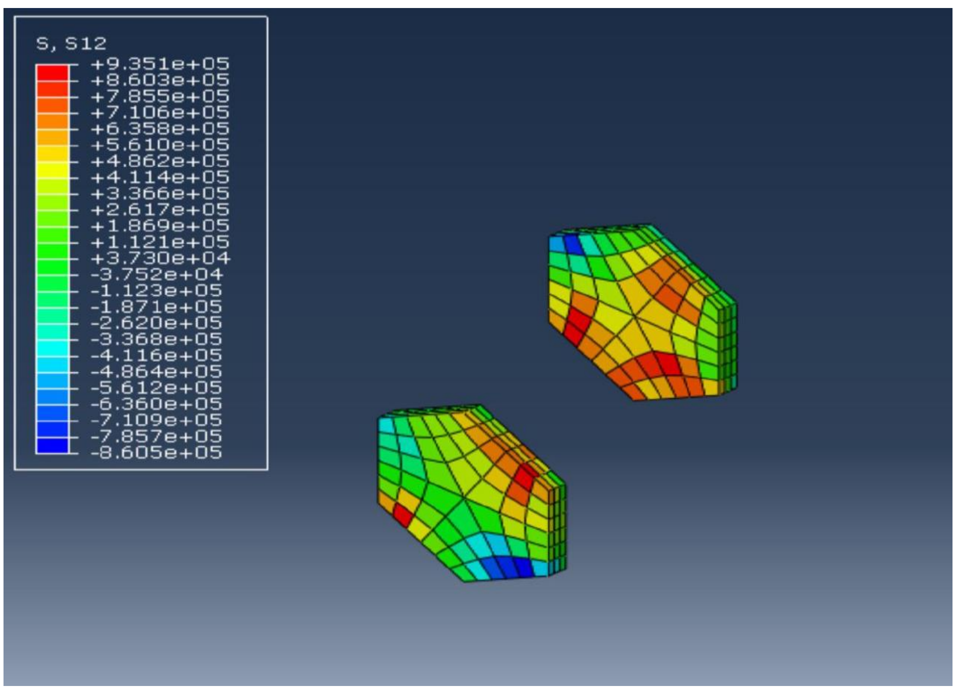


Figure 5-13: Shear stress of concrete pavers under loads (Pa).

5.7 Summary

Pavement assessment is essential to determine the functional and structural conditions of the pavement throughout its life cycle. This new and innovative concrete paver showed excellent performance for urban roads and the selection of the paver thickness is according to the high traffic loading in these areas. Subsequently, the thickness of pavers in high traffic areas are greater than low traffic areas such as parking lots and sidewalks.

The structural strength of the ICPs measured by the deflection shows the structural capacity of the pavement to withstand traffic loads. The maximum allowable deflection based on the standard is 3.8mm, and the maximum deformation for this simulation is 0.0021 mm. The contact pressure in the concrete paver and foundation layers were assessed to determine if the concrete pavers are well connected. Based on the contact pressure contour, the concrete pavers are well concreted and the applied loads on concrete pavers transfer through to the pavement and foundation layers.

The Von Mises stress was used to determine if a given material or layer will yield or fracture. Von Mises performance criterion is that the material will yield if Von Mises stresses on the material under loading is greater or equal than the yield strength of the same material. The compressive strength of conventional Portland cement concrete is within 20-40 MPa. Von Mises stress value is 3.41 MPa which is within the allowable range of stress for this pavement. The shear stress analysis is also crucial to identify the structural performance of the pavement. The maximum shear stress that ICPs endure is 1.424 MPa. If we consider the typical property of conventional Portland cement concrete, the shear strength is within the range of 6-17 MPa so the proposed ICPs performed adequately for this application.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

This study aims to adopt a new and innovative Interlocking Concrete Pavers (ICPs) for typical high-traffic urban areas that is sustainable, people-centric, structurally sound and functional. To achieve this goal, the Finite Element Model (FEM) was developed to simulate field conditions so that various pavement designs could be evaluated. This study is mainly focused on modelling ICPs for heavy truck vehicles in high-traffic urban areas with the ABAQUS software. The critical aspects of the ICPs are analyzed as provided in the following paragraphs:

- **Optimal Pavement Thickness**: The thickness of pavement plays an important role to withstand heavy traffic which is typically slow moving or static in urban areas. Thus, the pavement will fail if the thickness is not structurally adequate for these conditions. On the other hand, it is not economical if it is too thick. In order to have a practical model, the thickness is considered in such a way that can respond to typical high urban traffic loading, and at the same time be cost-effective.
- **Deflection**: The overall strength of the pavement structure can be determined using the maximum possible pavement deflection. Higher deflection indicates that the overall pavement structure is poor while strong pavements have low deflection. Other parameters such as fatigue are indeed important to evaluate the long-term performance of the pavement structure. Proper thickness plays a key role in achieving the desired result for deflection. In this study, the calculated deflection was 0.0021 mm which is less than the allowable maximum value recommended by specifications (3.8mm).
- **Contact Pressure**: It is important that tire pressure be transferred throughout the entire pavement structure. Concrete pavers should be fully connected by jointing materials. In this model, there is contact pressure between the concrete blocks as joining materials and concrete pavers are well connected. This means that the concrete blocks act as integrated systems like asphalt pavement. The maximum contact pressure should be seen in a loaded area. If the tire pressure is greater than the concrete strength capacity, the concrete will break. Based on this model, jointing materials and concrete blocks do not yield under the 827.4 KPa pressure.
- **Von Mises Stress:** The principal stresses are represented through the Von Mises Stress. The main advantage of using this method is to detect the problematic areas. If Von Mises stresses in the loaded material are greater than (or equal to) the yield strength of the same material, the material

would yield. The compressive strength of conventional Portland cement concrete varies between 20 MPa and 40 MPa. The maximum Von Mises Stress of ICPs is 3.41 MPa which is within the allowable range of stress for this pavement.

- **Shear Stress:** The shape of ICPs is an important parameter for shear analysis. Some ICPs are subject to shear stresses, which could cause failure in the pavement. Shear stresses are highly important to this design. Honeycomb blocks are subjected to shear stresses, as there is an offset between two parts of the block. The pavement will fail if the maximum shear stress passes the shear strength of the concrete block. The shear strength of conventional Portland cement concrete is within 6-17 MPa and the maximum induced shear stresses in ICPs under loading is 1.42 MPa.

6.2 Recommendations and Future Work

- Determine the optimum mix design for this innovative, people-centric, sustainable Interlocking Concrete Pavers. As the performance of ICPs has been evaluated mainly on the low traffic areas, achieving the optimum mix design that improves the performance of this pavement is important. It will be ideally addressed through another on-going research project at CPATT.
- For practical purposes, field performance evaluation should be conducted along with simulation results and laboratory works.
- Further research to predict fatigue crack propagation in ICPs under cycling loading is recommended.
- The constructability of ICPs is important. The simulation and experimental tests results do not necessary lead to desirable long-term performance of ICPs. Today’s advanced construction method and techniques can contribute greatly to achieving this aim.

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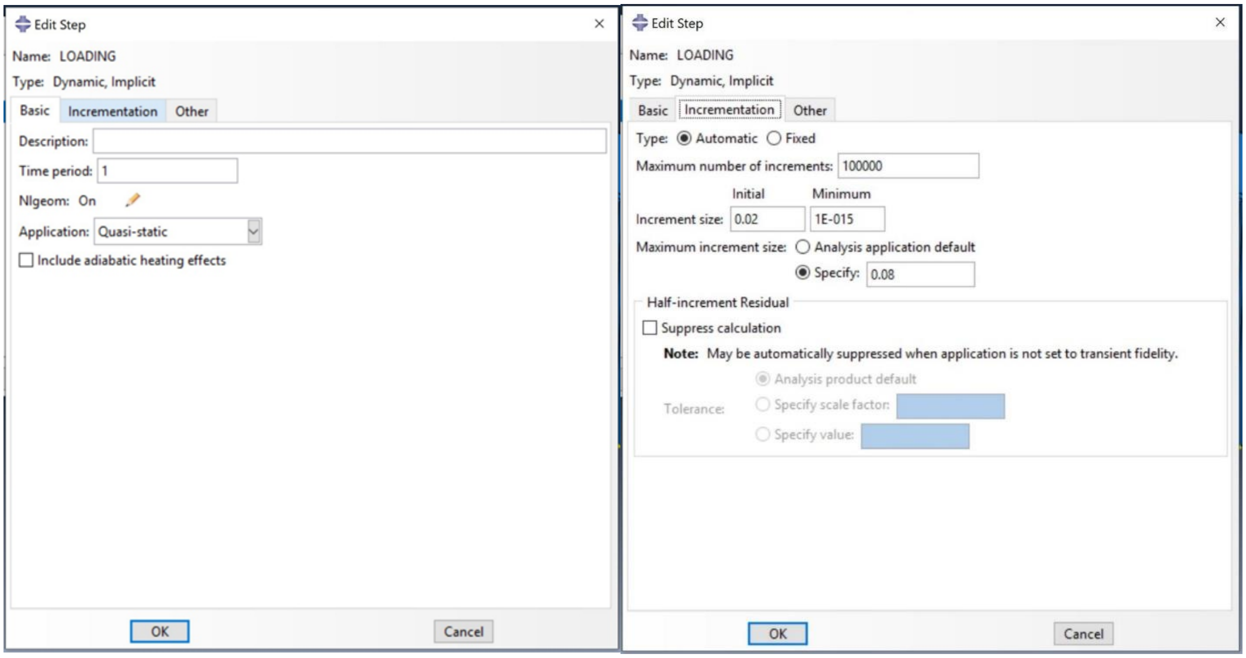
APPENDIX



The setting of step module in ABAQUS.