

Evaluation of Structural Dome Formwork Systems in Concrete Pavement Applications

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.

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Abstract

The concrete pavement industry is actively seeking new and innovative solutions to build more economical, more sustainable and more durable roads. Cupolex® is one innovative product that is being evaluated for use as a concrete pavement technology. This product consists of interlocking, modular, dome-shaped plastic units that serve as a permanent formwork within the concrete pavement structure. The resulting product is a concrete pavement slab with a system of interconnected vault-like voids below the surface. The dome shape is capable of providing carrying capacities equivalent to conventional slabs, but requires less concrete to do so, and also provides additional drainage and ventilation benefits.

A collaborative research effort was undertaken to evaluate the feasibility of using Cupolex® in road and highway applications. As part of this study, a full-scale, instrumented trial section was designed and constructed to evaluate the performance of concrete pavements built using Cupolex® in an accelerated loading scenario.

This thesis presents an evaluation of the Cupolex® technology in a pavement application through the evaluation of numerous parameters during the pavement's first year of service. Data from various embedded sensors, including strain gauges, pressure cells and moisture probes, as well as Falling Weight Deflectometer testing results and visual condition surveys are all used to assess performance.

The results obtained to date indicate that Cupolex® has great potential as a concrete pavement technology. The trial pavement sections are performing very well after one year of service, carrying heavily loaded aggregate trucks in the harsh Canadian climate. Over 1.3 million cumulative Equivalent Single Axle Loads (ESALs) have been applied to the pavement to date without any significant pavement degradation. The findings obtained also

indicate that the Cupolex® technology can provide significant material and potential cost savings, when compared to conventional jointed plain concrete pavements.

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Chapter 1

Introduction

1.1 General Statement

Modern, safe and effective transportation systems are a necessity for the economic and social well-being of all Canadians. One essential component is a well-functioning road and highway network. Roads and highways play an integral role in enabling economic productivity and competitiveness by providing the mobility needed to access employment and recreation and to transport goods between different markets. Ninety percent of goods in Canada are transported by truck (TAC 2012). Nationally, Canada has over one million equivalent two-lane kilometres of roadway, 40% of which is paved (Transport Canada 2011). This major asset has an approximate value of 120 to 160 billion dollars, highlighting the significance of this investment (Transport Canada 2004).

High quality pavements are a key component of any effective road or highway system. Portland cement concrete is one material that is widely used to pave highways, roads, airports, parking lots and other similar types of infrastructure. These pavements typically provide years of service with little or no maintenance needs when properly designed and constructed (Delatte 2008).

The concrete pavement industry is currently facing many challenges, including pressure to design and build longer lasting, more durable pavements with fewer financial resources, while incorporating more marginal materials, reducing environmental impacts and minimizing construction impacts on the travelling public (FHWA 2012). This seemingly impossible goal is attainable through innovative solutions that have been thoroughly researched and evaluated.

Consequently, much effort is currently underway to innovate and modernize concrete pavement designs and construction methods. In short, current concrete pavement design methodologies and construction techniques can be transformed to meet the various competing needs of modern transportation networks, including heavier traffic loads and climate change. Consequently, the concrete pavement industry and researchers are exploring more economical and more environmentally friendly pavement materials and placement techniques in an effort to make concrete pavements more efficient by lasting longer at a lower overall cost over their lifecycle.

Innovation is a key component to developing the next generation of transportation solutions for our roads and highways. Proposed changes to designs, materials and construction processes can provide many benefits to highway agencies and road users, including reduced costs, simplified construction and extended service lives.

Despite the advent and usage of mechanized equipment, as well as new materials and techniques in the concrete paving sector, such as the slipform paver, materials recycling, precast/prestressed concrete panels and quieter surface textures, the basic pavement structure has not changed dramatically since the first concrete pavements were constructed over one hundred years ago.

However, Cupolex®, a structural dome formwork system, is an innovative product that challenges the status quo in the concrete pavement industry. As with any new and innovative concept, new technologies in the pavement industry must be thoroughly investigated to evaluate feasibility. The evaluation must ensure that comparable performance to conventional technologies can be obtained and must assess the costs and benefits. As part

of this research, a collaborative research study was undertaken to evaluate the feasibility of using Cupolex® in road and highway applications.

1.2 Cupolex®

Cupolex® consists of interlocking, modular, dome-shaped plastic units that serve as a permanent formwork, shown in **Figure 1-1**. The resulting product is a concrete slab with a system of interconnected vault-like voids below the concrete surface. The Cupolex® system is manufactured from 100% recycled polypropylene, a thermoplastic material (Pontarolo Engineering 2009).



**Figure 1-1: Example of Cupolex® formwork
(Pontarolo Engineering 2011)**

This product, developed in Italy by Pontarolo Engineering, has seen use across the world in Europe, North America, Australia and Asia in the construction of floor slabs in residential, commercial, industrial and institutional buildings (Pontarolo Engineering 2009). Over 46.4 million square metres (500 million square feet) of Cupolex® have been installed since 1990. This technology was originally developed as a solution to passively ventilate radon gas emitted from the ground from new buildings at United States Air Force Bases in Italy. This method is more cost-effective and simpler to implement than traditional sub slab

depressurization, which involves actively venting the gas with fans through a gravel layer (Pontarolo Engineering 2009).

The Cupolex® system provides some potential benefits. The dome shape is capable of providing carrying capacities equivalent to conventional slabs, but requires less concrete (Pontarolo Engineering 2009). The underslab void reduces the slab's contact with the base layers. Water cannot leach up through the bottom of the concrete slab, providing protection from moisture and humidity. The plastic layer does not allow moisture to enter into the concrete slab, eliminating any concerns with mould and mildew growth or damage to floorings when used in building applications. The underslab void also allows for the quick, easy and cost-effective installation and repair of buried utilities, such as cables and pipes, after construction. The Cupolex® system has inherent properties associated with the dome shape which reduce slab curling, when compared to conventional concrete slabs. The use of Cupolex® can also reduce the need for granular base materials or engineered fill. This product can also be incorporated into creative stormwater management solutions, using the underslab void as a reservoir.

Although it has been used in the construction of floor slabs in residential, commercial, industrial and institutional buildings as noted above, this product had not been previously utilized in concrete pavement applications. Pavements are subject to different conditions than most floor slabs, including frequent and heavy dynamic loads and exposure to a wide range of harsh environmental conditions. Furthermore, it is not clear what kind of structural contribution the Cupolex® system contributes to the concrete pavement structure and how much concrete consumption savings can be achieved. Additionally, the performance characteristics of a Cupolex® pavement over time are still unknown. Lastly, whether Cupolex® pavements can be constructed effectively with traditional slipform paving

equipment needs to be determined. The future maintenance and rehabilitation needs of Cupolex® pavements are also unknown. The applicability of conventional pavement maintenance and rehabilitation strategies to Cupolex® pavements must also be investigated.

The concrete industry is investing significant resources into reducing the environmental impact of its product. The production of cement and concrete require large amounts of raw materials and energy, making the cement and concrete industry a major producer of greenhouse gases. However, Cupolex® also has the potential to reduce this impact by reducing the amount of concrete required, while continuing to produce equally durable infrastructure. It should also be noted the Cupolex® system is made out of recycled polypropylene. The use of recycled materials keeps valuable resources out of landfills. Polypropylene, a durable thermoplastic material, can be easily re-used with minimal environmental impact (Pontarolo Engineering 2009). This results in both environmental and economic benefits. However, its technical performance in pavement applications must first be thoroughly evaluated prior to full scale implementation in the concrete pavement industry.

1.3 Research Objectives and Scope

A collaborative research effort was undertaken by Holcim (Canada) Inc, Dufferin Construction Company, Pontarolo Engineering Inc., Applied Research Associates, Inc. and the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo to evaluate the feasibility of using Cupolex® in road and highway applications as a concrete pavement technology.

This research project involved a number of objectives:

- Construct a full-scale trial, instrumented pavement section using the Cupolex® system in an accelerated loading scenario.
- Evaluate the constructability of the Cupolex® system in concrete pavements.
- Evaluate the mechanical responses of the pavement structure under heavy truck traffic and environmental loading using embedded instrumentation.
- Evaluate the performance of the trial pavement using non-destructive testing and visual evaluation methods.
- Validate the experimental designs and offer design recommendations for future designs.

1.4 Scope and Methodology

For the purpose of assessing the performance of the Cupolex® system in pavement applications, a full-scale, instrumented test section was designed and constructed. The trial pavement was subjected to an accelerated loading scenario. This site of the experimental pavement almost exclusively carries high volumes of heavily loaded trucks. The accelerated loading allows for a much quicker evaluation of the structural carrying capacity of Cupolex® pavements. The magnitudes and frequencies of the traffic loadings are easily quantified at this location, due to the fact that traffic data with vehicle/axle weights is readily available from the quarry's scales.

To evaluate the performance of the pavement, the test section was designed and equipped with a variety of sensors to monitor the pavement response to vehicular loads and environmental effects. Pavement response data from the sensors, including concrete strain

and base pressure, is recorded regularly for review and analysis. Falling Weight Deflectometer (FWD) testing has also been performed on a regular basis to evaluate the structural capacity and measure load transfer efficiency at the transverse joints. Visual distress surveys of the test section were also completed as necessary to document the manifestation of pavement distresses. The complete research framework for this study is highlighted in Figure 1-2.

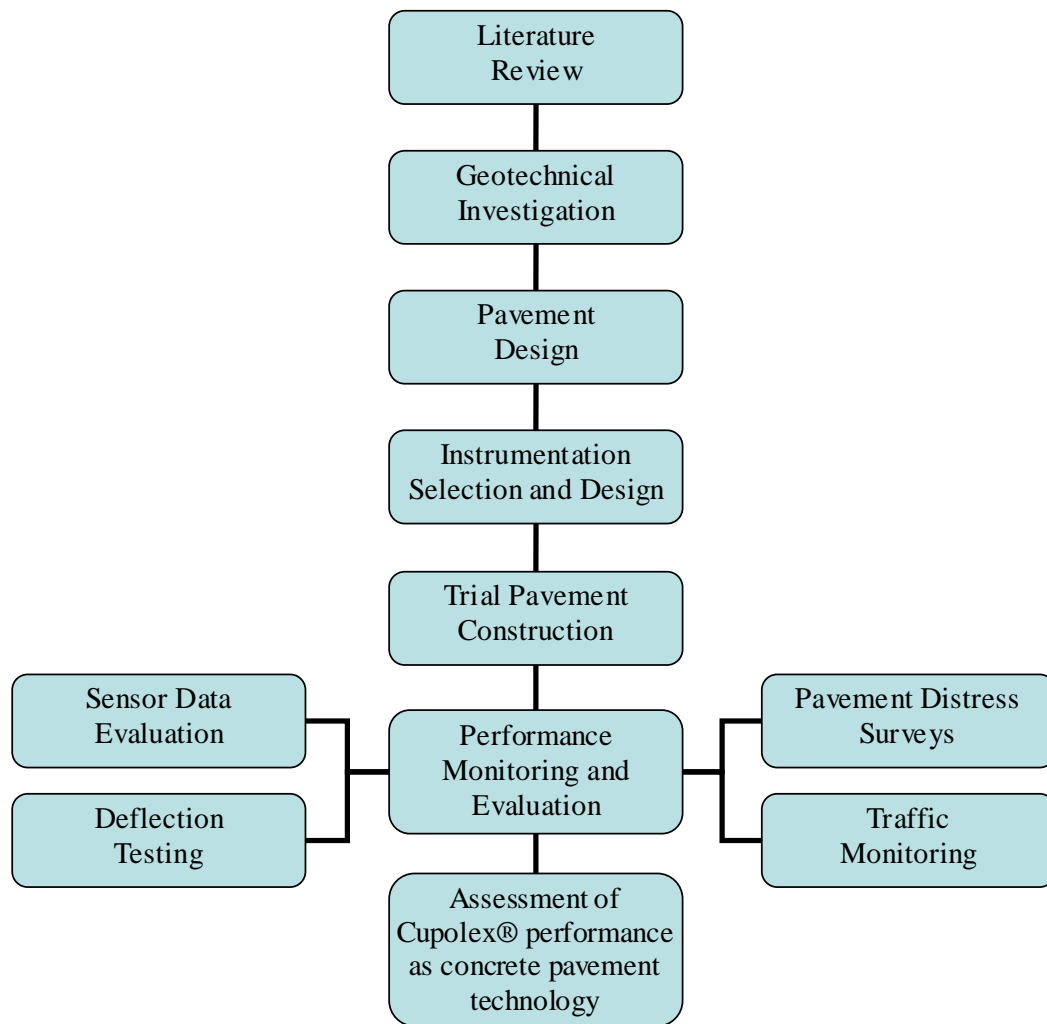


Figure 1-2: Research framework

The instrumented trial pavement at the accelerated loading site provides an excellent opportunity to gain further knowledge and understanding of Cupolex® as a pavement technology. The inclusion of instrumentation in the test section provides a basis for better insight into the behaviour of the dome-shaped slab under heavy traffic loads in a concrete pavement. Ongoing performance monitoring allows for the assessment of the benefits and challenges associated with the use of Cupolex® in pavements.

1.5 Thesis Outline

This thesis consists of five chapters:

Chapter 1 details the motivation, scope and objectives of the research presented in this thesis.

Chapter 2 presents a literature review of concrete pavements, their design and construction, as well as information about pavement instrumentation and pavement testing. Background information about the Cupolex® system is also included.

Chapter 3 describes in detail the design, instrumentation and construction of the experimental pavement sections built as part of this research effort.

Chapter 4 presents an analysis of the pavement performance observed to date and discusses the significance of the results obtained.

Chapter 5 summarizes the research findings, presents the conclusions to date and provides recommendations for future work relating to this project.

Chapter 2

Literature Review

2.1 Overview of concrete pavements

Portland cement concrete (PCC) is one of the two primary pavement types, the other being asphalt concrete. Although the vast majority of the road network in the USA and Canada consists of asphalt pavements, concrete pavements are widely used on roads and highways that carry high volumes and heavily loaded traffic. In the United States, 56% of the Interstate network is comprised of pavements consisting of a significant layer of concrete, i.e. rigid or composite (FHWA 2008).

Three types of concrete pavements are generally used in highway applications: Jointed Plain Concrete Pavements (JPCP), Jointed Reinforced Concrete Pavements (JRCP) and Continuously Reinforced Concrete Pavements (CRCP).

Jointed Plain Concrete Pavements use regularly spaced contraction joints to control cracking (TAC 2012). It does not make use of any reinforcing steel in the concrete slab. Transverse joint spacing is typically no longer than 6.1 metres in order to ensure that stresses induced by temperature and moisture do not cause cracking between the joints. Dowel bars are typically used at transverse joints to assist in load transfer and prevent faulting, except in very low/light traffic scenarios, as seen in Figure 2-1 . Tie bars are also used at longitudinal joints to prevent lane separation. In Ontario, the most common type of concrete pavements is JPCP. These pavements consist of a concrete slab, typically 150 mm to 300 mm thick, over a drainage layer, such as a granular base (Granular A) or an open graded asphalt-treated base (Open Graded Drainage Layer).

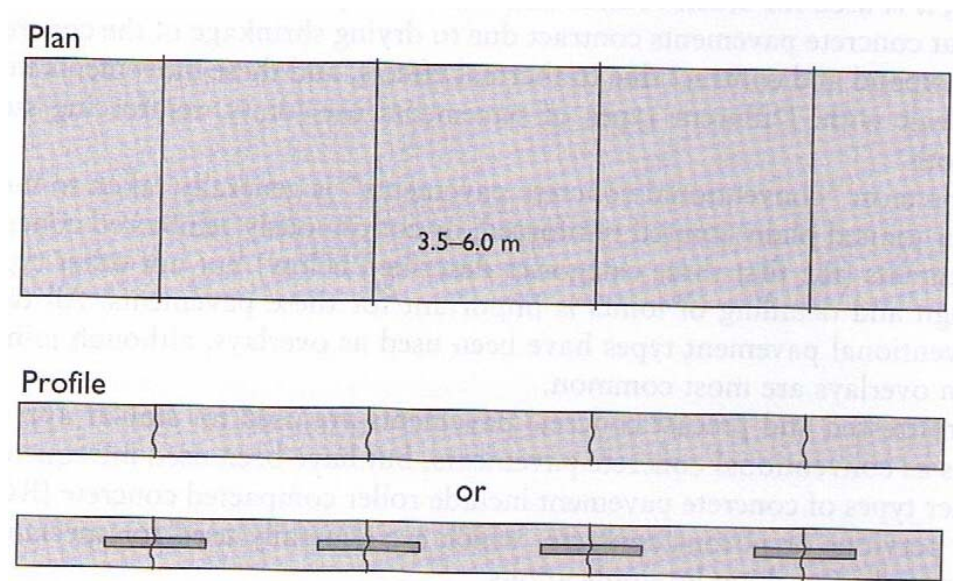


Figure 2-1: Jointed plain concrete pavement (JPCP)
(Delatte 2008)

Jointed Reinforced Concrete Pavements are similar to Jointed Plain Concrete Pavements in that both use contraction joints to control cracking, but JRCP also includes a reinforcing steel wire mesh (TAC 2012), as seen in Figure 2-2. Temperature and moisture effects are expected to cause cracking between the joints; however, steel reinforcement is used to keep the cracks tightly together and provide load transfer across mid-slab cracks. Since cracking is expected anyway, the transverse joint spacing is generally longer than that for JPCP, typically ranging from 7.6 m to 15.2 m. Similarly to JPCP, dowel bars are typically used with JRCP to assist in providing load transfer across transverse joints and tie bars.

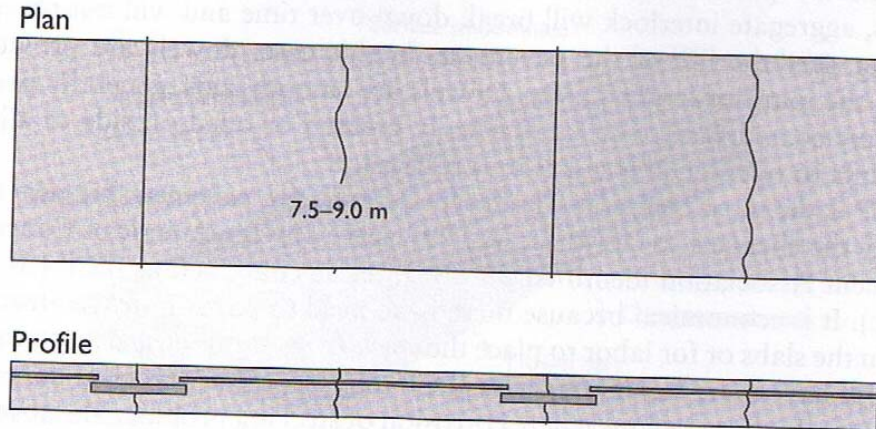


Figure 2-2: Jointed reinforced concrete pavement (JRCP)
(Delatte 2008)

On the other hand, Continuously Reinforced Concrete Pavement does not use contraction joints. Transverse cracks are allowed to form, but are held tightly together with continuous reinforcing steel, as illustrated in Figure 2-3. Transverse cracks typically form at a spacing of 1.1 – 2.4 m. In order to keep crack widths below 0.5 mm to minimize chances of spalling and water penetration, the amount of steel required usually constitutes about 0.6 percent of the cross-sectional pavement area and is located near mid-depth in the slab (TAC 2012).

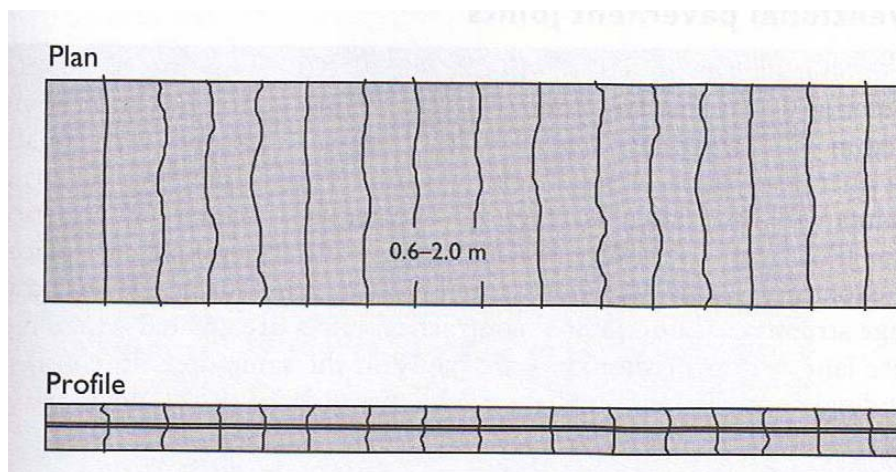


Figure 2-3: Continuously reinforced concrete pavement (CRCP)
(Delatte 2008)

JPCP is the most common type of concrete pavement among Canadian agencies and U.S. state departments of transportation (TAC 2012). Although much of the Interstate network in the Eastern and Midwestern United States was initially constructed with JRCPP, this pavement type has fallen out of favour, due to performance concerns.

Approximately 70% of US state departments of transportation build JPCP, 20% build JRCPP and 6 or 7 individual agencies build CRCP (Rajib and El-Korchi 2009).

2.1.1 Sustainable concrete pavements

Sustainability has been defined as activity or development “that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). The development of sustainable solutions involves balancing three competing factors: economic, social and environmental (Van Dam et al. 2011). Concrete pavements already provide many sustainable benefits, including longevity, recyclability, use of waste materials and minimal maintenance requirements (Delatte 2008). However, cement and concrete production are major producers of greenhouse gas emissions worldwide. The environmental impacts of cement and concrete production must be considered when considering the lifecycle analysis of concrete pavements.

2.1.1.1 Environmental Impacts of Concrete

Concrete is one of the most commonly used civil engineering materials. Globally, approximately 1.6 billion tonnes of cement and 10 billion tonnes of aggregates are used annually (Mehta 2001). Concrete structures are durable and economic, but these features do not come without a significant impact on the natural environment. Portland cement production is an energy intensive process with notable impact on the physical environment, including the ground, the air and water sources. Annually, the production of cement results in

about 7% of worldwide carbon dioxide emissions (Mehta 2001). In 1996, about 26% of all concrete used in the United States (roughly 226 million tonnes) went to highway and road applications (Low 2005). To put this into perspective, approximately 51,800 tonnes of aggregate are required to construct one kilometre of six-lane expressway (APAO 2004).

Large amounts of raw materials are required, e.g. limestone, clay and fuel, such as coal or gas. Greenhouse gas emissions from cement plants primarily come from two sources: calcination of the limestone, the primary raw ingredient of Portland cement clinker, and fossil fuel consumption to heat the raw materials to the temperature required to form clinker (Tennis et al. 2011). The production of one tonne of Portland cement requires about four gigajoules of energy and emits 1.25 tonnes of carbon dioxide into the atmosphere (Wilson 1993).

In addition to the greenhouse gas contributions of cement production, aggregate production also has an undeniable environmental impact. The amount of high quality aggregate available for construction use is declining rapidly. Worldwide aggregate use is estimated to be ten to eleven billion tonnes each year. Of this, approximately eight billion tonnes of aggregate are being used in Portland cement concrete every year (Naik 2005, Mehta 2001). In Canada, annual aggregate consumption is estimated as approximately 350.5 million (Panagapko 2003).

The extraction of aggregates has many significant environmental impacts (Naik 2005). The development of pits or quarries requires the removal of all natural vegetation, top soil and subsoil. This results in the destruction of habitats and therefore, a loss in biodiversity. Aggregate extraction also disrupts surface water and groundwater flows.

Moreover, pit and quarry operations results in noise, dust and contaminated water, which can be harmful to adjacent residents and wildlife.

The transportation of aggregates and cement also contributes to the negative environmental impact of concrete. As nearby quarries are depleted, high quality aggregate must be transported from further away, directly increasing the associated costs.

The environmental impacts of concrete can be reduced in various ways. The use of supplementary cementing materials, such as fly ash and steel slag reduce the need for virgin cement. Waste concrete can be reused as Recycled Concrete Aggregate in new concrete, reducing the need for quarrying, processing and transporting virgin natural aggregates.

There are three key aspects to sustainable development in the concrete industry (Mehta 1999). First, conserve concrete making material. This can be achieved by recycling aggregate by crushing demolished concrete. Also, using recycled water from mixing plants and wash water from trucks would decrease the need for fresh mixing water. Finally, using by-products, such as fly ash, slag and silica fume, from other industries reduces the amount of cement needed in the concrete.

Recent advances in cement production have helped reduce the impact of this industry on the environment. Examples of these advances include energy efficiency improvements at cement manufacturing facilities, alternative fuels, blended cements and carbon capture systems (EPA 2010). However, much work remains to be done. Future innovations will also assist in reducing the impact of cement and concrete.

2.2 Concrete pavement design and construction state-of-the-practice

2.2.1 Concrete pavement mechanics

Portland cement concrete's high modulus of elasticity (23-35 Gigapascals) gives it significant rigidity compared to other pavement materials (TAC 2012). Portland cement concrete also has a reasonable degree of beam strength, derived from its flexural strength, which typically ranges between 3.3 to 6.0 MPa in pavement mixes. These properties result in a stiff pavement, which is capable of distributing loads over wide areas. By distributing loads over a greater area, the pressures applied to the subgrade are minimized.

The application of wheel loads causes bending in the concrete slab, which induces both compressive and tensile stresses (TAC 2012). The compressive stresses induced are usually low in comparison to the high compressive strength of concrete and consequently, are not critical in design. However, the tensile stresses produced tend to be fairly high with respect to the fairly low flexural strength of concrete. As a result, the tensile stresses must be minimized to ensure long life. The fatigue life of concrete structures is directly proportional to the ratio of stress to strength (TAC 2012). By keeping the induced stresses low, the potential for fatigue failure approaches zero, as stated in Miner's hypothesis.

Most of a concrete pavement's strength is derived from the PCC material itself. Unlike asphalt pavements, the base or subbase layers in concrete pavement systems do not provide significant load carrying capacity. These underlying layers, however, play an important role in ensuring uniform slab support, providing good drainage, reducing erosion of materials near joints and providing buffer space for frost heave, shrinkage and swelling of subgrade materials (TAC 2012). This layer also serves as a platform for pavement construction.

Environmental factors play a significant role in concrete pavement performance. These factors include temperature, humidity, precipitation, and frost heave. Temperature gradients throughout the depth of the concrete slab cause curling and warping on a daily basis, which can be cumulatively damaging. During the day, the air temperature and solar radiation will increase the temperature of the slab, resulting downward curling (Papagiannakis and Masad 2008). The top of the slab will expand more than the bottom of the slab. However, since the self-weight of the slab prevents free expansion or contraction, this will induce compressive stresses at the top of the slab and tensile stresses at the bottom of the slab. The opposite behaviour is observed overnight. The bottom of the pavement is warmer than the top, resulting in upward curling. Compression is induced at the bottom of the slab and tension at the top. Temperature gradients not only induce curling stresses, but also affect the slab–subgrade contact. A partial loss of subgrade contact can increase the stresses in concrete. Temperature gradients in concrete slabs can amplify fatigue damage significantly. A gradient of $0.02^{\circ}\text{C}/\text{mm}$ ($1^{\circ}\text{F}/\text{in}$) increases the fatigue damage caused by truck traffic by a factor of 10, in comparison to that of a slab with no thermal gradient (Mashad 1996, Ahmad 1998).

The moisture content of the concrete slab can also affect pavement performance. Moisture gradients may result in differential shrinkage between the top and the bottom of the pavement (Papagiannakis and Masad 2008). This leads to additional curling stresses, placing the top of the pavement into tension and the bottom into compression. Again, the slab is susceptible to additional damage from traffic loads when deformed due to moisture effects.

Similarly, the moisture content of the underlying layers affects the structural capacity of the concrete pavement structure. Poor drainage of the base materials will diminish the ability of the underlying layers to support the concrete slab. The presence of water in the

aggregate layers results in a loss of shear strength, resulting in increased deformations when subjected to traffic loads (Rajib and El-Korchi 2009).

2.2.2 Design considerations for concrete pavements

Structural design of concrete pavements is generally based on limiting the pavement stresses, strains and deflections to prevent damage and deterioration of the pavement beyond acceptable levels and delaying pavement failure (REF). Stresses are influenced by a number of factors including restrained temperature and moisture deformation external loads, volumes changes of the supporting layers (including frost action), continuity of subgrade support through plastic deformation and material loss from pumping action. The foremost factor affecting concrete pavement performance is traffic loading (Hillier and Roesler 2005). Ambient environmental conditions also have a significant influence.

Generally, the goal of pavement design is to develop the lowest-cost structure that is capable of supporting the predicted traffic loads over the design life period while resisting degradation from external environmental factors, such as temperature and moisture.

Pavement performance can be divided into two categories: structural performance and functional performance (Delatte 2008). Structural performance is the expectation that the pavement thickness to provide sufficient structural strength to sustain the traffic loads over the performance period. Functional performance is the expectation that a pavement type will provide an acceptable level of service to the road user over its design life. The major component of serviceability is riding comfort or ride quality, with safety being an additional consideration.

Concrete pavements can be analyzed fairly easily using mechanistic principles. A concrete pavement's slabs can be modelled in a similar fashion to concrete beams. Typical

models represent the slab as a concrete plate subjected to biaxial bending and supported by a continuous elastic foundation, also known as Winkler springs or a dense liquid foundation (Papagiannakis and Masad 2008). This permits the use of well-established moment-curvature relationships for concrete beams to complete the thickness design for the anticipated loadings (traffic and environmental) and check critical responses for adequacy.

The slab thickness is often considered to be the primary design output for a concrete pavement. However, a complete concrete pavement design also includes the selection of base materials and thickness, concrete mix design properties, joint properties (e.g. spacing, use of dowel bars) and drainage features (Delatte 2008).

2.2.3 Concrete pavement design methodologies

Concrete pavement design is a complex procedure with multiple interacting variables. Many factors that must be considered are difficult to quantify. Various different concrete pavement methodologies are currently in use. These design methodologies all revolve around the design of a flat concrete slab resting on a base layer or directly on subgrade. Empirical methods, based on observations of pavement performance, are the simplest. However, these methods usually do not accurately account for the influences of factors such as material properties and drainage. Mechanistic methods use theoretical models to predict stresses and strains, which can in turn be minimized in the design to ensure long-term performance.

2.2.3.1 American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures

The American Association of State Highway and Transportation Officials (AASHTO) design procedure is based on the results of American Association of State Highway Officials (AASHO) Road Test of the 1960s. The AASHO Road Test was an experiment, conducted in

Ottawa, Illinois, that consisted of around the clock loadings of various test loops for two years. Six test loops with a variety of asphalt and concrete pavement structures were tested to establish performance trends. This experiment was used to develop the 1972 AASHTO Guide for Design of Pavement Structures (AASHTO 1972). Subsequent revisions were released in 1986 and 1993 (AASHTO 1986, AASHTO 1993). The 1993 AASHTO Guide currently remains the most common pavement design methodology in North America (Canada and the United States) for both new construction and rehabilitation designs (TAC 2012). However, a major shift towards mechanistic-empirical pavement design is in progress. Current pavement design needs require extrapolating the AASHO Road Test data far beyond the measured values, which is somewhat imprudent.

Despite its prevalence, the AASHTO Pavement Design Guide has a number of deficiencies that are associated with the limitations of the AASHTO Road Test. The empirical data collected from the AASHO Road Test is highly dependent on the specific conditions of the experiment, including the subgrade soil type, construction materials, unique Illinois environmental conditions and the single traffic type (NCHRP 2004). Some basic assumptions are applied to the empirical equations to allow for the use of the AASHTO procedures in other locales with different materials, environmental conditions and traffic loadings.

In 1998, AASHTO published a supplement to 1993 pavement design guide. This supplemental guide, entitled Part II – Rigid Pavement Design & Rigid Pavement Joint Design, provides an alternate concrete pavement design procedure to address flaws that were resulting in premature pavement failures (AASHTO 1998). The existing AASHTO design procedure for concrete pavement was exhibiting numerous deficiencies associated with poor transfer, long joint spacings, subbase erosion and poor drainage. This procedure is not based

on the AASHO Road Test. Instead finite element structural modeling was used to develop designs and the designs were validated using data from the FHWA's Long-Term Pavement Performance (LTPP) program.

2.2.3.2 Mechanistic Empirical Pavement Design Guide (MEPDG)

The state-of-the-art Mechanistic Empirical Pavement Design Guide (MEPDG) incorporates the principles of engineering mechanics in a rational design process to improve the designs of asphalt and concrete pavements (NCHRP 2004). In 1996, the American Association of State Highway and Transportation Officials (AASHTO) identified the need for a new modern pavement design methodology, based on mechanistic-empirical principles. This need led to the start of the National Cooperative Highway Research Program's (NCHRP) project 1-37A. The MEPDG considers numerous factors such as climate, traffic and materials properties to propose a trial design. Using integrated pavement response models, the trial design is evaluated for performance by predicting roughness and distresses such as cracking and rutting using performance models developed with data from the Long-Term Pavement Performance database. This process is repeated iteratively until the performance meets the established criteria.

Accurate finite element models for calculating pavement structural behaviour under traffic and environmental loadings are at the core of mechanistic design. Stresses, strains and deflections must be correctly determined to design long-lasting, sustainable and cost-effective pavements. Furthermore, pavement response information is also necessary to calculate fatigue damage and predict distress manifestation. The MEPDG is able to provide significant improvement over existing design methods, achieving more cost-effective pavement designs and rehabilitation strategies. However, its reliability is dependent on the quality of the performance models and the input data.

The MEPDG must be calibrated for local conditions and materials to validate the integrated distress models and ensure the desired level of reliability (Swan and Hein 2008). This task is difficult and time consuming. Some agencies lack historical pavement performance data, traffic data, materials characterization data and construction and maintenance history. Furthermore, the effects of advances in pavement design and construction may not be accurately reflected in these models. Accurate performance models are dependent on a good understanding of pavement mechanics, which determine the associated responses.

In addition to different levels of material inputs depending on the availability of material properties, the MEPDG is able to simulate variations in material properties due to climate and load (NCHRP 2004). A master climate database is used to model the variation in the properties of the pavement and subgrade materials. These models allow engineers to determine the impact of a change in environmental conditions on a specific material property. For example, hot mix asphalt (HMA) is considered a visco-elastic material which is affected by temperature change. As the temperature increases the HMA modulus decreases. Similarly, precipitation and various environment conditions can negatively impact subgrade strength. The MEPDG is able to model these changes based on environmental condition.

The traffic characterization method used in the MEPDG also differs significantly from the 1993 AASHTO design procedure. Rather than using the conventional Equivalent Single Axle Load (ESAL) technique used by previous guides to convert mixed traffic to a single value, the MEPDG has adopted an axle load spectra method (TAC 2012). Detailed traffic data, including truck count by class, direction and lane are required for traffic characterization. Axle load spectra distributions are then obtained for each vehicle class from

known axle weight data. The traffic volumes are then forecasted by vehicle class over the selected design period.

The complexity of the MEPDG design procedures requires the use of computer software. The procedures of the MEPDG are distributed through the AASHTOWare Pavement ME Design software, which can be obtained through the American Association of State Highway and Transportation Officials. In the MEPDG, concrete pavements are modeled using Westergaard theory using finite element analysis based on the ISLAB2000 suite developed at the University of Illinois (Delatte 2008). The outputs from this system have been well validated. The program computes and sums the load-related and load-independent stresses and strains at each time increment.

Most US state and Canadian provincial transportation agencies are working towards full implementation of the MEPDG (TAC 2012). However, the MEPDG is a sophisticated tool which requires substantial effort to implement. MEPDG implementation requires large amounts of reliable data, technical skills and financial resources. Most agencies are using their existing design methodologies and the MEPDG simultaneously, with the goal of eventual transition to using the MEPDG solely.

2.3 Evaluation of new pavement technologies

The detailed evaluation of new pavement technologies is necessary to determine whether they provide the expected levels of performance. Various tools are available to assist with this objective. The use of embedded instrumentation and accelerated load testing are two options that can provide valuable insight into in-situ pavement performance.

2.3.1 Pavement instrumentation

A good understanding of pavement responses to traffic loads and environmental effects is necessary to predict a pavement's future performance. Mechanistic design procedures are being more widely adopted. These new design procedures can be significantly more reliable than existing design methods and can be used to develop the most optimized and cost-effective designs. However, the success of mechanistic pavement design is dependent on the accuracy of integrated pavement response models. The models must be able to correctly predict pavement responses to be able to reliably complete design pavements and predict their performance. The embedment of instrumentation into newly constructed or rehabilitated pavements can provide the data necessary for developing new pavement responses models and also for verifying existing models.

A wide range of sensors can be installed in pavements to provide meaningful data about pavement responses. The primary responses of interest in all pavements are loads, strains, pressures, displacements, temperature and moisture (Al-Qadi 2010). Some of the most common gauges used to monitor these responses are listed in Table 2-1.

**Table 2-1: List of commonly used sensor in pavement structures
(Willis 2008)**

Strain Gauges	Pressure Cells
Thermistors or Thermocouples	Moisture Probes
Linearly Variable Differential Transducers (LVDTs)	Traffic Sensors (traffic loops, weigh-in-motion scales)

The determination of concrete strains is important in predicting crack development. Unreinforced concrete pavements have fairly low flexural strengths (TAC 2012). If traffic and environmental loadings induce strains such that flexural strength, cracking will initiate

and propagate with repeated load applications. Strain gauges can monitor the tensile strains and quantify the fatigue damage induced (Willis 2008). Concrete pavements are also sensitive to thermal effects (expansion and contraction). Strain gauges can also be utilized to measure these environmental effects (Willis 2008).

Subgrade materials are typically the most stress sensitive components of a pavement structure. Pavements are typically designed with multiple strong layers to reduce the pressures on the subgrade (TAC 2012). Pressure cells can be used to measure the resulting pressures and are typically placed at the top of the subgrade materials (Willis 2008). These gauges can also be placed at the top of the base materials to verify the loadings on the intermediate structural layers.

Portland cement concrete is also a temperature sensitive material (TAC 2012). As discussed earlier, thermal expansion and thermal gradients can contribute to increased pavement damage. Thermocouples and thermistors can be used to quantify temperature change and its contribution to the changes in other responses such as strain (Willis 2008). Many vibrating wire strain gauges have integrated thermistors (RST Instruments 2004).

The moisture content in subgrade materials and unbound granular materials is also a key performance factor (Willis 2008). The strength of these structural layers is sensitive to their water content. Moisture gauge data can be placed in these layers and the resulting data can be analyzed to understand the quality of the pavement's drainage characteristics and the variability in soil strength owing to moisture.

In concrete pavements, displacements such as those due to temperature gradient-related curling and warping and those related to joint movement can have an impact on pavement performance. Gauges such as Linearly Variable Differential Transducers (LVDTs)

can be employed to measure these displacements and model the contributions of changing slab shapes and positions on pavement life (Willis 2008).

The ability to quantify the traffic loads on an instrumented test section is necessary to quantify the impacts of traffic on pavement performance. For closed test sites with vehicles of known weights, traffic loops must be sufficient to estimate the required values. However, on sites with variable traffic types and weights, weigh-in-motion (WIM) scales may be more beneficial to measure more precisely the traffic loads (Zhang et al 2008).

The sensors used in pavement instrumentation must be carefully evaluated prior to their selection. Suitable sensors are produced by many different manufacturers. When evaluating possible equipment choices, a number of factors must be considered. Six primary considerations for sensors selection have been outlined by Willis (2008):

- Ability to measure the desired response with the desired accuracy (e.g. strain, pressure)
- Cost
- Availability (delivery time)
- Reputation for performance and reliability
- Compatibility with existing equipment and continuity with previous research
- Vendor support

In Canada, it is also important to ensure that the selected sensors are suitable for the harsh climatic conditions, which include both warm and cold temperatures, as well as extensive freeze-thaw cycling.

As agencies continue to experiment with new mix designs, new materials and new design features for a variety of reasons, including improved performance, lower costs and sustainability, the use of instrumentation in these experimental pavements helps agencies understand the behaviour of the pavement and provides detailed information that helps evaluate their suitability for widespread use (Goulias et al. 2011).

For example, in order to address increasing traffic congestion, user delay costs, reduced construction budgets and requirements to keep lanes open, the state of Minnesota is striving to build long-life pavements (Rohne 2009). The Minnesota Department of Transportation (MnDOT) wants to construct concrete pavements with 60 year design lives. However, there have been no experiences with such pavements and consequently, service life and performance estimates are based on significant extrapolation from experiences based on current design methods. To evaluate trial design, MnDOT has built a test section in their MnRoad test facility on the limited-access low volume test track. A large number of electronic sensors have been integrated to monitor performance. The sensors used include dynamic strain gauges for measuring traffic impacts, static strain gauges for measuring environmental loads, LVDTs for measuring curling/warping displacements, moisture probes, joint opening sensors, maturity gauges and temperature sensors.

Numerous challenges complicate the use of instrumentation in pavement structures. The embedment of pavement instrumentation is not a simple task and not suitable for all projects (Willis 2008). The biggest challenge is associated with designing the

instrumentation plan. Very few guidelines for determining sensor type, quantity and placement exist. However, it must be noted that each experiment has its specific research objectives and the instrumentation must be selected to satisfy these objectives and any other constraints, such as access to site, and loading and environmental conditions. The pavement responses of interest for each site and their locations must be selected, resulting in significant differences in instrumentation plans for each project (Willis 2008). Often, instrumentation plans are developed by checking how comparable sites with similar objectives were established and how the data collected has assisted with evaluating the research objectives.

Another major impediment is the significant added cost. The required robustness and precision of the equipments raises the prices of sensors and data acquisition systems (Willis 2008). The gauges must have sufficient sensitivity to record minor changes in pavement response and also be sufficiently durable to survive the initial construction process, while remaining reliable in the long-term when subjected to traffic and environmental loadings in the pavement (Willis 2008). Also, since duplication of gauges is desirable to allow researchers to check the quality of the data, further costs are incurred.

Additionally, the installation of sensors is a complicating factor. Most contractors are not used to the placement of instrumentation and this will result in related issues, such as time delays. The gauges and their wiring will often create significant inconvenience in construction activities. Care must be taken to protect the sensors from damage from construction equipment and processes. Diligent quality control during installation will reduce the likelihood of future issues with sensor performance and data quality.

The final major challenge is associated with data analysis. In order for pavement instrumentation experiments to be successful, the data collected must be accurate and precise.

A number of factors can affect the accuracy and precision of the sensor readings. However, errors may present themselves and need to be addressed accordingly (Willis 2008). The variability might be associated with the precision of the instruments, variability in construction, such as materials properties or thicknesses and shifting gauge alignments. The identification of these sources of error need to be identified and mitigated as best as possible to ensure that reliable data is used for modeling.

2.3.2 Accelerated load testing of pavements

The pavement industry has seen many advances in finite element modeling and materials characterization that have helped greatly in predicting and evaluating pavement performance. However, empirical performance continues to have an important role in the evaluation of new pavement technologies. Prior to their widespread adoption, the suitability and durability of new technologies must be proven. However, pavement structures are typically designed to last 20 or more years. Agencies do not have the time to take on uncompressed evaluation strategies.

Full-scale accelerated pavement testing (APT) is defined as the controlled application of loadings at or above the appropriate legal load limit to a prototype pavement system to determine pavement response and performance under a controlled, accelerated accumulation of damage in a compressed time period (NCHRP 2012). By accelerating damage through increased load repetitions and heavier loads, results can be obtained faster. Accelerated field testing helps bridge the gap between laboratory work and theoretical computer models, and real long-term performance. This method has successfully been used to develop and verify design procedures, evaluate material selections and validate pavement performance.

The NCHRP Research Synthesis 235 (1996) lists many specific applications of accelerating pavement testing:

- Extrapolating existing designs to heavier traffic levels;
- Introducing designs for new materials and pavement configurations;
- Evaluating non-traditional, recycled, by-product and waste materials;
- Evaluating stabilization and geofabric treatments for subgrades;
- Defining pavement deterioration phenomena;
- Characterizing the effects of new axle, wheel and tire loads and configurations;
- Investigating environmental effects, especially frost heave; and
- Estimating remaining pavement life.

Four basic APT methods have been identified: test roads, circular tracks, linear tracks, and pulse or static loading (NCHRP 2012). Test roads and circular tracks use loaded trucks to apply traffic loadings. Linear tracks use specialized pavement testing equipment, such as the Heavy Vehicle Simulator (HVS), to apply traffic loads.

Accelerated pavement testing programs have been undertaken for almost a century in the United States. One of the earliest test roads was the Bates Experimental Road, built in Illinois in 1922. The State Bureau of Roads, in search of the most effective designs, ran trucks with various axle loads over different brick, asphalt and Portland cement concrete pavement sections. Various major road testing programs have since been constructed. The most notable experiment is the AASHTO Road Test, discussed previously, which led to the

development of the AASHTO Guide for Design of Pavement Structures, which remains the predominant design methodology in most of the US and Canada.

Construction of APT facilities and implementation of the associated testing programs are long-term commitments that require considerable investment (NCHRP 2012). In addition to the price of the facility and the initial construction cost of the experimental pavements, further costs are associated with laboratory testing, pavement surveys, pavement and facility maintenance, data analysis and reporting.

Although APT programs are costly undertakings, waiting for results to accumulate at an actual low traffic rates and the potential cost of failures under actual traffic provide good justification for their implementation. APT programs also provide additional control over experimental variables, such as traffic and environment (NCHRP 2012).

2.4 Overview of aerated slab systems

Although Cupolex® has been successfully used in all manners of floor slab applications, this product had not been previously used in pavement applications. Pavements are subject to different conditions than most floor slabs, including frequent and heavy dynamic loads and exposure to a wide range of environmental conditions.

A review of the literature shows that this dome formwork product is unique. No comparable products are available on the market. Furthermore, a search shows that nothing similar has been previously implemented in any pavement or roadway application other than by this research team.

2.4.1 Mechanics of arches and domes

Arches and domes have been used since early times. The semicircular arch was first used by the Romans 2000 years ago (Giancoli 2008). These structures primarily resolve any forces into compression, making them suitable for masonry or concrete construction.

An arch is two-dimensional architectural feature that can span large distances without intermediate supports (Reid 1984). Arches carry loads by resolving external loads into mainly internal axial compression forces. This is a particularly beneficial property for materials with low tensile strengths, e.g. unreinforced concrete and masonry. Although bending moments, causing both compressive and tensile stresses are generally induced, they are typically small in magnitude (Schodek and Bechthold 2008). The supports of the arch must carry horizontal and vertical forces. The thrust of externally applied loads tend to force the bottom of the arch outwards, which can cause it to collapse. Consequently, sufficient buttressing is required at the bottom of the arch to prevent this movement. It was discovered that pointed arches, as compared to semicircular arches, have lower lateral thrusts and require less resistance to prevent collapse.

A dome can be considered to be an arch that has been rotated around its central axis, making it in essence a series of radial arch ribs (Sandaker et al. 2011). Similar to arch behaviour, the bottom of a dome tends to thrust outwards from the compressive forces in the arch ribs. These forces must be restrained in order to prevent collapse. Two primary methods are employed to restrain the outward thrust. The first is the use of base tension ring. The forces in the dome will apply radial horizontal forces to a base ring, putting it into a state of tension. Materials such as cast iron and steel are used for this purpose. The other method is to restrain the outward forces using sufficiently thick buttresses. The self-weight of the buttresses resists the outward thrust of the dome structures, putting it into static equilibrium.

In a dome shaped shell, two sets of forces in separate directions act on the surface (Schodek and Bechthold 2008). The in-plane meridional forces are always compressive under full vertical loading. Hoop forces act in the circumferential direction, perpendicular to the meridional forces. However, these forces may be tensile or compressive, depending on their location in the shell. At the top of the shell, the hoop forces are typically compressive, resisting inward movement. At the bottom of the same shell, the shell has a tendency to deform outwards. Consequently, the resisting hoop forces are tensile. Uniform loading generally induces fairly small stresses associated with hoop and meridional forces. However, point loads may cause very high stresses and should be minimized in dome structures.

2.4.2 Summary of Previous Use of Structural Dome Formwork System in Concrete Pavements

A review of the literature has not revealed any previous use of structural dome formwork systems in concrete pavement construction nor the construction of aerated slabs in road or highway applications other than by the members of this research team.

The first preliminary Cupolex® pavement section was constructed by Dufferin Construction at Dufferin Aggregates' Mill Creek Pit in Puslinch, Ontario in October 2010 (Rouault 2012). This initial experimental section was built to establish the possibility of using Cupolex® in pavement applications. The first trial consisted of a 100 m long section of pavement leading to the pit's scalehouse. This section was constructed using fixed formwork and consisted of three adjacent sections of 30 m, each with a different thickness (75 mm, 115 mm & 150 mm). Smooth, gradual transitions were built from one section to the next.

Cupolex® units with dimensions of 560 mm x 560 mm x 260 mm were used for the Mill Creek trial. At the recommendation of the manufacturer, a welded wire mesh was placed

on top of the Cupolex prior to paving, with the expectation that the steel mesh will help hold together any cracks that form. However, no load transfer devices were installed.

Falling Weight Deflectometer (FWD) testing, Ground Penetrating Radar (GPR) testing, visual condition surveys and coring have been completed on this section to evaluate pavement performance. Traffic data (truck volumes and weights) from the scalehouse have been used to compute the number of Equivalent Single Axle Loads (ESAL) carried by the test sections.

The Mill Creek Cupolex® trial is still in service, with the exception of the 75 mm section, which failed prematurely and was removed and replaced with the pre-existing gravel material. The remaining sections continue to perform adequately. The 115 mm section is in fair condition, with moderate cracking and a few areas of surface spalling. The 150 mm is somewhat better condition, showing only minimal low severity cracks. This section has carried over 1.07 million ESALs to the end of May 2013 (over 30 months after opened to traffic).

Additionally, Dufferin Construction had previously experimented with the possibility of using a slipform paver to place concrete onto the Cupolex® formwork. Two short test areas were built at Dufferin Construction's Bronte Yard (Oakville, Ontario) in May and September 2011, respectively, to evaluate the compatibility of modern paving equipment with this product.

The instrumented test road constructed as part of the research presented in this thesis is the second major pavement trial involving Cupolex® in Ontario. Lessons learned from the Mill Creek trial were incorporated into the Milton trial.

Chapter 3

Trial Design and Construction

3.1 Introduction

To evaluate the potential of Cupolex® as an innovative concrete pavement technology, a full-scale trial was designed and constructed by the research team. In order to obtain valuable performance data in a reasonable period of time, an accelerated loading scenario was proposed.

The trial Cupolex® pavement section for this research project was constructed in April 2012 at the Dufferin Aggregates Milton Quarry. The Milton Quarry is located on Dublin Line in the Town of Milton, Ontario (northwest of Highway 401 and Highway 25, as indicated in Figure 3-1, forty minutes west of Toronto). This facility is Canada's largest active limestone quarry, drawing material resources from the Niagara Escarpment. This quarry has been providing a wide range of aggregate materials for construction activities in the densely populated Greater Toronto Area since 1962. Annual production consists of approximately three to four million tonnes per year (Holcim 2010).

The Milton Cupolex® trial consists of a ninety-eight metre (98 m) long section of two-lane roadway. Each lane is four metres wide. The Cupolex® trial was constructed on the main access road into the quarry, adjacent to the tarping station, shown in Figure 3-2. This road sees high volumes of heavy truck traffic. The primary vehicles on this access road include multi-axle aggregate trucks, most of which exit the quarry with a full load of aggregate products.

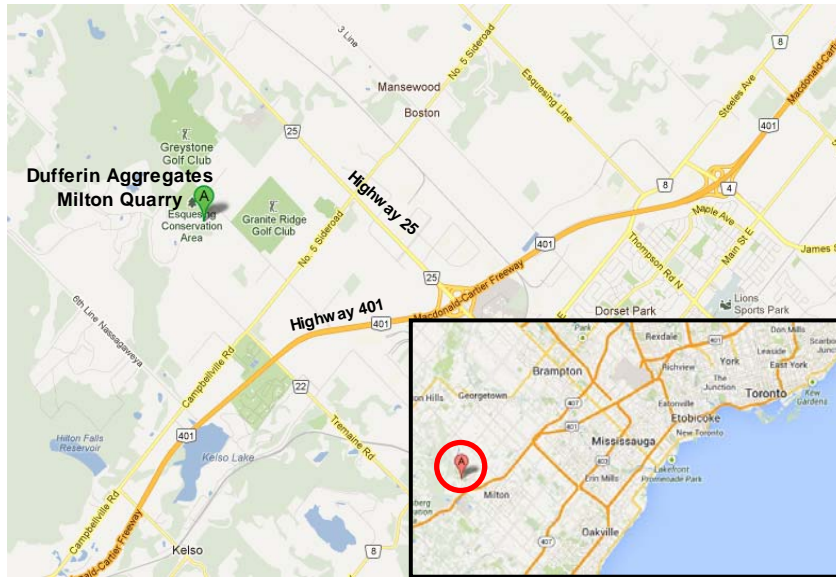


Figure 3-1: Location of the Dufferin Aggregates Milton Quarry (Milton, Ontario)
(Google 2012)

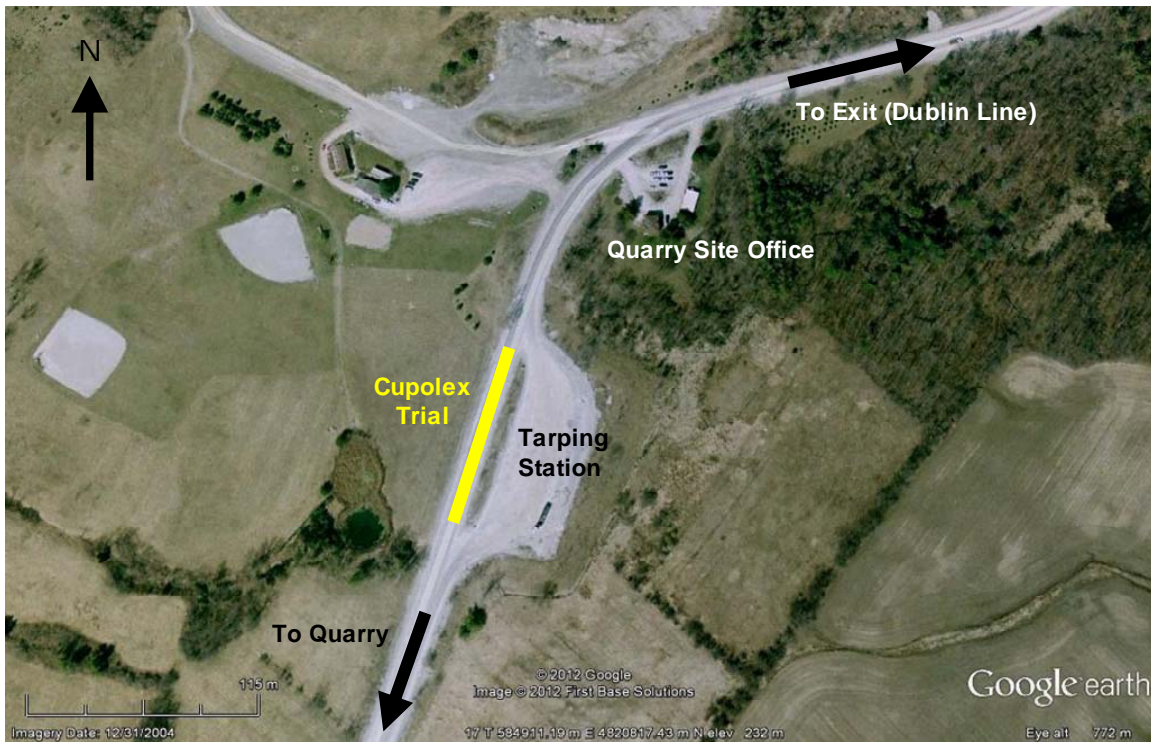


Figure 3-2: Location of the Cupolex® trial at the Milton Quarry
(Google 2012)

3.2 Concrete Pavement Design

A number of well-established pavement design methodologies are available for the design of conventional concrete pavements. However, design procedures for pavements built with Cupolex® have not been yet developed.

A geotechnical investigation was first completed on the test site prior to the construction to identify the existing conditions. The test pits excavated in the shoulders of the existing asphalt pavement revealed that the natural subgrade consists of a shaly granular material, shown in Figure 3-3. Falling Weight Deflectometer (FWD) testing performed in the spring of 2011 indicated a base support k-value of approximately 40 MN/m³. This would be considered a strong subgrade material. Its high strength and excellent drainage characteristics make it a good base material for road construction.



Figure 3-3: View of excavated test pit showing shale subgrade material

Based on the manufacturer’s experience with floor slab construction, recommendations from the pavement engineering design consultant and the limited previous field experience with Cupolex® roadways, two pavement designs were proposed to satisfy the requirements for the design vehicle, described in

Table 3-1, representing a typical quarry vehicle, and the geotechnical conditions. The southern half of the roadway consists of 150 mm of concrete above the Cupolex® unit, whereas the northern half consists of 175 mm of concrete above the Cupolex® unit. Both pavement designs are illustrated in Figure 3-4. On-going monitoring and evaluation will show whether the slight difference in thickness has any noticeable effect on pavement performance, if any. Both pavement designs would rest on the pre-existing 300 mm thick granular base, which had placed over the natural subgrade for drainage and structural support. This granular material meets Ontario Provincial Standards Specification 1010 for base aggregates (OPSS 2013).

Table 3-1: Design vehicle characteristics

Design vehicle:	Full size aggregate truck
Number of axles:	2
Weight per axle:	5,000 kg
Weight per dual tire configuration:	2,500 kg
Weight per individual tire:	1,250 kg
Average axle width (between outside edges of tires):	2.60 m
Dual tire spacing (centre to centre):	0.30 m
Tire pressure:	830 kPa (120 psi)
Axle spacing (distance between the centre point of contact between consecutive dual axles):	1.45 m

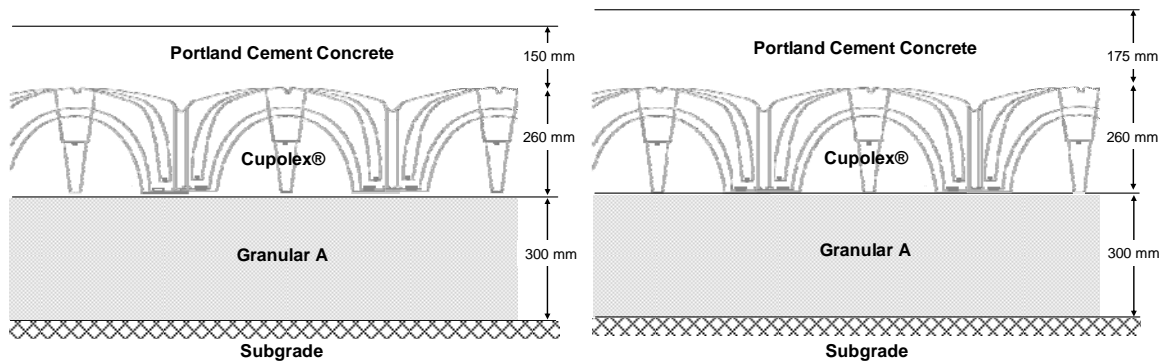


Figure 3-4: Pavement designs for Cupolex® trial

Cupolex® units with dimensions of 560 mm x 560 mm x 260 mm were selected for use and are shown in Figure 3-5. The construction of two 4 m lanes involved the placement of 13 Cupolex® units across the width of the road. A longitudinal bulkhead of solid concrete on either side was also installed to keep the units in place and to provide an anchor. The concrete bulkhead provides stiffness to the Cupolex® system and its mass provides the restraint necessary to keep the pavement from separating under traffic loads. In total, 174 Cupolex® units were laid along the length of the road to cover the 98 metre long section.

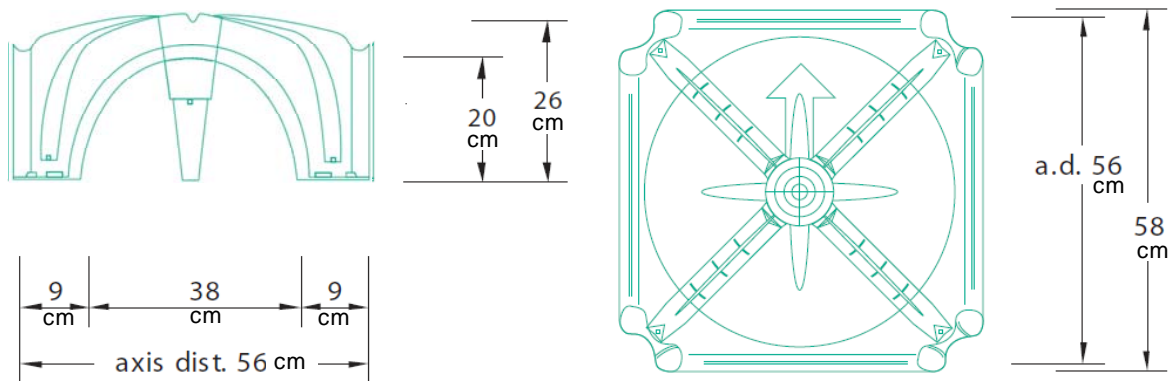


Figure 3-5: Schematic of Cupolex® units used

The BetonStop® end cap, a companion product to Cupolex®, was used to seal the open edges of the Cupolex® units along the outer perimeter. This product, shown in Figure 3-6, prevents concrete from flowing under the domes, where it is wasted. Based on previous experiences, the BetonStop® end caps were doubled up to prevent the pressure of the concrete from pushing them in and allowing concrete to flow into the void below. The first BetonStop® was placed such that it would be flush with the edge of the Cupolex® units and the second was placed such that it would protrude slightly (shown in Figure 3-7). This arrangement is expected to provide additional stiffness to the edges and eliminate the potential for concrete waste, as it prevents material flowing into the void beneath the domes.



Figure 3-6: BetonStop®, companion end cap for Cupolex® units



Figure 3-7: Installed BetonStop® products, doubled up to prevent punchout

3.3 Joint Design

The proper construction of joints in a rigid pavement is very important to ensure good performance. Joints installed at regular intervals are required to prevent shrinkage cracking, which can lead to poor ride quality and premature failures. However, good load transfer between adjacent slabs is critical for avoiding performance issues such as faulting and cracking, due to slab movement.

Typically, dowel bars are placed in most rigid pavements that are exposed to high volumes of traffic (TAC 2012). The anticipated traffic weights and volumes at a location such as a quarry would warrant the use of dowel bars.

However, the research team discussed at length whether load transfer devices should be included. Despite the recommendations of conventional pavement design methodologies to include load transfer devices, the ability of the Cupolex® pavement to transfer load across transverse through aggregate interlock alone warranted investigation. Additionally, the inclusion of dowel bars introduced some constructability concerns. Conventional dowel baskets are typically pinned to the granular base or subgrade. A creative solution would have been required to fasten the dowel baskets on top of the Cupolex® units. The use of a Dowel Bar Inserter (DBI) with the slipform paver was ruled out due to the minimal design slab thickness.

The positioning of the joint with respect to the top of the dome was also suggested as one possible factor affecting the quality of load transfer across a transverse joint. Joints located directly over the top of the dome have the minimum amount of concrete below the joint (150-175 mm of concrete with the selected Cupolex® units and concrete thicknesses),

whereas joints located over the legs of the Cupolex® have the maximum amount of concrete below the joint (410-435 mm of concrete in this scenario).

The increased thickness over the legs should theoretically provide additional shear area which should provide more aggregate interlock and consequently, better load transfer. However, the need to ensure that transverse joints are located over the legs complicates construction. Careful measurement would be required prior to concrete placement to accurately pre-determine joint locations. In the end, it was decided that load transfer devices, i.e. dowel bars, would be omitted.

3.4 Concrete Mix Design

A concrete mix design using a 19 mm aggregate mix and General Use Portland-Limestone cement (Type GUL) was developed for this project. Full mix specifications are shown in Table 3-2. The mix used had a specified 28 day compressive strength of 30 MPa, as well as a specified air content of 6.0% and slump of 70 mm.

Portland-Limestone cement is a more sustainable Portland cement product, prepared by replacing a portion of the cement clinker with raw limestone. In many applications, Portland-Limestone cements provide equal performance to conventional Portland cements with a lessened impact on the environment (Tennis et al. 2011).

Table 3-2: Concrete Mix Design

Material Description	Proportions
Portland Cement (Type GUL)	268 kg/m ³
Slag	87 kg/m ³
Sand	860 kg/m ³
19 mm limestone	1035 kg/m ³

Water	125 kg/m ³
Water reducing agent	250 mL/100 kg of cement
Air entraining agent	70 mL/100 kg of cement

Portland limestone cement (PLC) is produced by blending Portland cement and raw limestone. By replacing a portion of the Portland cement with limestone, the amount of greenhouse gas emissions from cement production is reduced, due to diminished clinker requirements. Generally, PLCs have similar physical performance characteristics to conventional Portland cements, including compressive strengths, strength development rates, chloride ingress rates and alkali-silica reactivity. Concrete mixes using PLCs also have additional benefits including improved workability and pumpability (Hooton et al. 2007).

3.5 Instrumentation Selection, Layout and Installation

As part of the Milton trial pavement's construction, instrumentation was installed at different locations in the pavement structure to monitor various pavement responses and other parameters of interest. The quantification of the behaviour of the Cupolex® pavement system under traffic and environmental loading was determined to be a primary objective of this research project. Pavement responses of interest, the required sensors and their layouts were selected based on experience obtained from previous University of Waterloo / CPATT research efforts (El-Hakim 2009, Smith 2009, Henderson 2012). The three types of sensors selected and the associated responses of interest are detailed in Table 3-3. These embedded sensors allow for the assessment of the pavement responses, validation of the pavement designs and the prediction of long-term pavement performance. The instrumentation was positioned in locations where it would produce the most valuable information. The general layout of the pavement instrumentation is shown in Figure 3-8.

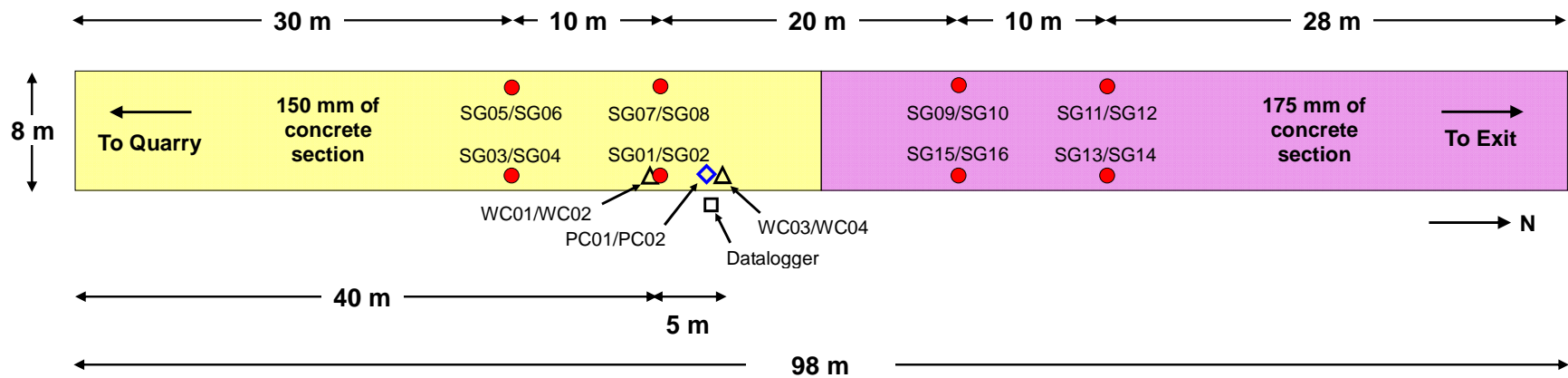


Figure 3-8: Plan view of pavement instrumentation layout

Table 3-3: Selected Instrumentation Types

Sensor Type	Quantity	Purpose
Vibrating Wire Strain Gauge	16	Measure changes in concrete strain and temperature due to environmental and vehicular loadings.
Vibrating Wire Total Earth Pressure Cell	2	Determine pressures imparted on the base layers by the Cupolex® pavement slab.
Moisture Probes (Water Content Reflectometers)	4	Measure moisture content of granular layers and evaluate its effect on concrete strain and base pressures.

3.5.1 Strain Gauges

Sixteen vibrating wire embedment strain gauges were placed in the concrete layer at the top of the Cupolex® units. The strain gauges were placed at eight different locations, in both the loaded and unloaded lanes and in each of the thickness sections. All the strain gauges are located in the right wheelpath of the lane, in order to capture the full effects of the heavy traffic on the pavement structures. Two sensors were installed at each of the eight locations: one gauge perpendicular to the direction of traffic (transverse orientation) and the other parallel to the direction of traffic (longitudinal orientation). The selected layout provides complete redundancy for quality assurance purposes. The strain gauges were placed on top of the Cupolex® unit because this location has the lowest concrete thickness overall and is expected to experience critical strains. This arrangement is illustrated in Figure 3-9. A description of each strain gauge and its location and orientation is provided in Table 3-4.

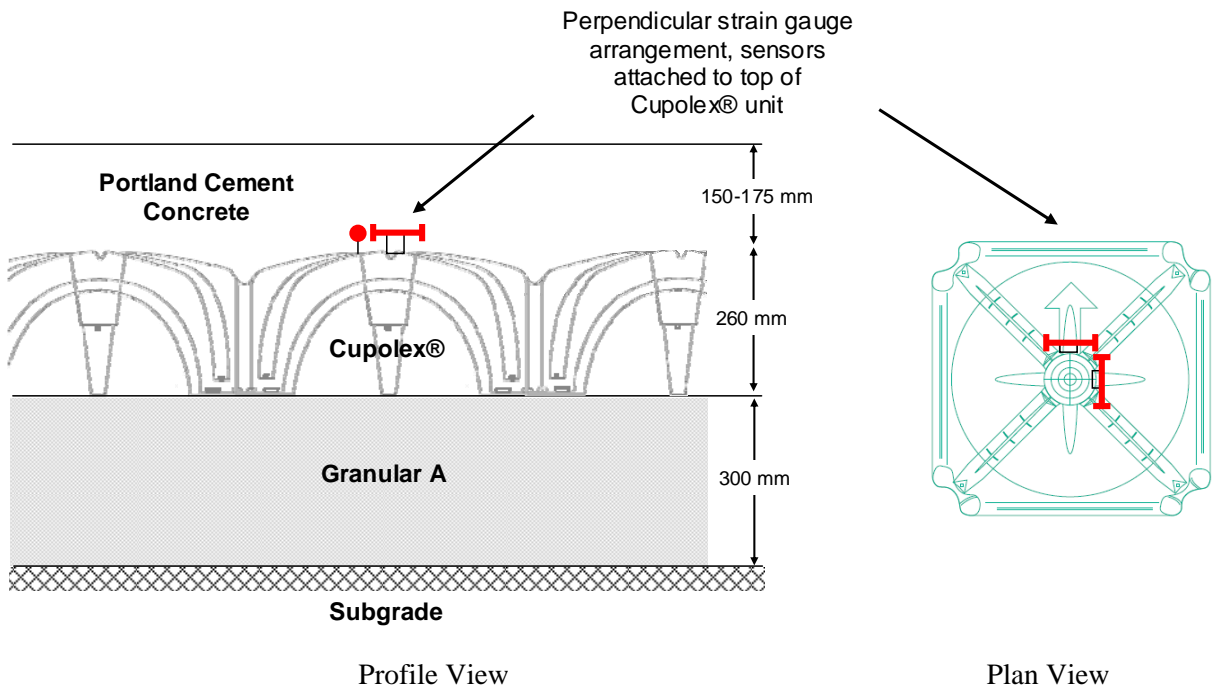


Figure 3-9: Schematic of strain gauge placement on Cupolex® unit

Table 3-4: Strain gauge locations

Location Number	Strain Gauge Number	Total Concrete Thickness	Lane	Orientation
1	SG01	150 mm of concrete	Loaded lane	Transverse
	SG02			Longitudinal
2	SG03			Transverse
	SG04			Longitudinal
3	SG05		Unloaded lane	Transverse
	SG06			Longitudinal
4	SG07			Transverse
	SG08			Longitudinal
5	SG09	175 mm of concrete	Unloaded lane	Transverse
	SG10			Longitudinal
6	SG11			Transverse
	SG12			Longitudinal
7	SG13		Loaded lane	Transverse
	SG14			Longitudinal
8	SG15		Transverse	
	SG16		Longitudinal	

The VWSG-E(M) model strain gauges installed were manufactured by RST Instruments Ltd. of Maple Ridge, BC. These sensors have a gauge length of 153 mm (6 in.) and include an integrated thermistor to record concrete temperature.

In order to install the strain gauges, U-bolts were pre-installed in the Cupolex® units prior to their placement on site. Once the Cupolex® units were laid out, the sensors were mounted to U-bolts using cable zipties. The cables were placed in a flexible plastic conduit for additional protection. The cables were then placed along in the “valleys” of the Cupolex® units to the location of the datalogger. The placement of the strain gauges prior to paving is shown in Figure 3-10. The need to cross the wires under the shoulder required a short section of cabling to be buried in a rigid polyvinyl chloride (PVC) conduit for protection.



Figure 3-10: Arrangement of strain gauges on Cupolex® unit

3.5.2 Pressure Cells

Two vibrating wire total earth pressure cells were installed in the granular layers to quantify the effects of the point loads imparted by the feet of the Cupolex®. The LPTPC09-V type pressure cells used were manufactured by RST Instruments Ltd. Both pressure cells were placed in the vicinity of the right wheelpath of the lane carrying outbound fully loaded aggregate trucks exiting the quarry. One pressure cell was placed such that the pressure cell plate is located directly below the foot formed by four adjoining Cupolex® and the other pressure cell plate was installed such that it was situated in the void between two adjacent Cupolex® units, as shown schematically in Figure 3-11 and

Figure 3-12, in both profile and plan views. A description of each pressure cell's location is provided in Table 3-5.

To install the pressure cells, a shallow rectangular trench, 150 mm deep, was dug at the desired location. Once it was determined that the pressure cells would be in the correct locations after the Cupolex® was laid, a protective steel plate was placed over the sensitive pressure plate and the trench was backfilled. A screened sandy material was compacted manually to protect the instrumentation. Shallow trenches were also dug to bury the pressure cell cabling in a rigid PVC conduit where it was then run to the location of the datalogger in the berm adjacent to the shoulder. The conduit trenches were also backfilled and compacted.

Table 3-5: Pressure cell locations

Pressure Cell Number	Orientation	Depth below grade	Lane	Total Concrete Thickness
PC01	Under void	150 mm	Loaded lane	150 mm
PC02	Under foot	150 mm	Loaded lane	150 mm

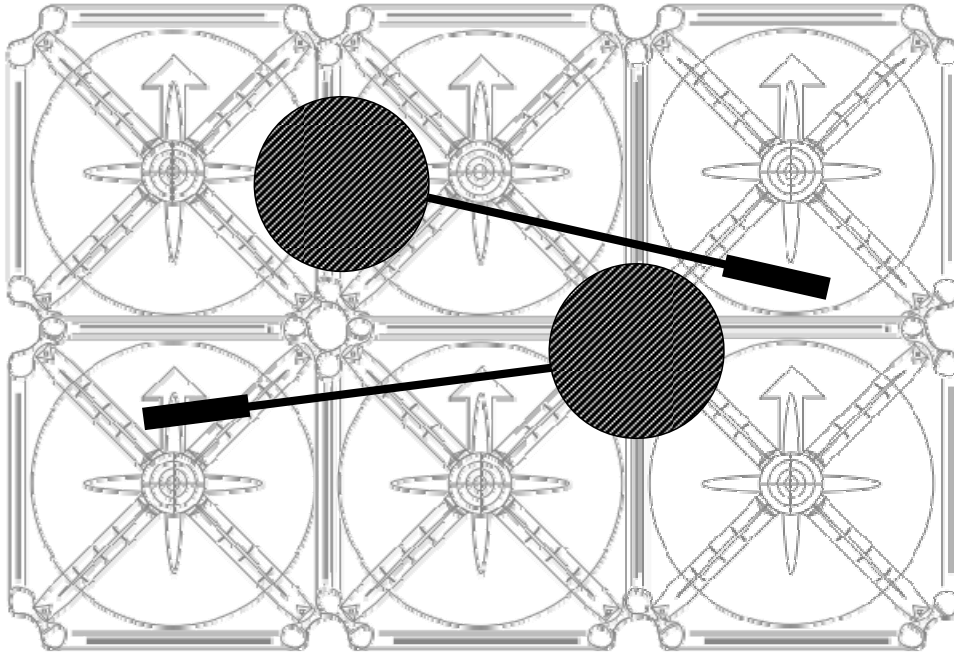


Figure 3-11: General arrangement of pressure cells in right wheelpath (Plan View)

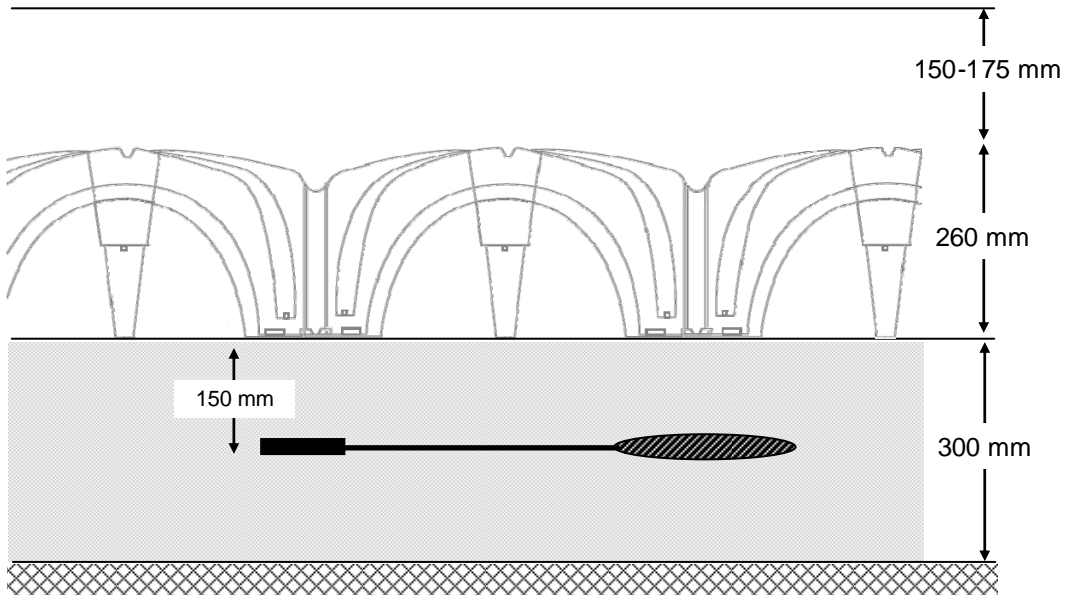


Figure 3-12: Typical Arrangement of Pressure Cells (Profile View)

3.5.3 Moisture Probes

Four moisture probes were placed in the compacted granular material below the Cupolex® to record the changes in water content in this layer. The moisture content of the unbound pavement layers impacts the strength of the overall pavement structure and may contribute to the performance of the roadway.

The gauges installed were CS616 Water Content Reflectometers, manufactured by Campbell Scientific Inc. of Logan, Utah. These two-pronged probes use the concept of Time Domain Reflectometry to determine the volumetric water content of the soil (Campbell Scientific 2012).

The moisture probes were installed at two different locations. At each location, two sensors were placed such that they would measure the vertical moisture profile of the layer. One sensor was placed at a depth of 300 mm below original grade. The hole was partially backfilled and compacted so that the second sensor could be placed 150 mm above the first sensor at 150 mm below the original grade. This layout allows for the examination of the drainage of water through the pavement structure. The moisture probe arrangement is illustrated in Figure 3-13. Each moisture probe's location is listed in Table 3-6.

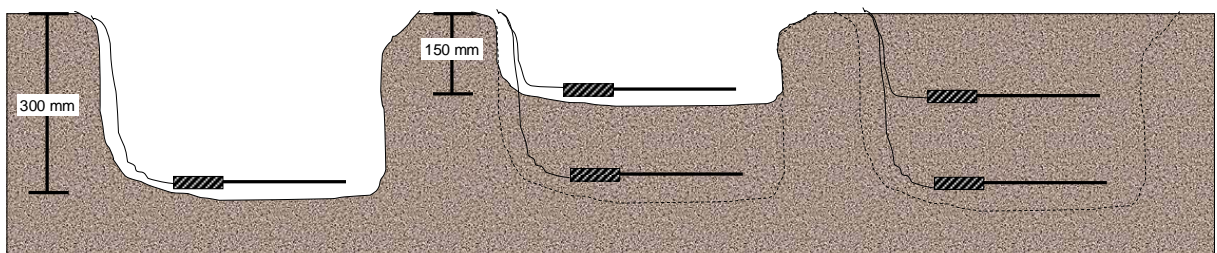


Figure 3-13: Moisture Probe Installation (Profile View)

Table 3-6: Moisture probe locations

Moisture Probe Number	Depth below grade	Material Type	Location
WC01	300 mm	Granular A	Below loaded lane
WC02	150 mm	Granular A	Below loaded lane
WC03	300 mm	Granular A	Below loaded lane
WC04	150 mm	Granular A	Below loaded lane

3.5.4 Data acquisition system

A Campbell Scientific CR1000 datalogger was used to collect and store readings from each of the sensors installed in the trial pavement. A datalogger program was developed to collect readings from all three types of installed sensors on an hourly basis. The data acquisition system, housed in a weatherproof enclosure mounted on a pole, was installed on the berm located on the east side of the road, as shown in Figure 3-14. All of the sensor cabling is routed to the enclosure through PVC conduit buried in the shoulder.



Figure 3-14: Weatherproof enclosure with data acquisition system, located on berm

3.6 Construction

3.6.1 Overview of Construction Activities

The contractor began construction activities with the establishment of a detour for the vehicles entering and leaving the quarry. The old asphalt pavement was removed and the existing granular base was excavated, re-graded and re-compacted. Additional Granular A material was placed where necessary. Once the base layer was prepared, the Cupolex® units were laid out and the instrumentation was simultaneously installed. Following the completion of the site preparation, the concrete pavement was placed. A Gomaco GHP 2800 slipform paver was used to form, consolidate and finish the pavement. The concrete was placed on the Cupolex® using a Putzmeister Telebelt conveyor. A fleet of ready-mix trucks supplied the concrete, which came from Dufferin Concrete's Georgetown plant. Following the vibration and strikeoff of the fresh concrete by the paver, the surface was finished by an automatic floating screed. Spot repairs to the surface and edges were completed using extra concrete and manual floating screeds. The surface was then textured using a wet burlap drag. Using a finishing machine, the surface was transversely tined (uniform spacing) and a curing compound was applied. The pavement texturing methods were selected so that the trial section would have similar surface characteristics to conventional concrete pavements. Paving progressed in a northerly direction (towards the entrance of the quarry) and was completed in one day on April 13, 2012. Photos of the construction activities are presented in Figure 3-15.



a)



b)



c)



d)

Figure 3-15: Construction photos

- a) Layout of Cupolex® units in progress (April 12, 2012) b) Placement of concrete in front of slipform paver with conveyor truck (April 13, 2012) c) Application of tining and curing compound (April 13, 2012) d) Finished pavement at the end of the day (April 13, 2012)**

CPATT researchers were on-site during the paving activities to assist with the placement of the pavement test section. Fresh concrete was manually placed around the strain gauges to ensure proper embedment and the lack of voids remain after the paver passed. Concrete was also placed on top of the conduit carrying the strain gauge wiring and in the

adjacent feet. This work was performed to weigh down these cables so that the paver would not be able to drag them as it passed to ensure survivability.

3.6.2 Construction Issues

The first 20 metres of roadway were paved without difficulty. At this point, it was observed that the weight of the concrete was causing the Cupolex® to buckle and separate, as seen in Figure 3-16. Further investigation showed that the Cupolex® units had not been installed properly, which prevented the adjacent units from interlocking securely. The Cupolex® units must be installed in a specified order (one row at a time, left to right, with the marked arrows all pointing in the same direction). This issue was quickly resolved. The orientation of the Cupolex® units in the unpaved section was verified and any incorrectly laid out unit was quickly re-installed to correct the problem. The neoprene sock attached to the concrete conveyor was also removed so that the conveyor did not drop the concrete from a great height. The remainder of the paving day continued without any issues.



Figure 3-16: Separation of Cupolex® units from incorrect installation

3.6.3 Concrete Testing

Quality control testing on the concrete was performed by the contractor. Slump and air content tests were carried out on the plastic concrete prior to placement. Afterwards, compressive strength and flexural testing was performed on the hardened concrete. Strength testing specimens were both field cured and lab cured. Three, four, seven and 28 day results are presented in Table 3-7 and Table 3-8. The measured 28 day compressive strength (46.6 MPa) significantly exceeds the specified 28 day strength of 30 MPa.

The measured slump was in the range of 60-70 mm, i.e. very close to the specified value. Air content, however, was shown to be slightly higher than the specified 6.0%, averaging 8.0-8.5% in reality.

Table 3-7: Concrete Compressive Strength Testing Results

Age	Cure Type	Average Compressive Strength	Cure Type	Average Compressive Strength
3 days	Field	22.1 MPa	Lab (wet)	24.5 MPa
4 days	Field	22.8 MPa	Lab (wet)	—
7 days	Field	24.5 MPa	Lab (wet)	28.9 MPa
28 days	Field	—	Lab (wet)	46.6 MPa

Table 3-8: Concrete Flexural Strength Testing Results

Age	Cure type	Average Flexural Strength
7 days	Lab	4.9 MPa
28 days	Lab	7.1 MPa

3.6.4 Jointing

Joints were sawcut soon after the concrete hardened, i.e. 12 hours after paving was completed. A continuous 75 mm deep longitudinal sawcut was made down the centreline to divide the roadway into the two 4 metre wide lanes. Transverse joints were sawcut in both lanes at a uniform spacing of 4 metres.

The joints were initially not sealed. However, it was observed the trucks using the road were continuously tracking fine dust and dirt from the quarry onto the trial pavement. A significant amount of fine aggregate was also blowing out of the truck beds onto the pavement as the vehicles exited the quarry. The research team subsequently decided to seal the joints after eight months of service. This was deemed to be necessary as the joints were being exposed to large amounts of incompressible materials and this would lead to the accelerated deterioration of the trial pavement, which would not be representative of typical road and highway pavements. All joints were cleaned out with a high pressure air lance and a pre-formed neoprene sealant was installed.

3.6.5 Other post-paving activities

Before the Cupolex® trial section could be opened to traffic, granular fill was placed on the shoulders and graded to eliminate edge dropoff. The approaches at both ends of the section were also backfilled with granular material and paved with asphalt. Finally, flexible plastic delineators were installed down the centreline of the test section. The delineators were placed to ensure that the trucks travelling along the road would remain in their designated lanes and not travel down the centre of the roadway. The Cupolex® trial section was opened to traffic one week after paving after verifying that the concrete had gained sufficient strength through quality control testing.

3.7 Summary of Field Test Section Design and Construction

A 98 metre long trial Cupolex® concrete pavement section was constructed at Dufferin Aggregates Milton Quarry in April 2012. This experimental pavement consists of two pavement structural designs. Three types of pavement instrumentation, strain gauges, pressure cells and moisture probes, were installed in the pavement structure to monitor pavement responses and assist with pavement performance evaluation. The pavement was placed using a conventional concrete slipform paver. The Cupolex® pavement was easily constructed using the standard concrete pavement construction equipment in one day. One critical point of importance was noted for successful construction. The Cupolex® units must be installed with the proper orientation, as directed by the manufacturer. Otherwise, the Cupolex® units will separate under the weight of the concrete, distorting the pavement and allowing waste concrete to flow under the plastic domes.

Chapter 4

Pavement Evaluation

Following construction, the performance of the Cupolex® pavement trial at the Milton Quarry has been evaluated through a variety of means. Strain, temperature, deflection, and visual condition surveys are effective means for evaluating pavement performance and validating pavement design. A summary of the performance data from the first year of service is presented in this chapter.

4.1 Sensor Evaluation

4.1.1 Strain Gauge Evaluation

Prior to the placement of concrete, initial strains were recorded to establish baseline measurements. Future strain measurements are compared to the initial baseline values to determine the change in strain. Changes in strain, related to both environment and traffic load effects, are recorded at hourly intervals. A positive strain value denotes that the pavement is in tension, while a negative strain value indicates that the concrete is in compression.

Each time a dataset was downloaded from the datalogging equipment, it was processed and underwent a quality control check. The measured strain value was subtracted from the baseline value to calculate the change in strain at that time interval. Correction factors to account for temperature variations and the different coefficients of thermal expansion of the gauge and the concrete were applied using the RST Instruments Ltd. recommended equations. Overrange and other erroneous values were removed from the dataset prior to analysis.

Some strain gauges have operated intermittently during the year. Consequently, no data from these inoperational periods is available. A noticeable gap can be observed in the strain data presented herein. This can be explained by a three week long outage of the strain gauges, which occurred in August 2012 for unknown reasons. Strain data was not collected during this period, although the moisture probes and pressure cells remained operational during this timeframe. However, it should be noted that strain data after this period was successfully collected and no major problems have been noticed since this time.

4.1.1.1 Pavement Response due to Thermal Effects

The strain data presented here includes the combined effects of thermal variation, vehicular loadings, creep, shrinkage, relaxation and subgrade settlement. However, given the data acquisition rate selected, the dominant factor affecting the data presented is changes in ambient temperature.

Distinct daily cycles are observed in the strain measurements. Temperature changes cause the slab to undergo uniform expansion and contraction. As the concrete temperature increases during the day with increasing ambient temperature and exposure to solar radiation, the slab expands. This is measured as an increase in strain, i.e. greater tension. The opposite behaviour is observed overnight. As the concrete cools after the sun sets and the ambient temperature drops, increased compression is measured by the strain gauges. If the slab was free to undergo such changes no stresses would develop, but as part of the pavement system, the slabs are restrained by each other. This causes stresses to develop within the slab, which are recorded by the strain gauges. An example of this daily behaviour, observed during the month of July, is illustrated in Figure 4-1.

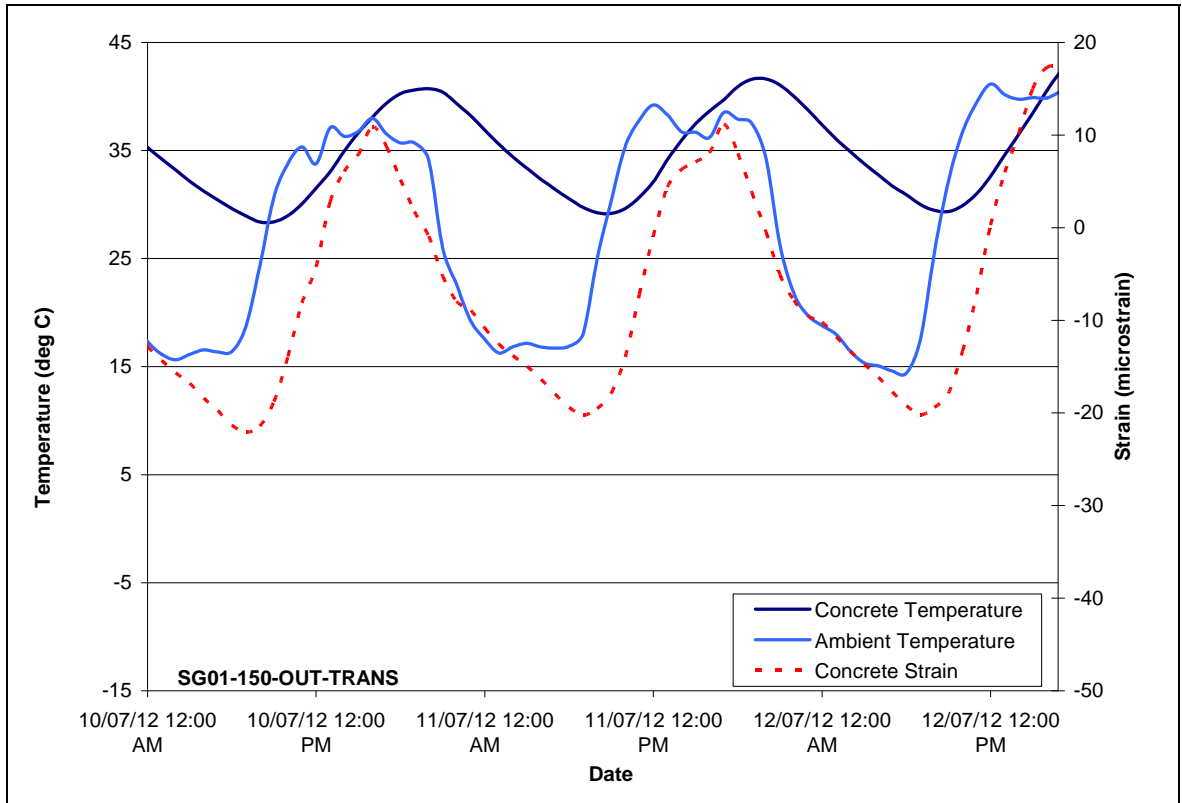


Figure 4-1: Daily cycles in strain and temperature in July 2012 (three months after construction)

Seasonal trends are also observed. The highest average strains are recorded during the summer (the warmest season) and the lowest average strains are measured during the winter (the coldest season). These observations are directly related to the relative magnitude of the seasonal ambient and concrete temperatures. Figure 4-2 shows the range of measured strain at one strain gauge throughout the pavement’s first year of service by month. The monthly measured concrete temperature ranges at that strain gauge location are similarly presented in Figure 4-3. Similar behaviour was also observed in the remaining fifteen strain gauges.

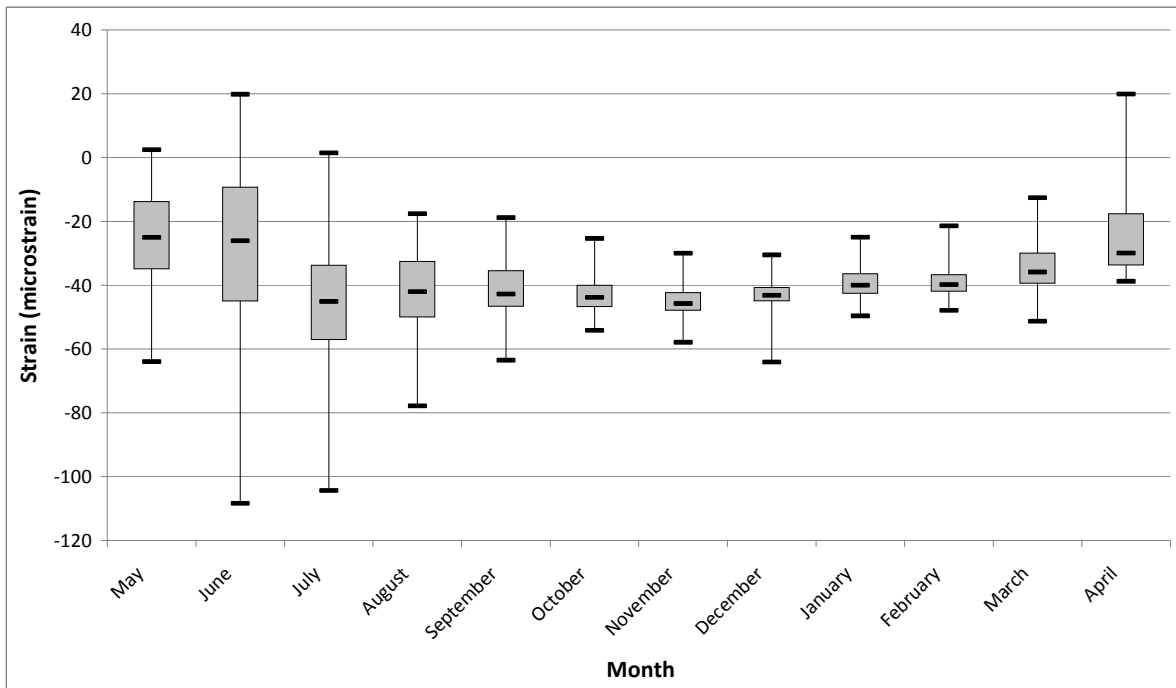


Figure 4-2: Measured concrete strain at strain gauge 08 (inbound lane, right wheelpath, longitudinal orientation, 150 mm of concrete) from May 2012 to April 2013.

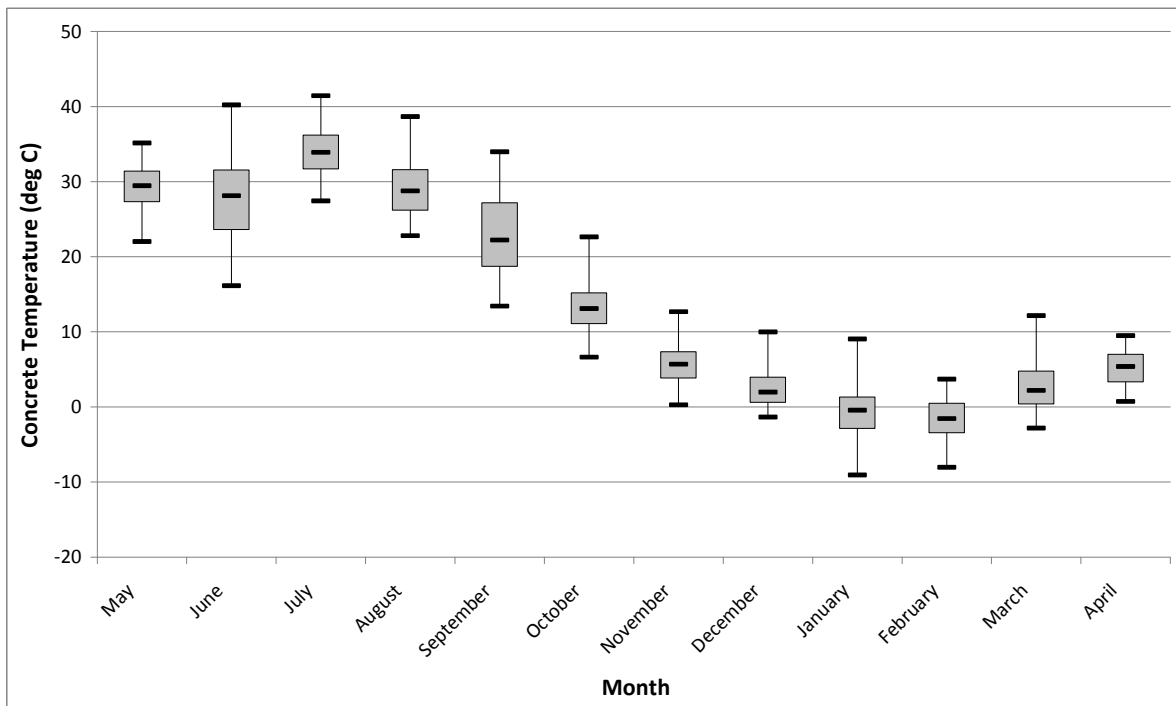


Figure 4-3: Measured concrete temperatures at strain gauge 08 (inbound lane, right wheelpath, longitudinal orientation, 150 mm of concrete) from May 2012 to April 2013.

In addition to the largest strain magnitudes, the summer season also brings the greatest variability in strain measurements. This observation is due to the fact that the largest daily ranges in ambient and, correspondingly, concrete temperatures are recorded during the summer. In July 2012, at age two months, the greatest difference between the highest and lowest daily concrete temperatures exceeded 28°C. On other hand, the strains measured during the winter are much more consistent throughout a 24 hour period, which results in much less fluctuation in strain measurements. In December 2012, after seven months in service, the average daily change in concrete temperature was only 7°C.

For the majority of the year, the measured strains at all sensors remain compressive, as seen in Figure 4-4. This behaviour is expected in dome shaped structures. Both the hoop forces and the meridional forces at the top of any stable dome are compressive (Schodek and Bechthold 2008). The highest concrete temperatures recorded in the summer (>35°C) have induced low positive (tensile) strains, no greater than 50 microstrain. However, these highest tensile values remain well below the anticipated tensile cracking threshold, which lies in the range of 100 to 200 microstrain (Neville 1995).

The fact that the measured strains at the top of the dome are compressive is encouraging. The dome shape of the Cupolex® ensures that the stresses at the location with the thinnest concrete remain compressive almost always. By virtually eliminating the tensile stresses, the possibility of cracks forming, particularly due to fatigue effects, is very low. It can also be noted from Figure 4-4 that the annual variability in strain remains fairly low as well. In 75% of the strain gauges, the interquartile range for strain is 25 microstrain or less, throughout the year, i.e. 50% of all annual measured strains throughout the year are within a range of 25 microstrain. This shows that the total change in strain is minimal and suggests that chances of fatigue failure are lessened. Although the annual range of strains for SG08

ranges from -108 microstrain to 20 microstrain (a range of 128 microstrain), it can be seen in Figure 4-2 that the median monthly concrete strain does not vary much from month to month, particularly in the fall and winter. It is observed to consistently range from -45 microstrain to -25 microstrain (a range of 20 microstrain). The standard deviation of median strain is only 7 microstrain, indicating consistency in the measured strain values.

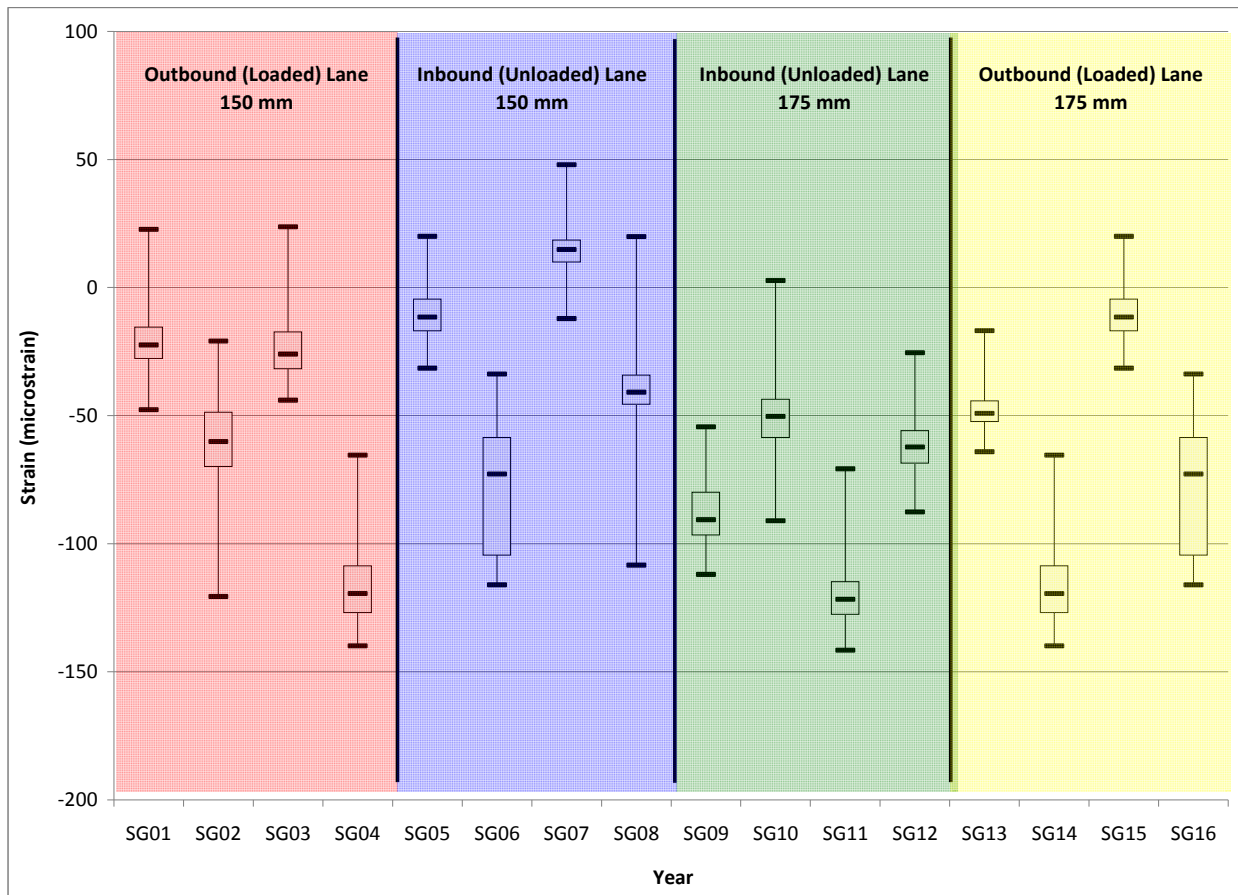


Figure 4-4: Measured strain ranges in all 16 strain gauges

A noteworthy difference is observed between the strain measurements of the transverse gauges in comparison to the longitudinal gauges. At each strain gauge location, the longitudinal strains (even numbered gauges) are significantly lower than the transverse

strains (odd numbered gauges), indicating greater compression. The difference in these results is being attributed to the edge restraint in the longitudinal direction, resulting in the observed variation. The strain gauges are all located in the right wheelpath of the lane, within 300 mm of the edge of the pavement. The outside of edge of pavement is essentially a free edge and allows for thermal expansion with less resisting forces. On the other hand, the longitudinal gauges all have at least 20 metres of concrete pavement on either side, providing significantly more restraint and reducing the amount of allowable slab movement in that direction. This additional restraint results in greater compression being measured by the strain gauges. One notable exception is observed in the 175 mm section of the inbound lane. Both strain gauges in this section, the measured transverse strains are greater than the longitudinal strains.

Although the two pavement structural designs constructed as part of this experiment only vary slightly, a difference is observed in the measured strains, as shown in Figure 4-4. In general, the strains measured in the 175 mm pavement section are lower than the 150 mm concrete section. It appears that the additional 25 mm of concrete thickness provides appreciable stiffness to the slab. The concrete temperatures do not vary significantly between the two concrete sections, so it seems like the additional concrete does not provide much additional insulation to reduce the strain variations.

Furthermore, differences between the strains measured by the strain gauges oriented parallel to the roadway centreline (even numbered gauges) and the strains measured by the strains gauges oriented perpendicular to the centreline (odd numbered gauges) are observed. The even numbered sensors record slightly lower strains. This difference is believed to be attributable to the level of available edge restraint. The strain gauges are all located in the outside wheelpath. The gravel shoulder is believed to provide less restraint and thus, permits

the concrete to expand more. Accordingly, the odd numbered gauges would record greater strain values. The one exception to this trend is found in the 175 mm section of unloaded lane, where the opposite trend is observed.

4.1.1.2 Pavement Response due to Vehicular Loading

The hourly data acquisition rate selected for the strain gauges is not able to capture the effects of traffic loads. Furthermore, even with a much faster data acquisition rate, vibrating wire strain gauges are not capable of capturing the effects of dynamic loads, due to their slow adjustment rate.

In order to quantify the pavement response due to vehicular loadings, testing was performed using a static, fully loaded tridem dump truck weighing 16615 kilograms (36630 pounds) in August 2012. Each of the dump truck's four axles was parked over a strain gauge location for a short period of time, allowing the static strain gauges to adjust and measure the load effects of the stopped trucks. The testing was repeated for each axle at each of the four strain gauge locations in the outbound lane.

The results of this testing revealed that external traffic loads have a minimal impact on the measured strain in the concrete. In all cases, the measured strain decreased slightly, indicating greater compression, with the application of each axle load. These variations ranged from a minimum change of -0.3 microstrain for the steering axle (the lightest axle) to a maximum change of -2.7 microstrain for middle rear axle (the most heavily loaded axle).

Given that the daily change in strain during the spring can exceed 50 microstrain during a 24 hour period, the impact from vehicular loading is almost insignificant. The changes in strain induced by static axle loads only make up 5% of the daily thermal strain variation.

The impact of dynamic truck loads, i.e. moving at highway speeds, is expected to be even less. The moving loads are removed as fast as they are applied. Furthermore, the vehicle used for static testing approaches the legal load limit in Ontario. The majority of vehicles travelling on public roads and highways weigh significantly less, further reducing the impact of vehicular loads.

4.1.1.3 Strain-Temperature Regression Analysis

The major factor influencing strains has been identified as temperature. The relationship between concrete temperature (as measured by the strain's gauge integrated thermistor) and the measured strain reading was compared. Linear regression analysis was performed to quantify the relationship between these two variables. The temperature-strain data for each sensors have been plotted below. The data from the 150 mm section concrete pavement (SG01-SG08) is presented in Figure 4-5, while the data from the 175 mm concrete pavement section (SG09-SG16) is presented in Figure 4-6. The linear lines of best fit have also been drawn on those plots.

In general, a positive relationship between temperature and strain is observed. This observation is consistent with the expected behaviour. The concept of thermal expansion suggests that as the concrete temperature increases, it experiences a corresponding increase in volume, which is captured as an increase in strain by the sensor, i.e. greater tension. However, in some cases, such as strain gauges 04 and 07, the data is very scattered which results in a near zero slope relation output from the regression analysis. A negative temperature-strain in SG02, where the data indicates that strains decrease with decreasing temperature. This observation defies established theories regarding thermal behaviour of materials.

The results of the regression analysis are presented in Table 4-1. The linear regression equations are listed, as well the corresponding coefficients of correlation (R^2 values). For the linear regression, the correlation is slight worse. The coefficients of correlation range from 0.000001 (extremely poor) to 0.69 (fair), averaging 0.26. The temperature-strain behaviour of the Cupolex® pavement is quite variable from sensor to sensor. There appears to be no correlation between the pavement thickness, sensor location or orientation.

Fairly strong relationships have been observed between concrete temperature and pavement strain in conventional JPCP. Irali et al. have observed a distinct linear relationship between these parameters at the University of Waterloo / Centre for Pavement and Transportation Technology rigid pavement test sections (Irali et al. 2013). Strain-temperature pavement from a three year period shows a good positive, linear relationship between temperature and strain. Some minor variation is observed, but the coefficient of correlation of 0.72, confirms the goodness of fit.

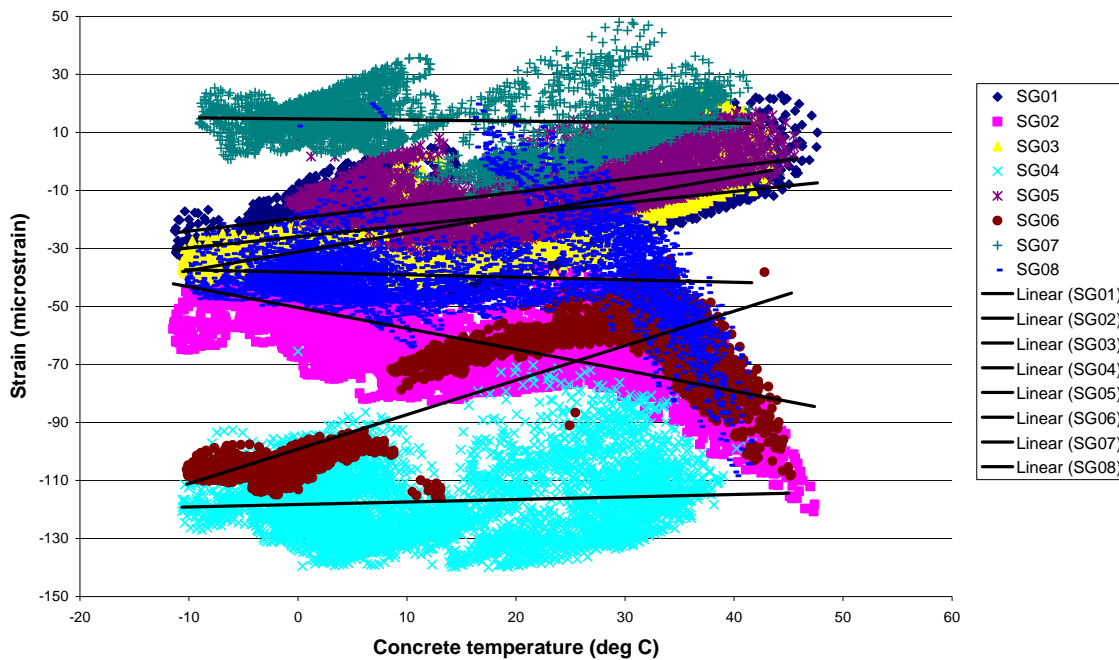


Figure 4-5: Strain-temperature relations in 150 mm of concrete section (SG01-SG08)

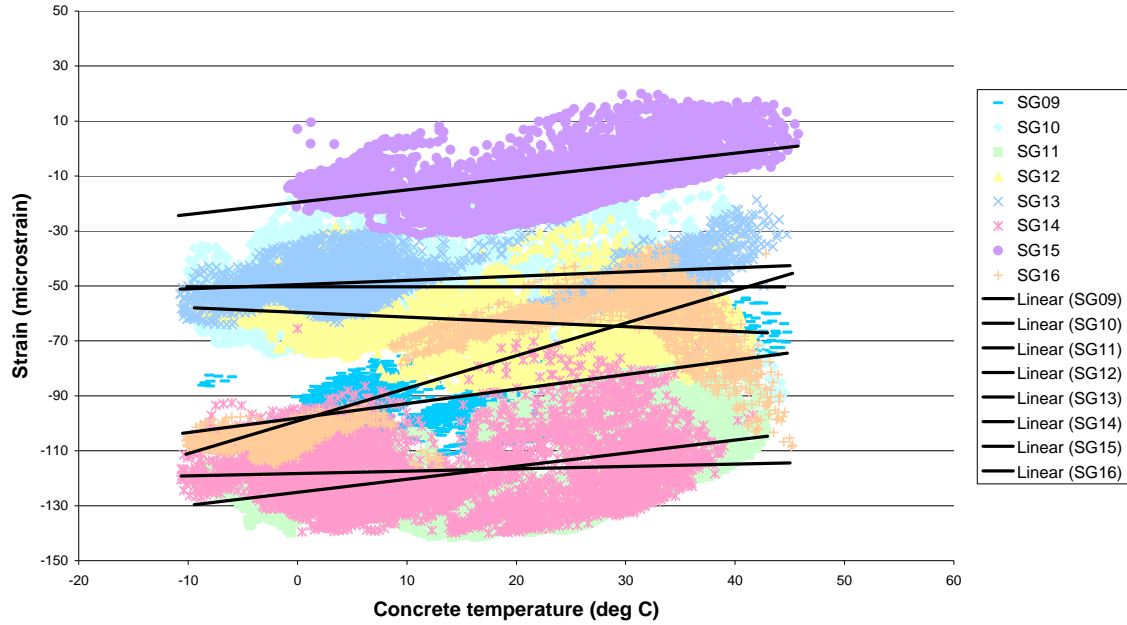


Figure 4-6: Strain-temperature relations in 175 mm of concrete section (SG09-SG16)

Table 4-1: Strain-Temperature Regression Analysis Results

Strain Gauge Designation	Strain Gauge Location	Linear Regression Equation	R ²
SG01	150-OUT-TRANS	$\epsilon = 0.3906T - 25.955$	0.25
SG02	150-OUT-LONG	$\epsilon = -0.7192T - 50.44$	0.46
SG03	150-OUT-TRANS	$\epsilon = 0.6457T - 31.148$	0.52
SG04	150-OUT-LONG	$\epsilon = 0.0851T - 118.26$	0.0076
SG05	150-IN-TRANS	$\epsilon = 0.4465T - 19.544$	0.31
SG06	150-IN-LONG	$\epsilon = 1.1885T - 99.183$	0.69
SG07	150-IN-TRANS	$\epsilon = -0.0388T + 14.688$	0.0044
SG08	150-IN-LONG	$\epsilon = -0.0854T - 38.249$	0.0082
SG09	175-IN-TRANS	$\epsilon = 0.527T - 98.065$	0.40
SG10	175-IN-LONG	$\epsilon = -0.0013T - 50.32$	0.000001
SG11	175-IN-TRANS	$\epsilon = 0.4745T - 125.08$	0.26
SG12	175-IN-LONG	$\epsilon = -0.1736T - 59.625$	0.059
SG13	175-OUT-TRANS	$\epsilon = 0.1526T - 49.505$	0.095
SG14	175-OUT-LONG	$\epsilon = 0.0851T - 118.26$	0.0076
SG15	175-OUT-TRANS	$\epsilon = 0.4465T - 19.544$	0.31
SG16	175-OUT-LONG	$\epsilon = 1.1885T - 99.183$	0.69

4.1.2 Pressure Cell Evaluation

4.1.2.1 General Pressure Cell Trends

The pressure data obtained from both pressure cells between May 2012 and April 2013 is presented in Figure 4-7. A gradual increase in pressure is observed in the pressure cell under the foot (PC01) from May 2012 until approximately late December 2012. After that period, the measured pressure levels off to a certain degree, in the range of 35 kPa. It should be noted that the vibrating wire type earth pressure cells are sensitive to temperature changes, which results in the “noisiness” seen in Figure 4-7. Temperature changes result in changes in fluid pressure in closed hydraulic systems such as these, which influence the pressure reading. Temperature corrections have been applied, but this does not completely eliminate the problem.

The data from the pressure cell in the void (PC02) was particularly noisy for the first three and a half months. Seeing this was not observed in the other pressure cell, it is believed that some external factor, such as a loose connection or electrical interference, was affecting the pressure cell readings. In early September 2012, this pressure cell’s readings became more consistent. A gradual increase was observed until the month of December, at which point the measured pressures remain fairly consistent in the range of 7 kPa.

The peaks recorded in base pressures occurred during the month of January at an age of seven months. At this point, the unbound soil layers were frozen. The frozen soils would have had significantly more stiffness than unfrozen materials. The frozen materials would have provided additional support to the buried pressure cell. Under the same consistent dead load, the measured pressure would be higher due to this fact.

Part of the observed increases in pressure is believed to be associated with continued consolidation and densification of the granular layer under the dead load of the pavement over time plus the effects of dynamic truck loads. Much of this behaviour is expected to occur within the first year. In the future, it is expected that pressure readings will remain more consistent, with the exception of the temperature associated variability.

The results obtained indicate that much greater vertical stresses are applied to the granular base directly below the feet, as the dead load of the Cupolex® concrete slab is transferred to the subgrade. The maximum difference in pressure recorded by the two pressure cells was 28 kPa. The areas beneath the void are not greatly influenced by the self-weight of the slab, indicating a narrow zone of influence for the individual legs. Most of the pressure measured in the void is due to the weight of the 150 mm of granular A above the pressure cell.

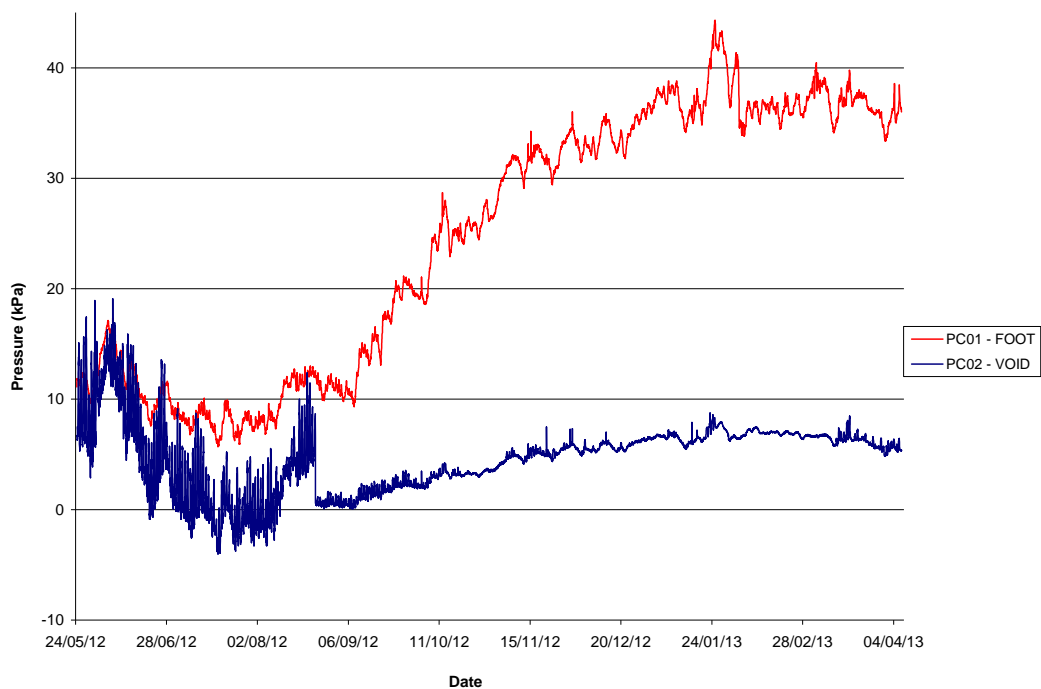


Figure 4-7: Pressure Cell Behaviour during first year of service – May 2012 to April 2013

4.1.2.2 Pressure Cell Response to Static Vehicular Loads

The vibrating wire type strain gauges are not designed to measure the effects of dynamic loads, such as moving vehicles. In order to evaluate the effects of traffic loads on the base pressures, a static testing program was devised. In August 2012, testing was performed over top of the buried pressure cells using a tridem dump truck having a gross weight of 36 000 lbs. Each of the dump truck's axles was parked over top of the pressure cell location for a few minutes, allowing the pressure cell to respond to the applied load. Pressure measurements were recorded for each test.

Conventional concrete pavements, such as jointed plain concrete pavements, can distribute loads over a large area. However, with Cupolex®, the concrete slab rests on individual “feet”. This design elicits concerns about the application of very high point loads to the underlying pavement layers. Concentrated point loads can cause the overconsolidation, as well as the settlement of the base and subgrade, if these layers are overstressed. Differential action can induce high stresses in the concrete, which is then susceptible to cracking if the tensile flexural stresses induced are greater than the concrete's modulus of rupture.

The key results obtained from the steering axle test are presented in Figure 4-8. A tire load of approximately 13 kN was applied directly over top of the “foot” located above the pressure cell location. The bearing area of each “foot” is approximately 150 cm². The application of the external load resulted in an increase in pressure of 1.3 kPa in PC01 (located under the foot) and 1.1 kPa (located in the void directly adjacent to the loaded foot). Recall that both pressure cells are located 150 mm below the top of the base layer. If the tire load had directly traveled from the point of application to the base layer, an increase in

pressure of approximately 35 kPa would have been expected in the pressure cell below the foot. However, the measured increase was only approximately 1 kPa.

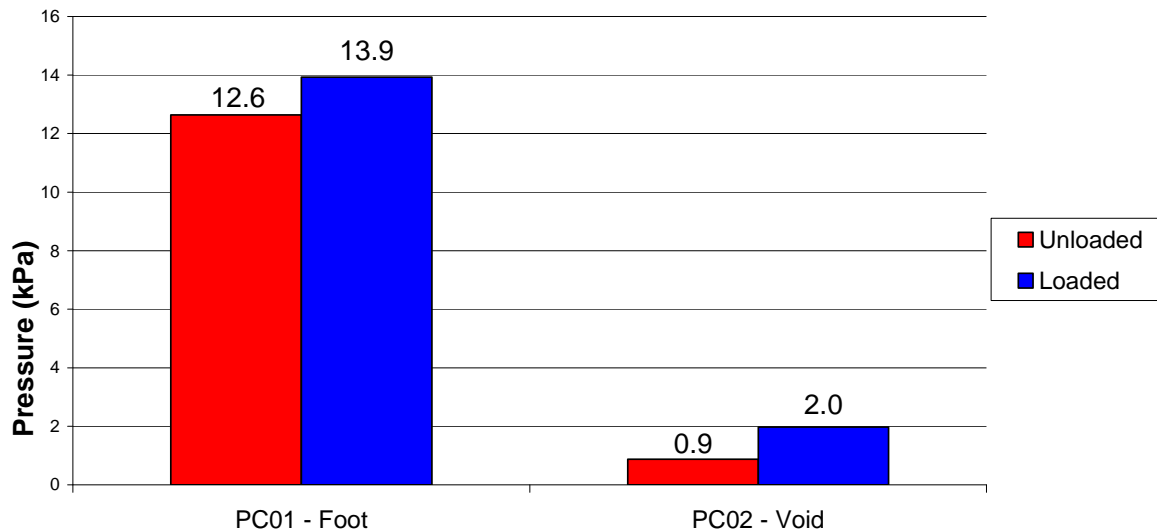


Figure 4-8: Static pressure cell testing results

These results are significant. The static testing shows that the Cupolex® system behaves as an interconnected system that is able to efficiently distribute loads over a wide area. The applied loads do not appear to become concentrated near the point of application. Structural engineering theories propose that any load applied within a particular column's tributary area is transferred to that supporting element. The "feet" of the Cupolex® units were assumed to carry loads similar to columns, which should then result in load concentrations. However, this does not appear to be the case, based on the sensor readings obtained. The observed behaviour is encouraging, as it suggests that the load transfer to individual Cupolex® "feet" is not occurring.

4.1.3 Moisture Probes

Although the concrete slab is the primary load carrying component of a rigid pavement system, the underlying layers also play an important role in providing support. The unbound granular layers and the subgrade material are moisture sensitive. High moisture contents result in a loss of strength, which can have many consequences, including settlement and pumping.

4.1.3.1 Data collection issues

Initially, some problems were encountered with the moisture probes, due to a wiring issue. Soil moisture data was collected intermittently until the problem was resolved in late September 2012 and full, reliable connectivity was achieved.

4.1.3.2 Rain Events and Soil Moisture Content

Figure 4-9 plots the volumetric water content of the granular layer of each of the four moisture probes on a timescale. Daily precipitation totals, obtained from Environment Canada's meteorological station at Lester B. Pearson International Airport in Toronto, Ontario (approximately 30 kilometres away), are also plotted on the same timescale. The measured water contents range from 9% to 58%, averaging 25%. In total, 57 precipitation events were recorded during the time interval presented. An average of 5 mm of precipitation fell during each rain event, however, one day with 30 mm of rainfall was recorded in January 2013. It is observed that the similar trends are observed at each moisture probe location.

As noted earlier, the moisture probes buried 150 mm below grade typically measure higher water contents by a few percent than the sensors buried 300 mm below grade, with few exceptions. Very similar trends in water content are observed at both moisture probe locations. The curves for the shallow sensor and the deep sensor have almost identical slopes

at every time location. However, with a few individual exceptions, the moisture content recorded by the deep sensor is never higher than the moisture content recorded by the shallow sensor. This observation indicates that the granular is well-draining. Any water that enters the pavement structure flows vertically through the base layer before the next set of hourly measurements is taken. Good drainage is key for good pavement performance and ensuring good support for the concrete slab.

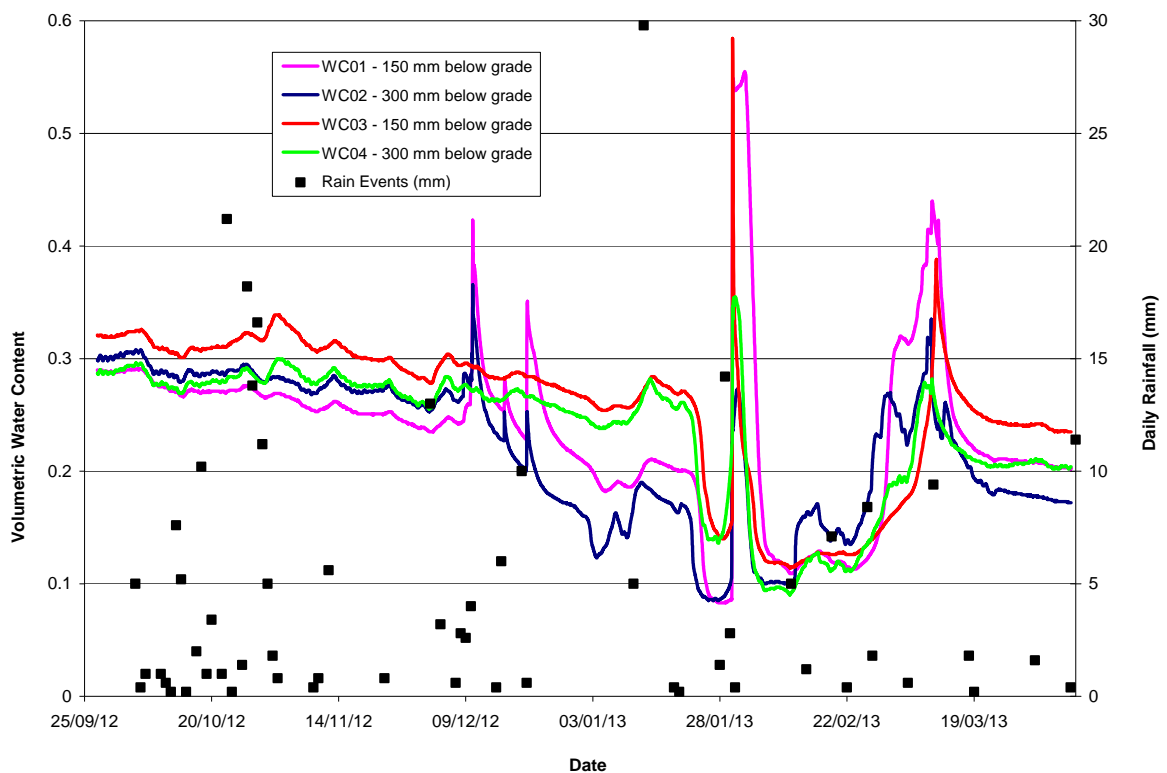


Figure 4-9: Granular Moisture Content and Rain Events

An effort was made to identify the impacts, if any, of the granular moisture content on the parameters measured by the other two types of sensors: pressure and strain.

Some correlation between water content and base pressure is observed, which can be seen in Figure 4-10. An increase in moisture content appears to result in an increase in the pressure recorded under the foot. The infiltration of water into the pavement structure appears to result in a slight loss of strength in the base layer, which manifests itself as a greater recorded pressure. Similar spikes are also observed in the pressure cell in the void, although much less pronounced. A slight lag between the spike in pressure and the increase in moisture content would be expected. However, the pressure increase, unexpectedly, occurs before the moisture content increase.

In contrast, the comparison of granular moisture content and concrete strain did not reveal any existing relationship. The strains induced in the concrete do not appear to be significantly correlated to the moisture content of the base layer.

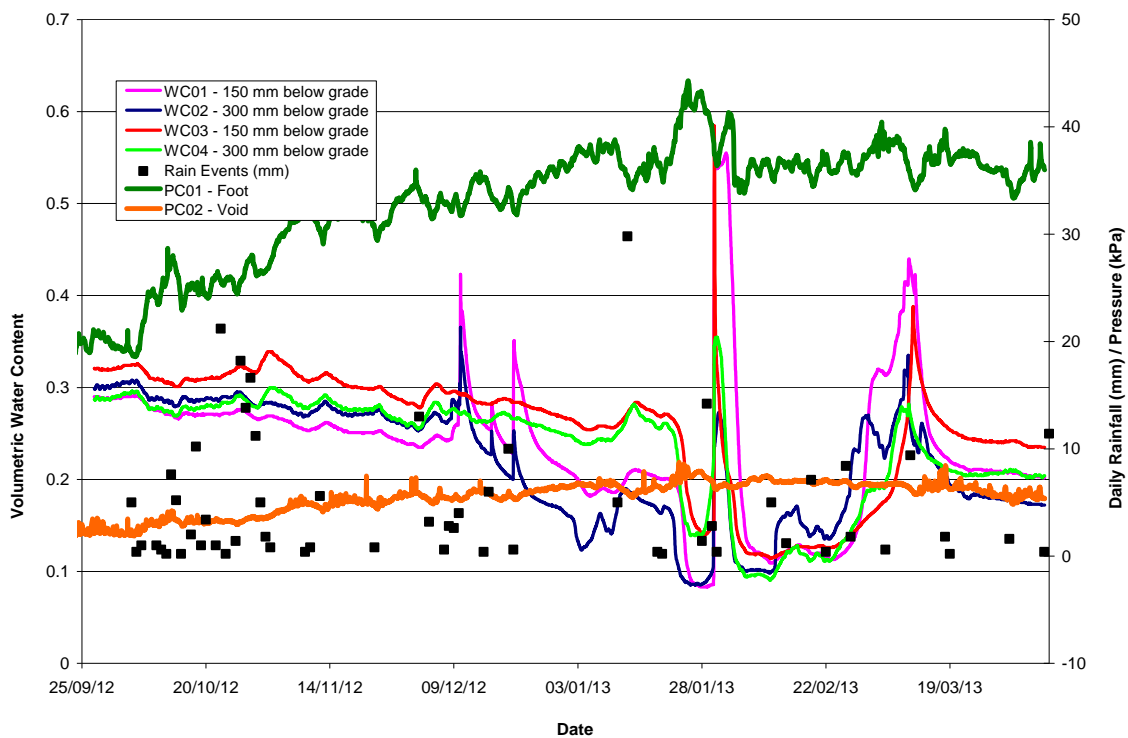


Figure 4-10: Comparison of Granular Moisture Content and Base Pressure Readings

4.2 Deflection Testing

As part of this research experiment, Falling Weight Deflectometer (FWD) testing has been completed on a number of occasions on the Milton trial section since construction by Applied Research Associates, Inc.

The FWD is a commonly used, industry-accepted piece of non-destructive pavement evaluation equipment that uses impulse loading to simulate moving wheel loads, as seen in Figure 4-11. A falling mass dropped onto a load plate to simulate the in-service truck loads applied to the pavement. The pavement response to the applied loads, i.e. the pavement deflection, is recorded by a number of geophones at various radii from the load plate. The equipment used was a Dynatest 8000 Series Falling Weight Deflectometer with the geophone configuration shown in Table 4-2.



Figure 4-11: Falling Weight Deflectometer testing in progress

Table 4-2: Geophone Sensor Configuration (mm)

D1	D2	D3	D4	D5	D6	D7	D8	D9
0	300	450	600	900	1200	1500	1800	-300

The testing program for each visit consisted of mid-slab testing and load transfer testing at the joints. Owing to the short length of the trial pavement, each slab and each joint was tested in both lanes.

At each test location, four loads were applied. A seating load was applied to ensure firm contact between the FWD's load plate and the pavement surface. The subsequent test program consisted of three drops, each applying a different load: one at 40 kN, one at 50 kN and one at 60 kN. For the load transfer testing at joints, the test program was first completed on the "approach" side of each joint. The FWD trailer was then advanced and the test program was repeated on the "leave" side.

Following the completion of each deflection testing visit, the data was reviewed and processed. The FWD results were normalized to a standard load of 40 kN and a standard temperature of 21°C (ASTHO 1993). The normalized data was used to backcalculate certain valuable pavement parameters, load transfer efficiency (LTE) at joints.

4.2.1 Joint Load Transfer

Adequate load transfer across transverse joints is important for ensuring good long-term pavement performance and avoiding issues such as faulting. Most concrete pavements with heavy traffic employ steel dowel bars to mechanically transfer loads from one slab to the next. Where dowels are not used, the load transfer takes place through aggregate interlock.

Undowelled concrete pavements are typically only used in low-volume scenarios, e.g. residential streets (Delatte 2008).

As part of the experimental plan for this research, as noted earlier, dowel bars were not placed in the Milton test sections. The inclusion of dowel bars with the Cupolex® formwork posed additional construction challenge and the need for their inclusion was not certain. Furthermore, a uniform transverse joint spacing of 4 m was used to simplify construction. However, the joint locations were pre-determined relative to the top of the dome or the leg of the Cupolex® prior to the placement of concrete. Of the 22 transverse joints that were sawcut, 13 were located above the dome and 9 above the leg. (For this purpose, joints located within 150 mm of either side of the centreline of the leg were determined to be in the “leg” category. The remaining joints were classified in “dome” category.) The joint categorization is outlined in Table 4-3.

Table 4-3: Transverse Joint Location Descriptions

Joint Station	Relative Location
10+003	Leg
10+005	Dome
10+010	Dome
10+015	Dome
10+020	Dome
10+024	Leg
10+029	Leg
10+034	Leg
10+039	Dome
10+043	Dome
10+048	Dome

Joint Station	Relative Location
10+052	Dome
10+056	Leg
10+061	Leg
10+065	Leg
10+069	Dome
10+074	Dome
10+078	Dome
10+083	Dome
10+087	Dome
10+091	Leg
10+096	Leg

Load Transfer Efficiency, as defined by the AASHTO Guide for Design of Pavement Structures, is calculated as the ratio of the deflection in unloaded slab to deflection in the loaded slab, multiplied by 100 (AASHTO 1993). A joint with 100% load transfer represents perfect load transfer, where identical deflections are measured on both sides. A value of 0 percent corresponds to no load transfer, i.e. the unloaded side of the joint did not deflect at all when a load was applied. Generally, load transfer values of 70 percent or above are considered good.

The load transfer results from the latest round of deflection testing, performed in June 2013, are presented in Figure 4-12. Excellent load transfer values were observed, ranging from 82 to 100 percent. The average value across both lanes was 95 percent.

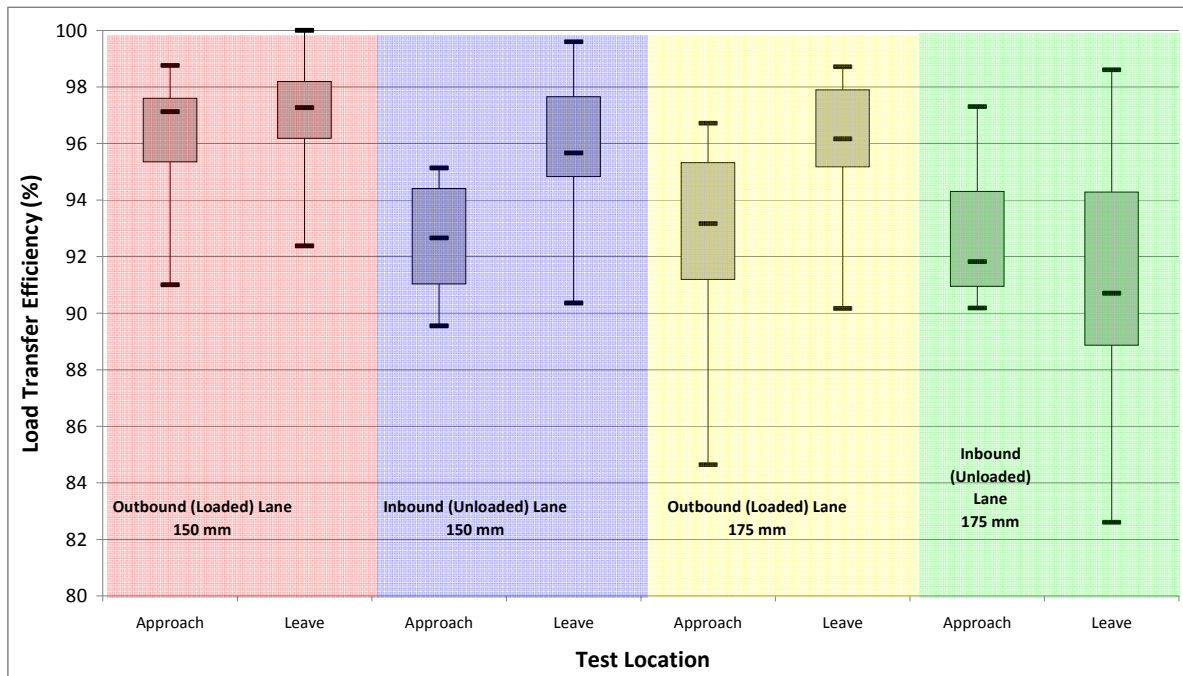


Figure 4-12: Load Transfer Efficiency Results – June 2013

These results show that the Cupolex® system is capable of carrying heavy traffic loads while providing the necessary load transfer without the need for dowels. Aggregate interlock alone appears to be sufficient in ensuring that traffic loads are carried across the sawcut joints.

Joint location also does not appear to affect load transfer efficiency measurements significantly. Equally good load transfer is observed at joints above the dome and above the “foot”, despite an appreciable difference in the amount of concrete and shear area between these two locations.

The load transfer results obtained to date are very positive. The ability to omit dowel bars simplifies construction and reduces cost. However, load transfer efficiency should be continued to be monitored into the future. Heavy traffic may have a degradational effect on the joints, if it causes, for example, shearing and cracking of aggregate particles. The need for dowel bars may become evident. However, their inclusion poses additional construction challenges that require further investigation.

4.2.2 Midslab Deflection Testing

The maximum normalized deflection (ND1), measured at the centre of the slab, is a good indicator of overall pavement strength. The deflection at this location is a function of the pavement layer stiffness, as well as the support capacity of the subgrade.

Notable differences were observed between the inbound lane (carrying unloaded trucks) and the outbound lane (carrying loaded trucks), as shown in Figure 4-13 . The midslab results from the unloaded lane were much more consistent. Average deflection in the loaded lane is 95 microns, with a standard deviation of 49 microns, whereas the average deflection in the unloaded lane is 58 microns, with a standard deviation of 18 microns. The

slabs with high deflections are clustered in any particular area. The slabs measuring high deflections are interspersed with slabs that experience low deflections. A slightly greater number of slabs with high deflections are located in the 150 mm of concrete section.

Despite the greater average deflection in the loaded lane, the deflections at certain slabs are directly comparable to the deflections in the unloaded lane. It is possible that additional loads carried by the loaded trucks can cause additional stress on the subgrade, which is degrading the slab's carrying capacity. Nevertheless, the measured deflections in either lane are not large enough to cause concern.

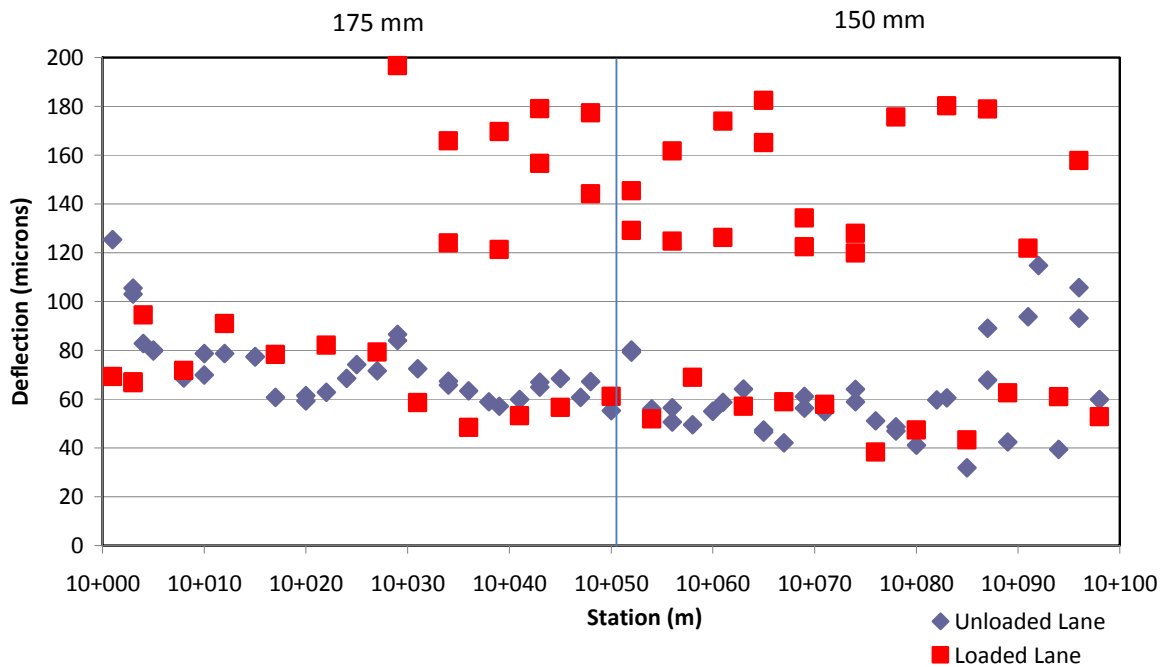


Figure 4-13: Midslab deflections – June 2013

4.2.3 Structural Equivalency Determination

The ability to compare the structural capacity of Cupolex® pavements to conventional concrete pavements is critical for optimizing pavement designs and calculating cost savings.

The midslab testing results were compared to FWD results from traditional Jointed Plain Concrete Pavement (JPCP) sections located in Southern Ontario. FWD data was obtained from two conventional JPCP sections in very good condition: 210 mm thick and 220 mm thick, respectively. The conventional concrete pavements were tested during similar weather conditions as the Cupolex® sections. This data, also presented in Figure 4-14, was compared to the midslab data from the unloaded Cupolex® pavement lane. The midslab data from the loaded lane was omitted from this exercise, due to its significant variability.

Using linear extrapolation methods, the Cupolex® pavements in place in Milton were found to be equivalent to conventional jointed plain concrete pavements 230-280 mm thick, averaging 250 mm. This finding indicates that Cupolex® can achieve significant cost savings in concrete pavement construction.

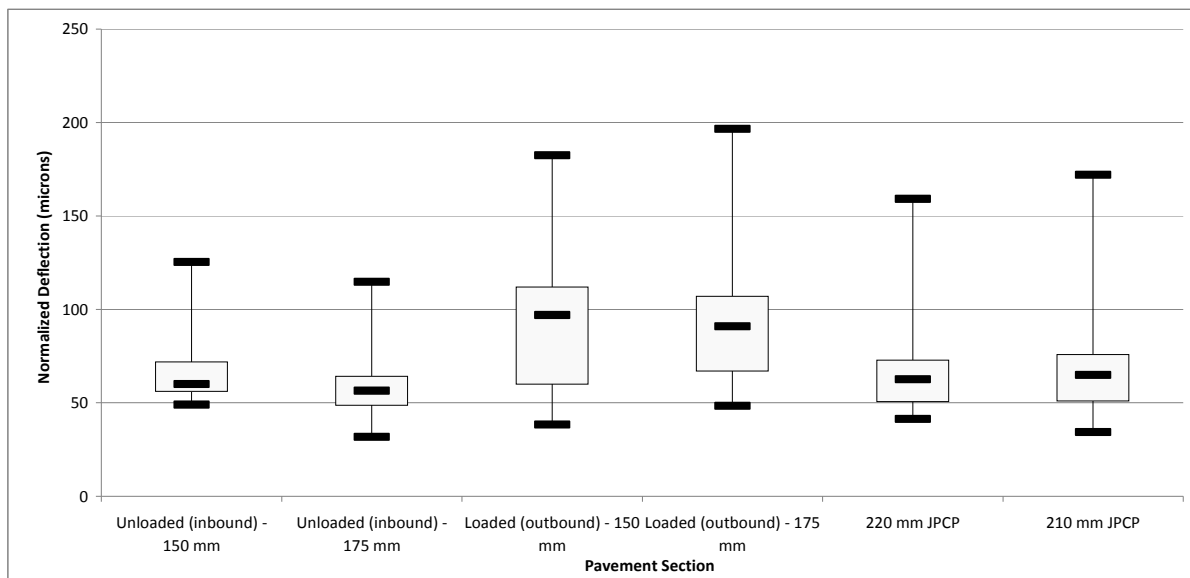


Figure 4-14: Comparison of midslab deflections between Cupolex® and conventional concrete pavements

4.3 Traffic Analysis

Dufferin Aggregates' Milton Quarry is an important source of high quality aggregates for the Greater Toronto Area and surrounding regions. The supplied aggregates are in high demand, and consequently the quarry sees high volumes of truck traffic year round. The quarry sees an annual average daily traffic of 450 trucks per day throughout the year, rising to a peak of 750 trucks per day throughout the primary construction season (May to November). A wide range of different dump trucks travel to and from the quarry, including standard tandem and tridem end dump trucks, semi-trailer end dump trucks, semi-trailer live bottom dump trucks and standard end dump trucks with trailers.

All trucks entering and leaving the quarry are weighed at the quarry scalehouse. Truck weight data has been provided regularly by Dufferin Aggregates. This data has been used to calculate the amount of Equivalent Single Axle Loads (ESALs) applied to the pavements. An ESAL, as defined by the American Association of State Highway and Transportation Officials (AASHTO), is equivalent to 80 kN (18 kips) (AASHTO 1993). The AASHTO pavement design procedure uses the ESAL concept to convert mixed traffic of various wheel loads and axle configurations to a standard load for easy comparison and analysis. ESALs are commonly used as a measure of the accumulated damage for a pavement.

By the end of May 2013, over 1.34 million ESALs have been applied to the Cupolex® test sections. On an annual basis, this level of traffic is equivalent to a typical major arterial road or a minor freeway. However, many minor collector and local roads are designed to carry even fewer ESALs over their 20-30 year design life.

The Cupolex® pavement test section is located directly next to the tarping station at the Milton quarry. On the way in to pick up aggregates, all vehicles travel over the Cupolex® section. However, on the way out, the drivers of fully loaded trucks have the option of driving over the Cupolex® test road or stopping at the tarping station, bypassing the experimental section. Most trucks have modern automatic tarping systems and drivers take the time to check their loads while being weighed, allowing them to avoid stopping at the tarping station and ensuring that fully loaded traffic consistently traverses the experimental section. The percentage of vehicles diverting via the tarping station is approximately 20%. The calculated ESAL estimates have been adjusted to reflect this fact.

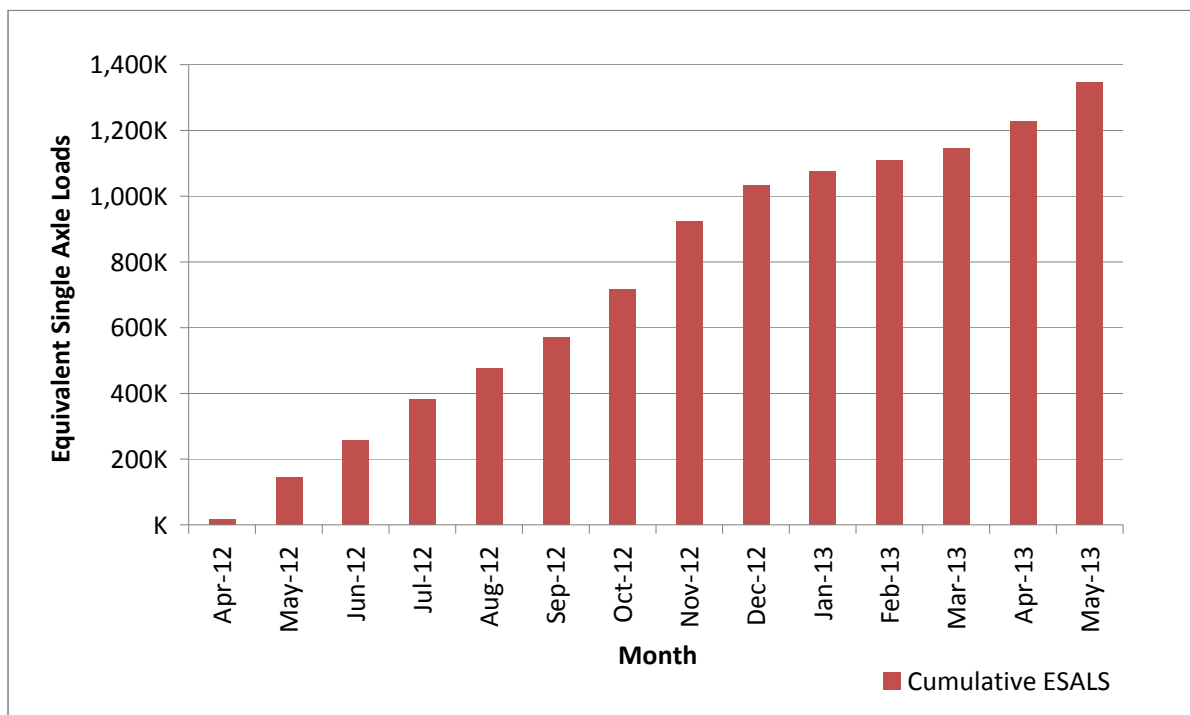


Figure 4-15: Milton trial cumulative ESAL progression

4.4 Visual Condition Surveys

The Milton test section has been regularly inspected visually for distresses. As of July 2013, the trial pavement sections remain in very good condition. Some minor localized surface distresses have been observed. A few examples are highlighted in Figure 4-17 and Figure 4-17. One slight transverse crack developed during the joint sawcutting operation and one slight corner break has formed. Some minor joint ravelling and edge spalling are also noted. The most extensive distress observed is the surface wear and abrasion of the tining in the wheelpaths. The macrotexture has worn down significantly in the first year of service. This observation is made is both wheelpaths of both lanes.

However, no structural defects are noted. The FWD results also confirm the good structural condition of the pavement.



a)

b)

Figure 4-16: Surface distress examples 1

a) Slight transverse crack, occurred during joint sawing

b) Wear and abrasion of pavement surface

achieved by eliminating the need for any steel reinforcement in the Cupolex® pavement. In the end, a net cost savings results from the use of Cupolex®, resulting in cheaper concrete pavement construction, in comparison to conventional concrete pavements, such as JPCP.

According to a research study performed for the Ready Mix Concrete Association of Ontario, a 230 mm jointed plain concrete slab over a 200 mm Granular A base is a suitable 25 year pavement design for suitable for major arterial roadways with an annual average daily truck traffic (AADTT) of 10 000 (ARA 2011). The Cupolex® slab, having slightly more capacity, should be able to carry additional truck on a daily basis or provide additional life beyond 25 years. Based on an MEPDG analysis, the equivalent flexible pavement would consist of 180 mm of hot mix asphalt, 150 mm of granular base and 600 mm of granular subbase (ARA 2011). Both concrete alternatives (Cupolex® and conventional JPCP) have significantly reduced pavement structure thicknesses, which conserves valuable aggregate and provides economic savings.

The cost reductions achieved through the use of Cupolex® make the construction of concrete pavements much more attractive. Judging by the percentage of flexible pavements in the Canadian and US highway networks, asphalt has been the much more popular material choice. However, the cost savings associated with Cupolex® make concrete pavements much more competitive from both economic and environmental points of view. The additional benefits of concrete pavements such as longer design lives and reduced maintenance and rehabilitation requirements may be able to entice more transportation agencies to build with concrete.

Chapter 5

Conclusion and Recommendations

5.1 Conclusions

The results obtained to date suggest that Cupolex® has very good potential as a concrete pavement technology. The trial Cupolex® pavement section in Milton has demonstrated very good performance since it was opened to traffic in April 2012. The pavement surface is in very good condition, with the exception of some surface wear and abrasion and a few individual minor distresses. The Cupolex® pavement appears to be in excellent structural condition visually. This observation has been confirmed through non-destructive deflection testing.

Over 1.34 million cumulative ESALs have been applied to the pavement to date. This trial project has successfully demonstrated that Cupolex® pavements can successfully carry heavy traffic close to the legal limit in the short term. The findings also suggest that Cupolex® pavements have the ability to carry the 20-30 year design traffic for low-volume roads, such as local streets. The load carrying capacity of Cupolex® pavements does not appear to be a concern. However, the susceptibility to loss of load carrying capacity for Cupolex® pavements has not been proven yet, with only one year of service. Continued monitoring will help develop a better understanding of the long-term performance trends of pavements using Cupolex®.

The technical viability of Cupolex® in pavement application translates to additional economic, environmental and social benefits. The results of this research indicate the trial

Cupolex® pavements constructed in Milton are approximately equivalent to a 250 mm thick conventional jointed plain concrete pavement in terms of pavement strength using FWD testing data. The equivalency results in a significant reduction in concrete requirements (approximately 20%). A reduction in the volume of concrete needed results in a significant materials and cost savings. The reduction in construction costs allows the transportation agency's limited funds to go further. The material savings preserves limited supplies of high quality virgin aggregates and reduces the amount of cement needed, meeting sustainability goals.

The construction experiences of the Milton trial section has shown that the Cupolex® product can be integrated into concrete pavement construction without much difficulty. Cupolex® is compatible with conventional slipform paving equipment, allowing for fast and easy paving. The construction process is slightly complicated, due to the need for a conveyor or pump truck to place the concrete, since regular dump trucks cannot simply dump their concrete loads in front of the paver. A small additional cost is associated with the need for this specialized equipment. The need to place concrete from the roadway shoulder also requires that sufficient room be available for these vehicles.

One minor issue was encountered with the incorrect orientation of the Cupolex® units during layout. The proper orientation and layout of the individual units is critical to ensure that they interconnect securely. Otherwise, the weight of the fresh concrete will cause the units to pop apart and allow concrete to flow under the Cupolex® units, where it is wasted. However, these issues were quickly identified and easily resolved after which paving continued without difficulty. Thorough training of the installers will ensure this problem does

not repeat itself. Discussions with the manufacturer have indicated they will attempt to simplify installation and construction with the next generation of Cupolex® units. The upcoming Cupolex® units will be much larger, allowing for quicker layout, and will securely “click” together to ensure that they separate or be blown away.

Thermal loads have been determined to have the greatest influence on measured concrete strains. The strain gauge data shows that the concrete strains generally remain compressive at the thinnest location, the top of the dome. This observation is very encouraging, as it suggests that the Cupolex® slab has a low potential for cracking. Furthermore, the low overall variability in strains reduces the potential for fatigue failures.

The Falling Weight Deflectometer testing has indicated that excellent load transfer can be expected without needing the use of dowel bars at transverse joints. Furthermore, the joint location with respect to the dome or the “foot” does not have an influence on load transfer either. Consequently, painstaking effort does not need to be taken to ensure that the joints lie in any particular location to get good load transfer values.

In Canada, where concrete pavements (rigid and composite) make up only 3.1% of federal, provincial and territorial pavement and 13% of municipal pavements (TAC 2012), there is much room for greater use of concrete pavement. The technical, environmental and economic benefits of Cupolex® can encourage competition with the asphalt industry to encourage further use of concrete.

Life Cycle Cost Analyses (LCCA) are typically performed for all pavement design projects. Concrete and asphalt pavement alternatives are typically compared. Although

concrete pavements have longer design lives and minimal maintenance requirements, they often have greater initial costs than asphalt pavements, which require intermittent rehabilitation activities, but can be constructed at lesser expense. Although the life cycle cost can influence pavement type selection, this decision is more often based on the initial construction costs. The ability of Cupolex® to reduce the initial construction costs of concrete pavements can make them much more attractive economically to transportation agencies.

5.2 Recommendations

The trial pavement constructed as part of this study has only been in service for one year. As a result, the scope of this thesis is limited to the design, construction and early age performance of a concrete pavement trial constructed using the Cupolex® technology. The performance data obtained to date only permits a preliminary evaluation of this technology. Continued monitoring and evaluation of the Milton test section are required to better understand the long-term performance of Cupolex® in pavement applications. Additional sensor data collection and analysis, visual inspection, deflection testing and traffic data collection are required to perform a more thorough evaluation. This additional information will help form stronger conclusions about the feasibility of using Cupolex®.

Finite element modelling should be performed to help quantify the effects of both dynamic vehicular loads and environmental loads, particularly thermal gradients, on the Cupolex® slab. Modelling will also assist help separate the thermal load induced effects from the vehicular loading induced effects and can possibly help explain the observed load

transfer mechanism from slab to base. The modelling results will help validate the measured pavement responses and predict future performance. These results can be utilized to optimize slab thickness in order to maximize cost and materials savings.

Numerous additional aspects of this technology have not yet been investigated and/or evaluated. For one, its maintenance and rehabilitation needs have not been determined. These needs are expected to be very similar to conventional concrete pavements. However, certain treatments, such as full-depth repairs or slab replacement, will likely need to be modified to account for the increased total slab thickness. Best practices will need to be developed to minimize cost and maximize performance. The end-of-life stage of Cupolex® concrete pavements will also need to be studied. How the inclusion of the plastic formwork impacts pavement decommissioning, reconstruction and/or recycling will need to be determined. If any hindrances are found, they will need to be addressed.

Furthermore, the use of Cupolex® should be investigated in alternative pavement applications. As an example, Cupolex® could be integrated into pervious concrete pavements. The void under the slab could serve an integrated reservoir for stormwater. This beneficial property can help reduce the need for thick clear reservoirs by incorporating the retention reservoir into the slab.

Finally, a complete detailed lifecycle cost analysis must be completed in order to better evaluate other long-term benefits and determine the true potential savings, such as reduction in greenhouse gases and conservation of construction materials. Only with information can the full potential of this technology be utilized.

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