Centre for Pavement and Transportation Technology Interlocking Concrete Crosswalk Research Project

Final Report

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Executive Summary

This final report provides performance data to date, evaluates the crosswalks in terms of their Pavement Condition Index (PCI), deflection including Portable Falling weight Deflectometer (PFWD) and Falling Weight Deflectometer (FWD) of the eight crosswalks is presented based on current performance.

The crosswalk research project involves the construction of a total of eight crosswalks with four different base and bedding materials at both the Centre for Pavement and Transportation Technology (CPATT) Test Track located in the Regional Municipality of Waterloo Waste Management Facility and at the University of Waterloo (UW) Ring Road. However it is notable that the Sand Set Asphalt Base Steel header (SSABSH) section required repair after 2,000,000 ESALs and the Sand Set Granular base Aluminum Header (SSGBAH) section is a newly placed test section. This section was placed in July, 2009. The first site consists of four crosswalks which were retrofitted into the existing asphalt pavement. The second site has four crosswalk sections that were constructed during the reconstruction of UW Ring Road.

The objective of the research project is to quantify the structural performance of four Interlocking Concrete Pavement (ICP) Crosswalk Designs under two loading scenarios. This research involves the validation of current industry crosswalk design recommendations, establishing threshold values for type and/or number of axle loads (ESAL's) for various crosswalk assemblies, recommending new designs (or modifications to existing designs) as needed based upon the load/traffic/environment/ failure modes from the study. The initial structural performance is carried out on the basis of measured value of strain and stress accumulation at different critical locations in the pavements.

In addition, the functional performance is evaluated in accordance with the ICPI distress guide. The type and severity of the projects are determined by visual inspection of each crosswalk section surface condition and Pavement Condition Index (PCI) is assigned to each section. ICPI spreadsheets are used to calculate PCI.

To date, the sections at the Test Track are showing the following: the maximum tensile stress is found in the subbase layer of the Sand Set Concrete Base Concrete Header (SSCBCH) crosswalk
while the Bituminous Set Concrete Base Concrete Header (BSCBCH) crosswalk has accumulated maximum tensile strain in the base. Compressive strain is observed in asphalt base layer and the tensile strain is found in the concrete bases. The total ESAL’s to date at this site is approximately 3,750,000 over the original three sections while the new section SSGBAH has only experienced 875,000 ESALs since its placement in July 2009.

To date, at the Ring Road the maximum strain of all four sections is observed in the Bituminous Set Concrete Base Concrete Header (BSCBCH). The tensile strain is observed in Sand Set Asphalt Base Aluminum Header (SSABAH) when the temperature was above 0⁰ Celsius. The total ESAL’s to date at this location is approximately 290,000.

At the Test Track, maximum deflection is observed in the Sand Set Granular Base Aluminum Header (SSGBAH) followed next by the Sand Set Concrete Base Concrete Header (SSCBCCH) while the Bituminous Set Concrete Base Concrete Header (BSCBCH) shows the minimum deflection despite the fact; heavy construction equipment was running over this section throughout the summer months. At the Ring Road, maximum deflection is observed in Sand set Granular Base Aluminum Header (SSGBAH) followed by the Sand Set Asphalt Base Aluminum Header (SSABAH) while Bituminous Set Concrete Base Concrete Header (BSCBCH) shows the least deflection.

Maximum deformations, rutting and heaving are observed in the Sand Set Concrete Base Concrete Header (SSCBCCH) crosswalk section at the Ring Road location and Test Track location. Even though the SSABAH was repaired in July, the rating in November is only good, according to PCI ratings in accordance with the new ICPI guidelines. Unfortunately, it appears to be showing similar signs of failure. The BSCBCH is in excellent condition at the Test Track whereas it is in very good condition in Ring Road. The asphalt base crosswalk (SSABAH) section at the Test Track and concrete base sand set (SSCBCCH) section on Ring Road are rated good. The SSGBCH and the SSABAH sections at the Ring Road are rated very good and good respectively.
1. Introduction and Objective

The Interlocking Concrete Pavement Institute (ICPI) and Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo, crosswalk research project involved the construction of eight crosswalks with different base and bedding materials at the CPATT Test Track located in the Regional Municipality of Waterloo Waste Management Facility and at UW Ring Road. The objective of the research project is to quantify the structural performance of four Interlocking Concrete Pavement (ICP) Crosswalk Designs under two loading scenarios. The CPATT Test Track encounters heavy truck loading primarily loaded garbage trucks with maximum load up to 56,000 kg while the UW Ring Road traffic is similar to a typical urban road with approximately 10% truck and 5% bus traffic. The research study is directed at defining the performance mechanics for designs with various bases and setting beds. The research involves validation of current industry crosswalk design recommendations, establishing threshold values for type and/or number of axle loads (ESAL's) for various crosswalk assemblies, recommending new designs (or modifications to existing designs) as needed based upon the load/traffic/environment/ failure modes from the study. In short the research provides design professionals with guidance on design protocols and performance of ICP crosswalks for various loading conditions.
2. Crosswalk Construction

2.1. CPATT TEST TRACK

2.1.1. Project Location

The first series of crosswalks is situated at the Centre for Pavement and Transportation Technology (CPATT) Test Track in the south east corner of the Regional Municipalities of Waterloo Waste Management Facility, located at 925 Erb Street West in the City of Waterloo. The University of Waterloo, CPATT Test Track is as shown in Figure 1.

There are four crosswalks with different bases and bedding materials located at the first section of Test Track. The center line of the first crosswalk is located at 0+060, the second is at 0+070, the third is at 0+080 and the fourth is at 0+090 of the Test Track as shown in Figure 2.

![Figure 1 CPATT Test Track Satellite View](image)

Four 8.4m long and 3m wide sections were cut on existing HL3 Asphalt pavement to build the research project. The construction of test sites was started on June 18, 2007 and completed on
June 26, 2007 for three crosswalks and the fourth crosswalk at the CPATT Test Track was constructed on July 16, 2009 and completed on July 24, 2009. The installation of the interlocking concrete pavers was installed manually by a crew of two to three members. Several sensors are installed to measure the response of the pavement in various locations during construction.

![Figure 2 University of Waterloo, CPATT Test Track Layout](image)

### 2.1.2. Preconstruction Phase

The preconstruction phase includes site selection, layout, sensors design and preliminary sensors checking. The approximate location of the research project was finalised during the preconstruction survey by Susan Tighe, University of Waterloo, Rob Burak, ICPI, Ross Yantzi, Ross Yantzi Pavestone Plus Limited and Sudip Adhikari, University of Waterloo graduate student. The centreline of all three crosswalks and approximate location of the data logger were marked in this stage.

Four different type of sensors namely vibrating wire strain gauges, earth pressure cells, temperature profiles and moisture probes were designed to determine vertical strain in asphalt and concrete bases, vertical earth pressure in base and subbase and temperature and moisture variation at different elevation in subbase.

A preliminary check of the sensors was made by connecting to the readout box and observing the displayed readout prior to the installation.
2.1.3. Pavement Section

The proposed project is retrofitted on HL3 asphalt pavement. Now HL3 is a standard asphalt mix design for cities and municipalities. It is commonly used on local collector and arterial roads. The structural components of the existing pavement are shown in Figure 3.

A typical interlocking concrete paver crosswalk consists of concrete pavers placed on top of a layer of bedding sand over a base and sub-base layers. Four different designs selected for this study are as follows and are shown in Figure 4, 5, 6, 7 and 8:

a) Sand Set Granular Base Aluminum Header (SSGBAH)
b) Sand Set Concrete Base Concrete Header (SSCBCH)
c) Sand Set Asphalt Base Steel Header (SSABSH)
d) Bituminous Set Concrete Base Concrete Header (BSCBCH)
Figure 4 Layout of Crosswalk Test Sections at CPATT Test Track
The first crosswalk design is composed of 80mm interlocking concrete paver on the top of 25mm bedding sand layer, 200 mm thick granular base is built on the top of 350mm granular subbase as shown in Figure 5 and is called Sand Set Granular Base Aluminum Header (SSGBAH). The L-shaped aluminum angle edge restraints are designed on top of the asphalt base on the both sides parallel to the center line of the crosswalk section.

The second crosswalk design is composed of 80mm interlocking concrete paver on the top of 25mm bedding sand layer, 200mm thick concrete base is built on the top of 400mm granular subbase as shown in Figure 6 and is called Sand Set Concrete Base Concrete Header (SSCBCH). The 150mm wide concrete header is placed and continues as a restraint on the transverse sides. Note that in a typical construction there would be a curb edge on each side but this is not the case at the Test Track so it was necessary to form a concrete restraint on the transverse ends of all of the Test Track sections.

The third crosswalk design is comprised of 80mm interlocking concrete paver on the top of 25mm bedding sand layer. The 100mm thick asphalt base is built on the top of 50mm granular A and 450mm granular B subbase as shown in Figure 7 and is called Sand Set Asphalt Base Steel Header (SSABSH). Two concrete curb restraints along the edge of the road are parallel to the road centerline while the L-shaped iron angle edge restraint with dimension of 95mm x 95mm x 6mm are designed on top of the asphalt base on the both sides parallel to the center line of the crosswalk section.

The fourth crosswalk design is composed of 80mm interlocking concrete paver on the top of 25mm bituminous sand layer. Concrete base with 200mm thickness is built on the top of 400mm granular subbase as shown in Figure 8 and is called Bituminous Set Concrete Base Concrete Header (BSCBCH). The 150mm wide concrete header is placed and continues as a restraint on the transverse sides.
Figure 5 Sand Set Granular Base Aluminum Header (SSGBAH)

CROSSWALK ON COMPACTED AGGREGATE
BASE ICPI/UW (July 2009)

NOTES:
1. BASE THICKNESS VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE CONDITIONS.
2. CONCRETE CURBS DO NOT DEFLECT TO THE SAME DEPTH AS Pavers OR EXISTING ASPHALT. THIS DETAIL IS NOT RECOMMENDED FOR OTHER THAN LOW VOLUME RESIDENTIAL STREETS.
3. THICKENING ASPHALT PAVEMENT ADJACENT TO CONCRETE CURB IS RECOMMENDED.
Figure 6 Sand Set Concrete Base Crosswalk Section (SSCBCH)

- **80mm Concrete Pavers**
- **25mm Bedding Sand**
- **200mm Concrete Base**
- **400mm Subbase**

**NOTES:**
1. **EXISTING ASPHALT PAVEMENT**
2. **SAW-CUT PAVEMENT**
   (RETROFIT ONLY - NOT NEW CONSTRUCTION)
3. **SEAL JOINT**
4. **CONCRETE CURB MIN. 6" (150 MM) WIDE x 12" (300 MM) DEEP**
5. **CONCRETE PAVER**
6. **3 1/8" (80 MM) MIN. THICKNESS**
7. **NON-WOVEN GEOTEXTILE, TURN UP AT CURBS**
8. **CONCRETE BASE**
9. **COMPACTED SOIL SUBGRADE**
10. **WIRE WELDED FABRIC OR REBAR AS REQUIRED**
11. **AGGREGATE SUB-BASE AS REQUIRED**
12. **3" (75 MM) DIA. DRAIN HOLE LOCATED AT LOWEST ELEVATIONS, FILLED WITH PEA GRAVEL**
13. **#5 (16 MM) REBARS PLACED AS SHOWN**
   (TYPICAL AT CURBS)
14. **1/4" (6 MM) MAX. RADIUS ON ALL TOOLED CONC. EDGES (TYP.)**

**NOTES:**
1. BASE THICKNESS AND REINFORCING VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE CONDITIONS.
2. CONCRETE BASE MINIMUM 2% SLOPE FROM CENTERLINE TO CURB.
3. DO NOT PROVIDE DRAIN HOLES TO SUBGRADE WHEN WATER TABLE IS LESS THAN 2 FT. (0.6 M) FROM TOP OF SOIL SUBGRADE. PROVIDE DRAIN HOLES TO CATCH BASINS.
4. DRAIN HOLES SPACED AT 2 FT. (600 MM).
5. CONCRETE CURB AND BASE TO BE POURED MONOLITHICALLY.
Figure 7  Sand Set Asphalt Base Crosswalk Section (SSABSH)

NOTES:
1. BASE THICKNESS VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE. COLDER CLIMATES AND WEAK SOIL MAY REQUIRE THICKER BASES.
2. DO NOT PROVIDE DRAIN HOLES TO SUBGRADE WHEN WATER TABLE IS LESS THAN 2 FT. (0.6 M) FROM TOP OF SOIL SUBGRADE. PROVIDE DRAIN HOLES TO CATCH BASINS.
3. STEEL OR ALUMINUM ANGLE TO BE MECHANICALLY FASTENED AT CUT ASPHALT PAVEMENT EDGE AT MAXIMUM SPACING OF 12" (300 MM).
4. DRAIN HOLES SPACED AT 2 FT. (600 MM).
5. AGGREGATE BASE MINIMUM 2% SLOPE FROM CENTER LINE TO ASPHALT PAVEMENT EDGE.
80mm Concrete Pavers
25mm Bituminous Bedding Sand
200mm Concrete Base
400mm Subbase

NOTES:
1. DO NOT COVER WEEP HOLES WITH SAND-ASPHALT SETTING BED.
2. 2 3/8 IN. (60 MM) THICK PAVERS MAY BE USED FOR PEDESTRIAN APPLICATIONS.
3. DRAIN HOLES SPACED AT 2 FT. (600 MM).
4. CONCRETE CURB AND BASE TO BE POURED MONOLITHICALLY.

Figure 8 Bituminous Set Concrete Base Crosswalk Section (BSCBCH)
2.1.4. Construction Phase

The construction of the CPATT interlocking concrete crosswalks at the CPATT Test Track were carried out by Ross Yantzi’s Pavestone Plus Limited in two phases as described below.

2.1.4.1. First Phase

The first phase of crosswalk construction was started on June 18, 2007 and completed on June 26, 2007 for three crosswalks SSCBCH, SSABSH and BSCBCH. The interlocking concrete pavers were supplied by NAVA STONE in Cambridge, Ontario. The entire construction phase lasted approximately seven days. Each of the crosswalks is 3m in width and 8.3m in length. The description of the activities is described in following sections.

2.1.4.1.1. Excavation of the Asphalt Pavement

The CPATT crosswalk construction involved the excavation of the existing asphalt section. The carpenter square was used to mark the section to be cut. The cutting of the sections started approximately at 8:30 a.m. on June 18, 2007 and the 100mm thick asphalt layer for all three sections were cut in approximately four hours as shown in Figure 9. Immediately following the cutting, the excavator removed the asphalt pavement and granular A materials to create a trench for each section with an approximate depth of 300mm for placing the crosswalk base. The entire excavation process took approximately five hours and was completed at 2 p.m. on June 18, 2007.

![Figure 9 Excavation of Asphalt Pavement](image-url)
2.1.4.1.2. Crosswalk Base Construction

Within the three crosswalk test sections, SSCBCH and BSCBCH have a concrete base underneath the ICP while SSABSH has an asphalt base underneath the ICP. The southernmost crosswalk BSCBCH base was constructed first. After excavating the trench, the sensors designed to be placed in subbase were installed. The subbase course then was levelled and compacted with a 20 kN/ 4500 lbs vibrating plate compactor. Wooden forms were installed around the perimeter of the crosswalk for curbs and headers. Reinforcement rebars having mesh size of 150mm/150mm were placed on the top of the subbase course before the concrete pouring as shown in Figure 8. High Early concrete from Dufferin Concrete’s Forwell Plant in Kitchener was brought to the construction site at 1:20 PM on June 20, 2007 and poured into the forms from 1:30 PM to 3:35 pm. A total of 6.5m³ of concrete poured in place over a two hour period. The first concrete base crosswalk was constructed on June 21, 2007 using concrete as the third crosswalk’s base. The concrete pouring started at 1:10 PM and lasted one and half hours as shown in Figure 10.

Figure 10 Concrete Base Construction
The length of the concrete base is 8.3m including curbs and the width is 3m including the headers on both sides. The thickness of the concrete bases is 200mm. Each base has curb and headers around the perimeter, the width of the curb/header is 150mm. Exposed concrete headers edges are trimmed to 3mm radius to reduce the likelihood of chipping. Three control joints for shrinkage were provided at three locations throughout the base. The procedure is shown in Figure 11, 12, and 13.

The construction of asphalt base crosswalk was started on June 22 at 9.30 am and took approximately two hours to complete the first 50mm lift. Within the two hours of paving, 3.6 tonnes of HL3 was spread, screeded, and compacted with a 20 kN plate compactor as shown in Figure 13. The paving of the second/final 50mm lift of asphalt was started on the same day at 2.00 pm and completed at 4.00 pm. The air temperature during this operation ranged from 27 to 34 degree Celsius. The mix temperature on arrival to the site was 114°C and 106°C before compaction of the first lift. Similarly, the mix temperature of the second lift before the compaction was 72°C. The mix was prepared at Kitchener Asphalt Plant of Steed and Evans Limited.

The asphalt base also has two concrete curbs similar to ones for the concrete bases along its two edges that are parallel to the Test Track and these curbs were constructed using the remaining concrete after constructing the second concrete base crosswalk.

Prior to the concrete pouring of the base, eight ABS pipes with diameter of 75mm and length of 300 mm were installed perpendicular to the road surface at the lowest level of the base course. The pipes are filled with pea gravel and covered with geotextile to prevent the loss of bedding materials. Their purpose is to remove excess water from the bedding sand. Since the road base is constructed with two percent slope towards the edge, four pipes were installed along the two outer edges of the bases. One set of four drainage pipes are located in northbound lane and another set at located in southbound lane. The distance between adjacent drainage pipes (centre to centre) is approximately 80cm and the first drainage pipe of each set is 20cm offset from the edge of the base.
Figure 11 Formworks, Drain Pipes and Reinforcement Bars for Concrete Base Section

Figure 12 Concrete Placement
Figure 13 Concrete Base Section

Figure 14 Asphalt Base Section
2.1.4.1.3. Bedding Material Placement

Prior to placing the interlocking concrete pavers, a layer of bedding material was placed in the base of each section. The CSA requirements and actual gradation of the bedding sand is provided in Table 1. Micro-Deval test was also performed before the placement as per ICPI Tech Spec Number 17. An 8.9% Micro-Deval degradation loss was calculated which is slightly greater than maximum recommended value 8%.

Table 1 Gradation of Bedding Sand

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Percent Passing (%)</th>
<th>Sieve Size (mm)</th>
<th>Percent Passing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>100</td>
<td>9.5 mm</td>
<td>100</td>
</tr>
<tr>
<td>5 mm</td>
<td>95-100</td>
<td>4.75 mm</td>
<td>99.9</td>
</tr>
<tr>
<td>2.5 mm</td>
<td>80-100</td>
<td>2.36 mm</td>
<td>86.6</td>
</tr>
<tr>
<td>1.25 mm</td>
<td>50-90</td>
<td>1.18 mm</td>
<td>71.1</td>
</tr>
<tr>
<td>0.630 mm</td>
<td>25-65</td>
<td>0.600 mm</td>
<td>53.2</td>
</tr>
<tr>
<td>0.315 mm</td>
<td>10-35</td>
<td>0.300 mm</td>
<td>26.3</td>
</tr>
<tr>
<td>0.160 mm</td>
<td>2-10</td>
<td>0.150 mm</td>
<td>6.2</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>0-1</td>
<td>0.75 mm</td>
<td>1.1</td>
</tr>
</tbody>
</table>

For SSCBCH, a layer of non-woven geotextile was placed in the constructed base and a layer of bedding sand with approximate thickness of 25mm was spread and screeded on top of the non-woven geotextile as shown in Figure 15.

For SSABSH, L-shaped iron angle were installed on top of the asphalt base and along the cut pavement edge. The angle iron is 9.5cm wide and 9.5cm high and 6mm thick. Nails and screws were drilled through the angle iron and into the asphalt base in every 60cm to fasten the angle iron onto the base. On top of the angle iron and the asphalt base, a similar layer of non-woven geotextile and bedding sand as SSCBCH were placed.

For BSCBCH, the concrete base surface was prepared with an emulsified asphalt tack coat. A hot-sand asphalt mix was brought to the site and spread and compacted to 25mm thick layers.
After the asphalt cooled, a thin coating of asphalt-neoprene adhesive was applied across the surface.

![Figure 15 Bedding Sand and Non-woven Geotextile](image)

### 2.1.4.1.4. Placement of Interlocking Concrete Pavers (ICP)

The interlocking concrete pavers were placed into the concrete/asphalt base at SSCBCH, SSABSH and BSCBCH on June 22, 26 and 25, respectively. Approximately 1070 pieces of interlocking concrete pavers with approximate dimension of 200mm × 100mm × 80mm were placed in each section. The pavers were laid in 45° herringbone pattern. Installation was started from the corner with securing 45° string lines on the bedding course. Edge pavers are saw cut to fit against the sailor and soldier courses. The sailor and soldier are interlocking concrete pavers which were placed in such a way that SSABSH and BSCBCH have three sides (one long side and two short sides) with sailor course and one long side with soldier course. In contrast, SSCBCH has sailor courses on the both sides. After the installation, the surface was compacted with a vibratory plate to compact the bedding sand, seat the pavers in it and force the bedding sand into the joints at the bottom of the pavers. Figure 16 provides details of the paver while Figure 17 and 18 presents the layout. The final elevation of the surface course was kept 6mm above the adjacent asphalt pavement to accommodate any future settlement.
Physical Characteristics of the Pavers

Brand – Cobble100-80™

Color – Antique Red (Red/}

Figure 16 Physical Characteristic of the Concrete Pavers

Figure 17 Laying Interlocking Concrete Pavers
2.1.4.1.5. Joint Sands Placement and Compaction
After initial compaction of the pavers, dry joint sand was spread on the surface and compacted with a vibratory plate compactor to ensure that the spaces between pavers are filled. Excess joint sand was then removed.

2.1.4.2. Second Phase
The crosswalk SSGBCH was being researched in the Ring Road test site with city traffic but it was not constructed at Test Track. The performance of this crosswalk under heavy load was still a mystery. For this reason, SSGBCH was constructed in the Test Track research site on July 2009.

The second phase of crosswalk construction was started on July 16, 2009 and completed on July 24, 2009. SSGBAH was constructed in this period. The interlocking concrete pavers used in this crosswalk were from Permacon. The crosswalk is 3m in width and 8.3m in length.
2.1.4.2.1. Construction of Curb

On July 16, 2009, the concrete curb was constructed for the new crosswalk along the edges. The work started at 8 am with saw cut of asphalt for the curb construction followed by excavation of asphalt, construction of form work and concrete placement on both sides.

Figure 19 Construction of Curb

Figure 19 shows the construction of the curb on the south bound lane. The construction of the curb occurred one week in advance of the construction to allow for proper curing. The curb area was protected by pylons and reopened to traffic. The saw cut of asphalt for the whole crosswalk section was completed the same day to decrease the work load on July 22. The work was completed around 3:30 pm.

2.1.4.2.2. Excavation of Asphalt Pavement and Existing Granular ‘A’

Since the saw cut of asphalt section was already completed, the work started at 8:15 am on July 22nd by excavating the asphalt layer in the south bound lane. Following the cutting of the asphalt sections, the excavator removed existing road base material (Granular ‘A’). The leveling was completed during this process with the assistance of the laser level to ensure an accurate depth to
be excavated. Approximately 300mm of depth was maintained. The process was completed in two hours. Figure 20 shows the excavation of existing asphalt pavement in the south bound lane. And Figure 21 shows the excavation of Granular A with the laser level on site.

Figure 20 Excavation of Asphalt Pavement

Figure 21 Excavation of Granular A
The moisture sensors and temperature sensors were installed by the CPATT team after the excavation of base material in the designed location were completed. The work started at 10:50am and the installation process took almost three hours. The details of Installation of sensors are described in the Instrumentation section of this report.

2.1.4.2.3. Crosswalk Base Construction

After the completion of sensor installation by the CPATT group on the subbase, at 2:45 pm, the subbase was compacted with a vibrating plate compactor. Caution was taken around the sensors. Crosswalk base material which is granular 'A' in this case was placed up to the height of 200 mm above subbase.

The base material was then compacted with 1000 lbs vibrating plate compactor. The vibratory plate compactor repeated six times to achieve 98% of compaction. The corners and the sides of the base were compacted with a Jumping Jack compactor with 254mm plate on the bottom. Figure 22 shows the vibratory plate compactor in operation in the north bound lane. The photo shows a group of students who also came to visit the site to see the construction work.

Figure 22 Vibratory Plate Compactor in Crosswalk Base
2.1.4.2.4. Installation of Header and Geotextile
On Day 2 of construction, July 23, 2009 the work started around 9:15 am but, was delayed for an hour because of rain. Granular 'A' was again compacted in the morning to confirm compaction with a small compactor and leveling was done for the base material. Aluminum header was brought from Permaloc Corp. The header was fastened in the granular base with 254mm long steel spikes as shown in Figure 23. The nails were spaced approximately 200 mm which were from Tree Island Industries. After the successful installation of Header, non-woven geotextile was spreaded over the crosswalk base.

![Figure 23 Installation of Aluminum Header](image)

2.1.4.2.5. Bedding Material Placement
The main function of bedding sand is to provide support to the pavers during installation and it is also an important structural component. It also helps to maximize interlock among pavers, and facilitates drainage of water that infiltrates through the joints. In this research project, the bedding sand materials were transported from Barrie, Ontario and were of good quality. The Gradation test for the sand recommended by ICPI, according to ASTM C 33 was performed in
The CPATT laboratory. Table 2 summarizes the ASTM requirements and actual gradation of sand.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
<th>Actual Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8 inch</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>No. 4</td>
<td>95-100</td>
<td>97.8</td>
</tr>
<tr>
<td>No.8</td>
<td>85-100</td>
<td>84.5</td>
</tr>
<tr>
<td>No.16</td>
<td>50-85</td>
<td>64</td>
</tr>
<tr>
<td>No.30</td>
<td>25-60</td>
<td>47.9</td>
</tr>
<tr>
<td>No.50</td>
<td>10-30</td>
<td>26.7</td>
</tr>
<tr>
<td>No.100</td>
<td>2-10</td>
<td>9.5</td>
</tr>
<tr>
<td>No.200</td>
<td>0-1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 Gradation of Bedding Sand

The Micro-deval test was also carried out in the CPATT laboratory on the samples and the result confirms the ICPI Tech Spec 17. Micro-deval gradation loss was calculated to be 8.32% which is only slightly higher than the 8% recommended by ICPI. The test was carried out through ASTM specification.

The 25mm of bedding sand was spread above the non-woven geotextile by placing screed rails on it. The bedding sand was screeded across the rails with a straight strike board as shown in Figure 24. Screed rails were removed after that, filling the void with the bedding sand.

![Figure 24 Spreading and Screeding of Bedding Sand](image)
2.1.4.2.6. Placing Interlocking Concrete Pavers

On Day 2 of construction, July 23, 2009 the Interlocking Concrete Pavers were placed on the crosswalk. Concrete pavers were placed in 45 degree herringbone patterns as shown in Figure 25. The interlocking concrete pavers used in the new crosswalk were from Permacon with a dimension of 200mm X 100 mm X 80 mm. The herringbone pattern is recommended in ICPI Tech Spec 2 as these interlocking patterns provide the maximum load bearing support (3). Construction was started from the corner with utmost care in the joint width, which should be between 2 mm to 5 mm according to Tech Spec 2. The pavers on the edges were saw-cut to maintain the pattern and cut pavers were used to fill gaps along the edges of the pavement.

![Figure 25 Interlocking Concrete Pavers](image)

After the installation of paver was completed, it was compacted with a vibrating plate compactor. Approximately three passes were made across the pavers to seat the pavers in the bedding sand. Since the construction was retrofitted to existing asphalt pavement, future settlement was considered and the elevation of the finished crosswalk was approximately 5mm above the adjacent asphalt pavement.

2.1.4.2.7. Joint Sand Placement and Compaction
Joint sand should be finer than the bedding sand to facilitate filling of the joints. Bedding sand can also be used to fill the joints. In this research project, during the construction the HP Polymeric Joint Sand from Techni-Seal was used. The sand was spread over the completed crosswalk and was swept out into the joints. After sand is uniformly spread, the pavers were compacted again using a vibratory plate compactor. However, after final completion of crosswalk, bedding sand was spread and compacted with a compactor as shown in Figure 26.

![Figure 26 Spreading of Bedding Sand on the Pavers](image)

2.1.5. Instrumentation

Pavement instrumentation is crucial to understanding material performance in the field, as well as pavement system response to loading and environment. Installation of sensors in the pavement allows the CPATT research team and ICPI to better understand the behaviour of interlocking concrete pavement performance during freeze thaw conditions. The goal of instrumentation is to assess the in-situ performance related to stress, strain, temperature and moisture. Sensors installed in pavement sections are divided into two categories. Temperature and TDR probes are installed to measure environmental responses whereas pressure cells and strain gauges are embedded to capture loading responses.
The sensors were installed during construction of the project. Different types of sensors namely vibrating wire strain gauges, earth pressure cells, temperature profiles/probes and moisture probes/sensor were designed to determine vertical strain in asphalt and concrete bases, vertical earth pressure in base and subbase and temperature and moisture variation at different elevation in subbase. The sensors are installed at different locations inside the pavement and all cables were collected at one point and placed in a trench together and routed to the edge. Phase 1 and phase 2 have two separate conduits running parallel to each other to the Data logger. Table 3 summarizes the purpose and locations of the sensors.

### Table 3: Summary of Instrumentation

<table>
<thead>
<tr>
<th>Crosswalk</th>
<th>Sensor</th>
<th>Quantity</th>
<th>Location</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SSGABH)</td>
<td>Temperature Probes</td>
<td>4</td>
<td>100mm and 300mm below from the top of the subbase at 1.5m offset from road edge</td>
<td>Measure the change of temperature</td>
</tr>
<tr>
<td></td>
<td>Moisture Sensors</td>
<td>2</td>
<td>200mm and 375mm below from the top of the subbase at 3m offset from road edge</td>
<td>Measure in-situ moisture content</td>
</tr>
<tr>
<td>(SSCBCH)</td>
<td>Concrete Strain Gauge (VWSGE)</td>
<td>2</td>
<td>50mm and 150mm below from the top of concrete base at 1.15m offset from road edge</td>
<td>Measure change of strain in concrete</td>
</tr>
<tr>
<td></td>
<td>Earth Pressure Cells (LPTPCO9-V)</td>
<td>2</td>
<td>Bottom of concrete base and at 250mm below from bottom of base at 1.6m offset from road edge</td>
<td>Measure vertical stress in base and subbase</td>
</tr>
<tr>
<td></td>
<td>Thermistor (TH0003-250-2)</td>
<td>2</td>
<td>50mm and 250mm below from bottom of concrete base at 1.4m offset from road edge</td>
<td>Measure the change of temperature</td>
</tr>
<tr>
<td></td>
<td>Moisture Probes (6005L40WGL)</td>
<td>2</td>
<td>100mm and 250mm below from bottom of concrete base</td>
<td>Measure in-situ moisture content</td>
</tr>
<tr>
<td>Equipment Type</td>
<td>Number</td>
<td>Measurement Details</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>--------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Asphalt Strain Gauge (VWSGEA)</td>
<td>3</td>
<td>Bottom of the asphalt base at 1.1m, 2.2m and 3.3m offset from road edge</td>
<td>Measure the change of strain in the asphalt</td>
<td></td>
</tr>
<tr>
<td>Earth Pressure Cells (LPTPCO9-V)</td>
<td>2</td>
<td>Bottom of asphalt base and at 250mm below from bottom of base at 1.6m offset from road edge</td>
<td>Measure vertical stress in base and subbase</td>
<td></td>
</tr>
<tr>
<td>Thermistor (TH0003-250-2)</td>
<td>2</td>
<td>50mm and 250mm above from bottom of asphalt base at 1.4m offset from road edge</td>
<td>Measure the change of temperature</td>
<td></td>
</tr>
<tr>
<td>Moisture Probes (6005L40WGL 60 60 cm)</td>
<td>2</td>
<td>100mm and 250mm above from bottom of asphalt base at 3m offset from road edge</td>
<td>Measure in-situ moisture content</td>
<td></td>
</tr>
<tr>
<td>Concrete Strain Gauge (VWSGE)</td>
<td>2</td>
<td>50mm and 150mm below from top of concrete base at 1.15m offset from road edge</td>
<td>Measure change of strain in concrete</td>
<td></td>
</tr>
<tr>
<td>Earth Pressure Cells (LPTPCO9-V)</td>
<td>2</td>
<td>Bottom of concrete base and at 250mm below from bottom of base at 1.6m offset from road edge</td>
<td>Measure vertical stress in base and subbase</td>
<td></td>
</tr>
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<td>Thermistor (TH0003-250-2)</td>
<td>2</td>
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<td>Measure the change of temperature</td>
<td></td>
</tr>
<tr>
<td>Moisture Probes (6005L40WGL 60 60 cm)</td>
<td>2</td>
<td>100mm and 250mm above from bottom of concrete base at 3m offset from road edge</td>
<td>Measure in-situ moisture content</td>
<td></td>
</tr>
</tbody>
</table>
2.1.5.1. Moisture Sensor

Two different kinds of moisture sensors are used in this research project as shown in Figure 27 and 28. A moisture sensor is a device which measures the in-situ moisture content. In the first construction phase a moisture sensor consisting of three 600mm long stainless steel rods for measuring moisture content was used as shown in Figure 27. Two probes are installed horizontally in each section at 100mm and at 250mm from the top of the subbase and at 3m offset from the road edge. In the second phase, moisture sensors which are as shown in Figure 28 were installed at depths of 200mm and 375mm below from the top of the subbase in second phase of the project. The Figure shows the calibrated sensors ready to be installed in the field. The offset from the road edge was three meter.

Figure 27 Moisture Probes for SSABSH, SSCBCH, BSCBCH

Figure 28 Moisture Sensors Ready to Install in SSGBAH
To install a moisture probe, a cavity of 700mm x 200mm x 300mm is excavated into the subbase to accommodate the moisture probe. A cable trench of 200mm wide x 250mm deep running from the cavity to the edge of pavement was also excavated as shown in Figure 29. This trench is used to run the cables of pressure cells and temperature probe. All sharp stone fragments were removed from the cavity and the trench. The cavity and the trench were filled with 5mm sand layer and the probes and cables were placed. After placing the sensors and cables the trench was filled with sand and subbase materials and compacted with a marshal hammer to ensure the density. Similarly, the second probe was installed at 150mm above the first probe and filled with sand and compacted with a marshal hammer.

![Figure 29 Installation of Moisture Probes in First Phase](image)

In the second phase, to install the moisture sensor, a pit of 400mm depth is excavated. The sensors fitted in the sensor tree at the depths 375mm and 200mm from the top of the subbase were installed. Sensor tree was constructed on site to hold two sensors at various depths in same area. Figure 30 shows the sensor tree ready to be placed on site.
2.1.5.2. Earth Pressure Cells

Earth Pressure Cells, a device to measure the vertical stress are constructed from two circular stainless steel plates and welded together around their periphery. An annulus exists between the plates, which is filled with de-aired glycol. The cell is connected via a stainless tube to a transducer forming a closed hydraulic system. As stress is exerted on the surface of the cell, it pressurizes the fluid within the cell, which in turn is measured by the pressure transducer.

Two pressure cells are installed horizontally in each section at the bottom of the concrete/asphalt base and at 250mm from the top of the subbase at 1.6m offset from the road edge.

To install pressure cells, a cavity of 700mm x 300mm x 300mm is excavated into the sub-base to accommodate the pressure cells. Cable trench excavated for moisture probes cables is used to run the pressure cells cables as well. All sharp stones fragments were removed from the cavity and the trench. The cavity and the trench were filled with 5mm sand layer and the probes and cables were placed. After placing the pressure cells and cables, the trench was filled with sand and subbase materials and compacted with a marshal hammer to ensure the density. Similarly, the second cell is installed at 250mm above the first cell and filled with sand and compacted with a marshal hammer.
The primary function of pressure cells is to monitor the change in the stress-state of the overlying layers and to measure the increase in vertical pressure due to traffic loading. The following equation is used to calculate the change of vertical stress-state.

\[ \sigma = E*(P_n-P_0)*10^{-6} \]  

(Equation 1)

Where, \( \sigma \) = Vertical stress (MPa)

\( E \) = Elastic Modulus of material where the pressure cell is placed (MPa)

\( P_n \) = Current pressure reading

\( P_0 \) = Initial pressure reading

A negative value indicates compressive stress and a positive value indicates tensile stress in above equation. Besides stress, these gauges can also measure temperature.

Figure 31 Earth Pressure Cells Installation

2.1.5.3. Temperature Probe

Temperature probes are installed to measure temperature variation at different elevations within the pavement structure. The temperature probe consists of two thermistors at the distance of 200mm are installed vertically in the subbase in each section. For the first phase of the project,
the thermistors are located at 50mm and 250mm from the top of the subbase at 1.4m offset from the road edge. Whereas in the second phase there are two each at 100mm and 300mm from the top of the subbase at 1.5m offset from the road edge.

To install the temperature probes, a cavity of 300mm x 300mm x 600mm is excavated into the subbase as shown in Figure 32. All sharp stones fragments were removed from the cavity and the trench. The cavity and the trench were filled with 5mm sand layer and the probes and cables were placed. After placing the temperature probe and the cables, the trench was filled with sand and subbase materials and compacted with a marshal hammer to ensure the density.

![Figure 32 Temperature Probe Installation in First Phase](image)

The temperature probes used in the second phase of the project is as shown in Figure 33 and the Sensor tree which was constructed for installation is as shown in Figure 34.
2.1.5.4. Vibrating Wire Strain Gauge

The strain gauges are designed to measure the change of strain and the change of temperature in the concrete. Concrete strain gauges (Model-VWSGE) are installed at 50mm and 150mm below from the top of the concrete base at the right wheel pathway at Test Track site. Two types of
strain gauges are installed to measure a strain in asphalt and concrete bases as shown in Figure 35 and 36 respectively. Three asphalt strain gauges are placed at the bottom of the asphalt base at 1.1m, 2.2m and 3.3m offsets from the road edge. Alternatively, concrete strain gauges are installed at the depth of 50mm and 150mm below from the top of the concrete base at 1.15m offset from the road edge.

Figure 35 Vibrating Wire Asphalt Strain Gauge

Figure 36 Vibrating Wire Concrete Strain Gauge
A HMA pad was placed at the asphalt strain gauges locations. After the asphalt is cooled, the strain gauges are hand placed and gently pressed into the mix as shown in Figure 37. A shallow cable trench was excavated and routed the cables to the edge. The backfill then was filled with sand and compacted with the marshal hammer.

![Figure 37 Asphalt Strain Gauge Installation](image1)

Concrete strain gauges are attached with U-shaped chairs and the chairs were driven into the ground and tied together to prevent from moving as shown in Figure 38. A shallow cable trench was excavated and routed the cables to the edge. The backfill then was filled with sand and compacted with the marshal hammer.

![Figure 38 Vibrating Wire Concrete Strain Gauges Installation](image2)
The strain gauge can measure actual strain changes due to changes in moisture content of the concrete and stresses from traffic loading. Thermal correction factor is used to adjust change in strain due to temperature changes. The following equation is used to convert measured resonance reading into change of strain.

$$\varepsilon_t = (S_n - S_0) \times GF + (T_n - T_0) \times (TC_{c/a} - TC_s)$$  \hspace{1cm} \text{(Equation 2)}

Where, $\varepsilon_t =$ True strain (microstrain)

$S_n =$ Current resonance reading

$S_0 =$ Initial resonance reading

$GF = 1,$ Gauge factor for strain gauges model VWSGEA and VWSGE

$T_n =$ Current temperature reading ($^\circ\text{C}$)

$T_0 =$ Initial temperature reading ($^\circ\text{C}$)

$TC_{c/a} =$ Thermal Coefficient of Concrete/Asphalt,

$TC_s =$ Thermal Coefficient of Steel

A negative value indicates compressive strain and a positive value indicates tensile strain in above equation.

Profile views of each type of crosswalk showing the various locations of sensors are presented in Figures 39, 40, 41 and 42 respectively.
Figure 39 Transverse View of Instrumented Sand Set Granular Base Crosswalk (SSGBAH)
Figure 40 Transverse View of Instrumented Sand Set Concrete Base Crosswalk (SSCBCH)
Figure 4.1 Profile View of Instrumented Sand Set Asphalt Base Crosswalk (SSABSH)
Figure 42 Transverse View of Instrumented Bituminous Set Concrete Base Crosswalk (BSCBCH)
2.1.6. Sampling and Testing

Extensive sampling was performed throughout the construction of the research project. Samples were taken from the original Granular A and Granular B and an HL3 sample were taken with the use of a shovel. Twelve concrete cylinders were casted to perform the laboratory compressive strength testing.

In addition to extracting samples, mix temperature of the HL3 and sand asphalt were also measured during the placement and before compaction. Slump and air-void testing were carried out for every batch of the concrete as shown in Figure 43.

![Figure 43 On-site Concrete Air-Void Testing](image1)

Figure 43 On-site Concrete Air-Void Testing

Figure 44 shows the performance testing using the PFWD (Portable Falling Weight Deflectometer) that was undertaken on subbase, base and surface course layers on the project.

![Figure 44 PFWD Testing on Crosswalk Subbase](image2)
2.1.7. Post Construction Phase

Laboratory compressive strength testing, laying conduits and feeding cables into conduits, connecting sensors with data logger are carried out in this phase.

Figure 45 A Cylinder after Compressive Strength Testing

2.1.7.1. Concrete Compressive Strength Test

During the concrete placement at the Test Track, twelve 100mm x 200mm concrete cylinders from each concrete mix were made. Two cylinders from each section were crushed using compressive strength testing machine at the 18 hrs, 24 hrs and on 2 day, 3 day, 7 day, 14 day, and 28 days after placement. The 28 day compressive strength for cylinders from both sections did not meet the 28 days compressive strength requirement (32 MPa) as shown in Figure 46.

Figure 46 Compressive Strength Testing Results
2.1.7.2. Sensors Validation
After installation, all sensors were tested for functionality by connecting to the data logger. All of them were working normally during the testing. The data logger was installed on August 14, 2007 and all sensors have been connected to the data logger were working properly as shown in Figure 47.

![Figure 47 A Preliminary Check of the Sensors after Installation](image)

2.1.7.3. Conduit and Data Logger Installation
A 100mm diameter ABS conduit was used to route the cables to the data logger. A 50cm wide trench was excavated along the road embankment and the conduits were laid and buried with the excavated materials. The Data logger is installed at 8.5m west of middle crosswalk section near the fence.

As for Phase two, a separate conduit was run parallel to the phase one conduit and the sensors are connected to the same data logger as shown in Figure 48.

![Figure 48 Conduit with Cables Running to Data Logger](image)
2.2. UNIVERSITY OF WATERLOO RING ROAD

2.2.1. Project Location

The second series of crosswalks is situated at the University of Waterloo Ring Road as noted in Figure 49. There are four crosswalks with different bases and bedding materials located at UW north campus gate. The sand set crosswalk over concrete base is installed at station 2+010 Northbound, bituminous set over concrete base is at station 2+010 Southbound, the sand set over asphalt is at station 1+140 and the sand set over aggregate base is at station 1+095.

Figure 49 University of Waterloo Ring Road and Project Locations (Source: Google Earth)

The research projects were constructed during the resurfacing of UW Ring Road. The length of asphalt base and aggregate base crosswalks are 12.5m and concrete base sections are 11.25m. The width of all sections is 2.635m. The construction was started on July 24, 2007 and completed on August 24, 2007. The installation of the interlocking concrete pavers was done
manually by a crew of two to three members. Several sensors are installed to measure the response of the pavement in various locations during construction.

### 2.2.2. Reconstruction Phase

The preconstruction phase includes site selection, layout, sensors design and preliminary sensors checking. Three different types of sensors namely vibrating wire strain gauges, temperature profiles and moisture probes were designed to determine vertical strain in asphalt and concrete bases and temperature and moisture variation at different elevation in subbase.

A preliminary check of the sensors was made by connecting to the readout box and observing the displayed readout prior to the installation.

### 2.2.3. Pavement Section

The proposed crosswalk projects were constructed during the resurfacing of UW Ring Road. Two 50mm thick asphalt layers of HL3 and HL4 were used as surface and binder courses for the resurfacing. The structural components of the pavement are shown in Figure 50.

![Figure 50 Existing Road Cross Section](image-url)
A typical interlocking concrete paver’s crosswalk consists of concrete pavers placed on top of a layer of bedding sand over a base and subbase layers. Four different designs selected for this study are as follows and are shown in Figure 51.

a) Sand Set pavers over Concrete Base with Concrete Header (SSCBCH)
b) Bituminous Set pavers over Concrete Base with Concrete Header (BSCBCH)
c) Sand Set pavers with Aluminum Header over Asphalt Base (SSABAH)
d) Sand Set pavers with Concrete Header over Granular Base (SSGBCH)

Figure 51 Layout of Crosswalk Test Sections at UW Ring Road
**Figure 52: Sand Set Concrete Base Crosswalk Section (SSCBCH)**

**NOTES:**

1. BASE THICKNESS AND REINFORCING VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE CONDITIONS.
2. CONCRETE BASE MINIMUM 2% SLOPE FROM CENTERLINE TO CURB.
3. DO NOT PROVIDE DRAIN HOLES TO SUBGRADE WHEN WATER TABLE IS LESS THAN 2 FT. (0.6 M)
   FROM TOP OF SOIL SUBGRADE. PROVIDE DRAIN HOLES TO CATCH BASINS.
4. DRAIN HOLES SPACED AT 2 FT. (600 MM).
5. CONCRETE CURB AND BASE TO BE Poured MONOLITHICALLY.

---

**EXISTING ASPHALT PAVEMENT**

**SAW-CUT PAVEMENT**

(RETROFIT ONLY - NOT NEW CONSTRUCTION)

**SEAL JOINT**

**CONCRETE CURB MIN. 6" (150 MM)**

WIDE x 12" (300 MM) DEEP

**CONCRETE PAVER**

3 1/8" (80 MM) MIN. THICKNESS

**NON-WOVEN GEOTEXTILE, TURN UP AT CURBS**

**CONCRETE BASE**

**WIRE WELDED FABRIC OR REBAR AS REQUIRED**

**COMPACTED SOIL SUBGRADE**

**AGGREGATE SUB-BASE AS REQUIRED**

**3" (75 MM) DIA. DRAIN HOLE LOCATED AT LOWEST ELEVATIONS, FILLED WITH PEA GRAVEL**

#5 (16 MM) REBARS PLACED AS SHOWN

(TYPICAL AT CURBS)
NOTES:

1. DO NOT COVER WEEP HOLES WITH SAND-ASPHALT SETTING BED.
2. 2 3/8 IN. (60 MM) THICK PAVERS MAY BE USED FOR PEDESTRIAN APPLICATIONS.
3. DRAIN HOLES SPACED AT 2 FT. (600 MM).
4. CONCRETE CURB AND BASE TO BE Poured MONOLITHICALLY.

80mm Concrete Pavers
25mm Bituminous Bedding Sand
200mm Concrete Base
300mm Subbase

Figure 53 Bituminous Set Concrete Base Crosswalk Section (BSCBCH)
Figure 54 Sand Set Asphalt Base Crosswalk Section (SSABAH)

NOTES:

1. BASE THICKNESS VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE. COLDER CLIMATES AND WEAK SOIL MAY REQUIRE THICKER BASES.

2. DO NOT PROVIDE DRAIN HOLES TO SUBGRADE WHEN WATER TABLE IS LESS THAN 2 FT. (0.6 M) FROM TOP OF SOIL SUBGRADE. PROVIDE DRAIN HOLES TO CATCH BASINS.

3. STEEL OR ALUMINUM ANGLE TO BE MECHANICALLY FASTENED AT CUT ASPHALT PAVEMENT EDGE AT MAXIMUM SPACING OF 12" (300 MM).

4. DRAIN HOLES SPACED AT 2 FT. (600 MM).

5. AGGREGATE BASE MINIMUM 2% SLOPE FROM CENTER LINE TO ASPHALT PAVEMENT EDGE.
3. Thickening asphalt pavement adjacent to concrete curb is recommended.

NOTES:
1. Base thickness varies with traffic, climate, and subgrade conditions.
2. Concrete curbs do not deflect to the same depth as pavers or existing asphalt. This detail is not recommended for other than low volume residential streets.
3. Thickening asphalt pavement adjacent to concrete curb is recommended.
4. Aggregate base minimum 2% slope from center line to curb.

Figure 55 Sand Set Granular Base Crosswalk Section (SSGBCH)
2.2.4. Construction Phase

The construction of the CPATT interlocking concrete crosswalks at the UW Ring Road were carried out by Ross Yantzi’s Pavestone Plus Limited and the interlocking concrete pavestone were supplied by NAVA STONE in Cambridge, Ontario. The entire construction phase lasted approximately one month. Each of the crosswalks is 2.635m in width and concrete base crosswalks are 11.25m and asphalt base and aggregate base are 12.50m in length. The sand set crosswalk over concrete base is installed at station 2+010 Northbound, bituminous set over concrete base is at station 2+010 Southbound, the sand set over asphalt is at station 1+140 and the sand set over aggregate base is at station 1+095. Table 3 below summarizes the construction activities.

<table>
<thead>
<tr>
<th>Crosswalk</th>
<th>Date</th>
<th>Construction Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSCBCH</strong></td>
<td>July 23, 2007</td>
<td>Excavation of subbase for concrete base, moisture and temperature probes installation</td>
</tr>
<tr>
<td></td>
<td>July 23, 2007</td>
<td>Compaction of subbase course and formworks for curbs and headers</td>
</tr>
<tr>
<td></td>
<td>July 24, 29, 2007</td>
<td>Reinforcement rebars and drainage pipes placement</td>
</tr>
<tr>
<td></td>
<td>July 24, 2007</td>
<td>Strain gauges installation and concrete placement</td>
</tr>
<tr>
<td></td>
<td>July 27, 2007</td>
<td>Non-woven geotextile installation and spreading and screeding of bedding sand</td>
</tr>
<tr>
<td></td>
<td>July 27-31, 2007</td>
<td>Installation of ICP</td>
</tr>
<tr>
<td></td>
<td>July 31, 2007</td>
<td>Spreading and sweeping of joint sands and final compaction</td>
</tr>
<tr>
<td><strong>BSCBCH</strong></td>
<td>July 25, 2007</td>
<td>Excavation of subgrade for concrete base, moisture probes and temperature probes installation</td>
</tr>
<tr>
<td></td>
<td>July 25, 2007</td>
<td>Compaction of subbase course and formworks for curbs and headers</td>
</tr>
<tr>
<td></td>
<td>July 25, 2007</td>
<td>Reinforcement rebars and drainage pipes placement</td>
</tr>
<tr>
<td></td>
<td>July 26, 2007</td>
<td>Strain gauges installation and concrete placement</td>
</tr>
<tr>
<td></td>
<td>August 1, 2007</td>
<td>Non-woven geotextile installation and spreading and screeding of bituminous sand along with coating of asphalt-neoprene adhesive</td>
</tr>
<tr>
<td></td>
<td>August 1, 2007</td>
<td>Placement of ICP</td>
</tr>
<tr>
<td>Date</td>
<td>Activity</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>August 1, 2007</td>
<td>Spreading and sweeping of joint sands and final compaction</td>
<td></td>
</tr>
<tr>
<td>July 24, 2007</td>
<td>Excavation of subbase and moisture probes and temperature probes installation</td>
<td></td>
</tr>
<tr>
<td>July 24, 2007</td>
<td>Compaction of subbase course</td>
<td></td>
</tr>
<tr>
<td>July 25, 2007</td>
<td>Installation of strain gauges, asphalt (HL4) paving</td>
<td></td>
</tr>
<tr>
<td>August 24, 2007</td>
<td>Installation of Aluminium angle edge restraint</td>
<td></td>
</tr>
<tr>
<td>August 24, 2007</td>
<td>Non-woven geotextile installation and spreading and screeding of bedding sand</td>
<td></td>
</tr>
<tr>
<td>August 24, 2007</td>
<td>Installation of ICP</td>
<td></td>
</tr>
<tr>
<td>August 24, 2007</td>
<td>Spreading and sweeping of joint sands and final compaction</td>
<td></td>
</tr>
<tr>
<td>July 26, 2007</td>
<td>Excavation of subbase and installation of moisture and temperature probes</td>
<td></td>
</tr>
<tr>
<td>July 27, 2007</td>
<td>Compaction of subbase course and formworks for curbs and headers</td>
<td></td>
</tr>
<tr>
<td>July 28, 2007</td>
<td>Concrete placement for curbs and headers</td>
<td></td>
</tr>
<tr>
<td>July 30, 2007</td>
<td>Base placement and compaction</td>
<td></td>
</tr>
<tr>
<td>June 31, 2007</td>
<td>Non-woven geotextile installation and spreading and screeding of bedding sand</td>
<td></td>
</tr>
<tr>
<td>June 31, 2007</td>
<td>Installation of ICP</td>
<td></td>
</tr>
<tr>
<td>June 31, 2007</td>
<td>Spreading and sweeping of joint sands and final compaction</td>
<td></td>
</tr>
</tbody>
</table>

### 2.2.4.1. Excavation of the Subbase for Base Construction and Sensors Installation

The first phase in the Ring Road crosswalk construction involved excavating the subbase layer for the resurfacing of the road as shown in Figure 56. After this was completed, the first crosswalk section used a backhoe excavator to excavate the newly built Granular B subbase layer. The cutting of the section started at approximately 8:00 am on July 23, 2007 and lasted for two hours. Immediately following the cutting, the moisture and temperature probes were installed in the designed locations in the subbase and backfilled and compacted with a small plate compactor.
Excavation of BSCBCH, SSCBCH and SSGBCH was carried out on July 24, 25 and 26, 2007 respectively. Backfill of the trench and compaction were done immediately following the installation of moisture and temperature probes.

![Excavation of Subbase](image)

**Figure 56 Excavation of Subbase**

### 2.2.4.2. Crosswalk Base Construction

Within the four crosswalk test sections, SSCBCH and two has a concrete base underneath the ICP while SSABAH has an asphalt base and SSGBCH has an aggregate base underneath the ICP. The concrete base crosswalk SSCBCH was constructed first. After the final compaction of the subbase with a 20 kN/ 4500 lbs vibrating plate compactor, wooden forms were installed around the perimeter of the crosswalk for curbs and headers. Reinforcement rebars having mesh of 150mm /150mm were placed on the top of the subbase course before the concrete placement as shown in Figure 57. High Early Concrete from Cross Country Concrete Ontario Limited, Heidelberg was brought to the construction site at 10:10 AM on July 24, 2007 and placed into the forms from 10:16 am to 10:50 am. A total of 7.0m$^3$ of concrete poured in place over half an hour period.
The concrete base of BSCBCH was constructed on July 26, 2007. High Early Concrete from Cross Country Concrete Ontario Limited, Heidelberg was brought to the construction site at 7:15 AM and poured into the forms from 7:20 AM to 7:55 AM. A total of 7.0m$^3$ of concrete poured in place over thirty five minutes period as shown in Figure 58.

Figure 58 Concrete Placement
The length of the concrete base sections is 11.25m and the width is 2.635m including the headers on both sides as shown in Figure 59. The thickness of the concrete bases is 200mm. Each base has curb and headers around the perimeter, the width of the curb/header is 150mm. Exposed concrete headers edges are trimmed to 3mm radius to reduce the likelihood of chipping. The curing agent was applied after the initial setting of the concrete.

Prior to the concrete placement, twenty four ABS pipes with diameter of 75mm and length of 300mm were installed perpendiculars to the road surface at the lowest level of the base course. Since the road base is constructed with a two percent slope towards the edge, four pipes were installed along the two outer edges of the bases and sixteen pipes were placed longitudinally along the inner side of the crosswalk. The pipes are filled with pea gravel and covered with non-woven geotextile to prevent the loss of bedding materials. Their purpose is to remove excess water from the bedding course. The distance between adjacent drainage pipes (centre to centre) is approximately 60cm and the first drainage pipe of each set is 20cm offset from the edge of the base.
The construction of the asphalt base of SSABAH was started on July 25, 2007 at 10.10 am and took approximately one hour to complete the first 50mm lift. Within the one hour of paving, 8.0 tonnes of HL4 was spread, screeded, and compacted with a 20 kN plate compactor. The paving of the second/final 50 mm lift of HL4 was started on the same day at 11:00 am and completed at 12:30 pm. The air temperature during this operation ranged from 28°C to 33°C. The mix temperature on arrival to the site was 148°C and 126°C before compaction of the first lift. Similarly, the mix temperature of the second lift before the compaction was 109°C. The mix was prepared at Cambridge Asphalt Supply of Steed and Evans Limited. Construction is shown in Figure 60.

The asphalt base also has two concrete curbs similar to the concrete bases along the two edges that are parallel to the Ring Road. Two sets of four ABS pipes were placed along the outer edges of the base and filled with pea gravel and covered with geotextile. The distance between adjacent drainage pipes (centre to centre) is approximately 60cm and the first drainage pipe of each set is 20cm offset from the edge of the base.

![Asphalt Base Construction](image)

**Figure 60 Asphalt Base Construction**

The construction of the aggregate base SSGBCH was started on July 26 2007, and the installation of moisture and temperature probes in subbase, 150mm thick Granular A base course
was placed and compacted with a 20 kN plate compactor. The concrete curbs and headers were built on July 27, 2007 as shown in Figure 61.

![Image of construction site](image)

**Figure 61 Aggregate Base Construction**

### 2.2.4.3. Bedding Material Placement

Prior to placing the interlocking concrete pavestone, a layer of bedding material was placed in the base of each section. Gradation of the bedding sand has already been provided in Table 1. For crosswalks with concrete base (SSCBCH) and granular base (SSGBCH), a layer of non-woven geotextile was placed in the constructed base and a layer of bedding sand with approximate thickness of 25mm was spread and screeded on top of the non-woven geotextile.

For asphalt base crosswalk (SSABAH), L-shaped aluminum angles were installed on top of the asphalt base and along the cut pavement edge. The aluminum angle is 9.5cm wide and 9.5cm high and 6 mm thick. Nails and screws were drilled alternatively through the aluminum angle and into the asphalt base 60cm apart to fasten the edge restraint onto the base. On top of the angle plate and the asphalt base, a similar layer of non-woven geotextile and bedding sand as SSCBCH were placed.

For crosswalk BSCBCH, the concrete base surface was prepared with an emulsified asphalt tack coat. A hot-sand asphalt mix was brought to the site and spread and compacted to 25mm thick
layers. After the asphalt cooled, a thin coating of asphalt-neoprene adhesive was applied across the surface.

Figure 62 Bedding Sand and Non-woven Geotextile

2.2.4.4. Placement of Interlocking Concrete Pavers (ICP)

The interlocking concrete pavers were placed into the SSCBCH, two, three and four on July 27, 2007, August 1, 2007, August 24, 2007 and July 31, 2007 respectively. Interlocking concrete pavers from NAVA STONE in Cambridge, Ontario with approximate dimension of 200mm × 100mm × 80mm were placed in 45° herringbone pattern. Installation was carried out in an identical manner to the test sections at the CPATT Test Track started from the corner with securing 45° string lines on the bedding course. Edge pavers are saw cut to fit against the sailor and soldier courses. The sailor and soldier are interlocking concrete pavers which were placed in such a way that each section has three sides (one long side and two short sides) with sailor course and one long side with soldier course. After the installation, the surface was compacted with a vibratory plate roller to compact the bedding sand, seat the pavers in it and force the bedding sand into the joints at the bottom of the pavers. The procedure is presented in Figures 63. The final elevation of the surface course was kept 6mm above the adjacent asphalt pavement to accommodate any future settlement.
2.2.4.5. Joint Sands Placement and Compaction

After the initial compaction of the pavers was completed, dry joint sand was spread on the surface and compacted with a vibratory compactor to ensure that the spaces between pavers are filled. Excess joint sand was later removed.
2.2.5. Instrumentation

The sensors were installed during the construction of the project. Three different types of sensors namely vibrating wire strain gauges, temperature profiles and moisture probes were designed for concrete and asphalt base sections. In contrast, only two types of sensors namely moisture and temperature probes are used in the aggregate base section. The sensors were installed at different locations inside the pavement and all cables were collected at one point and fed into conduits and routed to the proposed data logger station. Table 3 summarizes the purpose and locations of the sensors.

Table 3: Summary of Instrumentation

<table>
<thead>
<tr>
<th>Crosswalk</th>
<th>Sensor</th>
<th>Quantity</th>
<th>Location</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSCBCH</td>
<td>Concrete Strain Gauge (VWSGE)</td>
<td>2</td>
<td>50mm and 150mm below top of concrete base at 1.15m offset from road edge</td>
<td>Measures change of strain in concrete</td>
</tr>
<tr>
<td></td>
<td>Thermistor (THO003-250-2)</td>
<td>2</td>
<td>50mm and 250mm below bottom of concrete base at 1.4m offset from road edge</td>
<td>Measures change of temperature</td>
</tr>
<tr>
<td></td>
<td>Moisture Probes (LPTPCO9-V)</td>
<td>2</td>
<td>100mm and 250mm below top of concrete base at 3m offset from road edge</td>
<td>Measures in-situ moisture content</td>
</tr>
<tr>
<td>BSCBCH</td>
<td>Concrete Strain Gauge (VWSGE)</td>
<td>2</td>
<td>50mm and 150mm below top of concrete base at 1.15m offset from road edge</td>
<td>Measures change of strain in the concrete</td>
</tr>
<tr>
<td></td>
<td>Thermistor (THO003-250-2)</td>
<td>2</td>
<td>50mm and 250mm below bottom of concrete base at 1.4m offset from road edge</td>
<td>Measures change of temperature</td>
</tr>
<tr>
<td></td>
<td>Moisture Probes (LPTPCO9-V)</td>
<td>2</td>
<td>100mm and 250mm below top of concrete base at 3m offset from road edge</td>
<td>Measures in-situ moisture content</td>
</tr>
<tr>
<td>SSABAH</td>
<td>Asphalt Strain Gauge (VWSGEA)</td>
<td>3</td>
<td>Bottom of the asphalt base at 1.1m, 2.2m and 3.3m offset from road edge</td>
<td>Measures change of strain in the asphalt</td>
</tr>
<tr>
<td></td>
<td>Thermistor (THO003-250-2)</td>
<td>2</td>
<td>50mm and 250mm below bottom of concrete base at 1.4m offset from road edge</td>
<td>Measures change of temperature</td>
</tr>
</tbody>
</table>
2.2.5.1. Moisture Probes

A moisture probe is a device consisting of three 600mm long stainless steel rods for measuring moisture content as shown in Figure 65. Two probes are installed horizontally in each section at 100mm and at 250mm from the top of the subbase and at 3m offset from the road edge.

To install a moisture probe, a cavity of 700mm x 200mm x 300mm is excavated into the subbase to accommodate the moisture probe. A cable trench of 200mm wide x 250mm deep running from the cavity to the edge of pavement was also excavated as shown previously. This trench is used to run the cables of pressure cells and temperature probes as well. All sharp stone fragments were removed from the cavity and the trench. The cavity and the trench were filled with 5mm sand layer and the probes and cables were placed. After placing the sensors and cables the trench was filled with sand and subbase materials and compacted with a marshal hammer to ensure the density. Similarly, the second probe is installed at 150mm above the first probe and filled with sand and compacted with a marshal hammer. The cables were run along the trench together and then fed into conduit.
2.2.5.2. Temperature Probe

Temperature probes are installed to measure temperature variation at different elevations within the pavement structure. The temperature probe consists of two thermistors which are 200mm long and are installed vertically in the subbase in each section. The thermistors are located at 50mm and 250mm from the top of the subbase at 1.4m offset from the road edge. Figure 66 shows the top of the probe after installation.

To install the temperature probes, a cavity of 300mm x 300mm x 600mm is excavated into the subbase. All sharp stone fragments were removed from the cavity and the trench. The cavity and the trench were filled with 5mm sand layer and the probes and cables were placed. After placing the temperature probe and the cables, the trench was filled with sand and subbase materials and compacted with a marshal hammer to ensure the density. The cable was routed along the trench and then fed into conduit.
2.2.5.3. Vibrating Wire Strain Gauge

Two types of strain gauges are installed to measure a strain in asphalt and concrete bases as shown in Figures 67 and 68 respectively. Three asphalt strain gauges are placed at the bottom of the asphalt base at 1.1m, 2.2m and 3.3m offsets from the road edge. Alternatively, concrete strain gauges are installed at the depth of 50mm and 150mm from the top of the concrete base at 1.15m offset from the road edge.

A HMA pad was placed at the Asphalt strain gauges locations. After the asphalt cooled, the strain gauges are hand placed and gently pressed into the mix as shown in Figure 67. A shallow cable trench was excavated and routed the cables along the trench and fed into conduit. The trench then was filled with sand and compacted with the marshal hammer.
Concrete strain gauges are attached with U-shaped chairs and the chairs were driven into the ground and tied together to prevent from movement as shown in Figure 68. A shallow cable
trench was excavated to run the cable and finally fed into conduit. The trench then was filled with sand and compacted with the marshal hammer.

Profile views including installation are provided in Figures 69, 70, 71 and 72.

Figure 69 Transverse View of Instrumented Sand Set Concrete Base Crosswalk (SSCBCH)
Figure 70 Transverse View of Instrumented Bituminous Set Concrete Base Crosswalk (BSCBCH)
Figure 71 Transverse View of Instrumented Sand Set Asphalt Base Crosswalk (SSABAH)
2.2.6. Sampling and Testing

Extensive sampling was performed throughout the construction of the research project. Samples were taken from the original Granular A and Granular B and an HL4 sample was taken with the
use of a shovel. Fifteen concrete cylinders were casted to perform the laboratory Compressive Strength Testing.

In addition to extracting samples, mix temperature of the HL4 and sand asphalt were also measured during the placement and before compaction. Slump (Figure 73) and air-void testing were carried out for every batch of the concrete.

Performance testing using PFWD (Portable Falling Weight Deflectometer) was carried out on all test sections.

**2.2.7. Post Construction Phase**

Laboratory compressive strength testing, Figure 74, laying conduits and feeding cables into conduits were carried out in this phase.

**2.2.7.1. Concrete Compressive Strength Test**

During the concrete placement at the Test Track, twelve 100mm x 200mm concrete cylinders from each concrete mix were made. Two cylinders from each section were crushed using compressive strength testing machine on 1 day, 2 day, 3 day, 7 day, 14 day, and 28 days after
placement. As shown in Figure 75, the 28 day compressive strength for cylinders from both sections did meet the 28 days compressive strength requirement (32 MPa).

Figure 74 A Cylinder After Compressive Strength Testing

![Compressive Strength of Cylinders](image)

**Figure 63: Compressive Strength Testing Results**
2.2.7.2. Conduit Layout and Data logger Installation

The ABS conduits were 75mm in diameter and placed to route the cables from each crosswalk section to the collection point as shown in Figure 75 and a 100mm diameter conduit was installed to route all cables to the data logger from the collection point. The data logger is installed in between SSCBCH and BSCBCH on the road island. The data logger box is housed in a traffic cabinet which is placed on an existing concrete sidewalk and fastened with bolts. Figure 75 shows the plan view of conduits and data logger layout.

![Figure 75 Conduits and Data Logger Layout](image-url)
3. Crosswalk Repair / Maintenance

3.1. REPAIR OF SAND SET ASPHALT BASE STEEL HEADER AT TEST TRACK

3.1.1. Traffic Control

Construction of the Sand Set Granular Base Aluminum Header (SSGBAH) crosswalk and repair to the existing crosswalk Sand Set Asphalt Base Steel Header (SSABSH) was carried out during the four-day period. There was continuous flow of traffic in the Test Track, so, traffic control consisting of two flag persons was required and other students at CPATT assisted with this. Construction was carried out one lane at a time. To ensure safety of workers on the field, traffic control operation was performed for the four full days. Figure 76 shows the traffic control operation with a flag person.
3.1.2. Survey

In the survey done in July, 2009 out of the three crosswalks in the Test Track the second one which is Sand Set Asphalt Base Steel Header failed under existing loading conditions and repair was necessary. A Conference call was held on July 5, 2009 between the CPATT research team, Ross Yantzi the contractor and the ICPI technical committee to discuss about the condition and possible repair method. After the discussion, it was decided to remove the pavers and examine possible failure causes. As per discussion, Susan Tighe, Ross Yantzi and other CPATT members visited Test Track to investigate the cause of failure. Figure 77 shows the crosswalk’s picture before pavers were lifted.

![Crosswalk Before Lifting the Pavers](image)

Figure 77 Crosswalk Before Lifting the Pavers
The pavers with the soldier course which were against the steel edge were lifted and it was found that no bedding sand was remaining under the pavers. The geotextile in that area had also failed. Figure 78 shows the section right after the paver was lifted. However, the area under the paver, bedding sand and geotextile were intact and were performing well. It can be seen clearly in Figure 78, the sand is in good condition. It had shoved, but the gradation was very good. After a discussion, the team concluded that the reason for failure of this crosswalk at the edges is due separation of the steel edges from the asphalt edge which would vibrate when vehicles went over. As a result of the vibration, the steel edges moved and eventually resulted in the movement of pavers.

Consequently, the joint sand also was lost allowing for the infiltration of water into the pavers, which resulted in bedding sand being pumped out. The sample of bedding sand from the failing section and the good section were collected and gradation test was performed. The summaries of test results are provided in Table 3. All except three of the sieves are within the percent passing. The slightly higher percentage passing of the failed sample on the No. 100 sieve is most probably due to contamination.
Table 4 ASTM C33 Requirements and Actual Values

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
<th>Good Performing Area</th>
<th>Failed Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8 inch</td>
<td>100</td>
<td>98.1</td>
<td>97.4</td>
</tr>
<tr>
<td>No. 4</td>
<td>95-100</td>
<td>93.4</td>
<td>93.6</td>
</tr>
<tr>
<td>No. 8</td>
<td>85-100</td>
<td>75.8</td>
<td>76.6</td>
</tr>
<tr>
<td>No. 16</td>
<td>50-85</td>
<td>60.1</td>
<td>61.5</td>
</tr>
<tr>
<td>No. 30</td>
<td>25-60</td>
<td>40.9</td>
<td>45.4</td>
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<tr>
<td>No. 50</td>
<td>10-30</td>
<td>18.6</td>
<td>25.5</td>
</tr>
<tr>
<td>No. 100</td>
<td>2-10</td>
<td>6.0</td>
<td>13.1</td>
</tr>
<tr>
<td>No. 200</td>
<td>0-1</td>
<td>2.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>

A field report was presented by Ross Yantzi to the team and was discussed on the conference call on July 17, 2009. The decision was made to install an aluminum header, new geotextile, bedding sand and pavers.

The ESALs on the crosswalk for the period of 25 months starting from construction to repair would be 3.125 million. This crosswalk showed a sign of failure during May 2009. The rain of 2009 and the vehicle flow caused the crosswalk to deteriorate quickly.

### 3.1.3. Repair Work

As described in the earlier paragraph, the header was changed from steel to aluminum. The maintenance work was done along with the construction of the new crosswalk. The same methods and materials were used as for the SSGBAH. Following the repair this test section was renamed to reflect the change in the header. Please refer to section Construction of SSGBAH for the detail description of each work. However there are a few variations which are summarized in Table 4.
Table 5 Summary of Repair Work to SSABSH

<table>
<thead>
<tr>
<th>Crosswalk</th>
<th>Section</th>
<th>Date</th>
<th>Construction Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSABSH</td>
<td>South bound (loaded lane)</td>
<td>July 22, 2009</td>
<td>Removal of Pavers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Marked 610mm from the edge of the SSABSH crosswalk</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removing of bedding sand, geotextile and steel header in SSABSH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>July 22, 2009</td>
<td>Installation of Aluminum header</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non-woven geotextile installation and spreading and screeding of bedding sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>July 22, 2009</td>
<td>Installation of ICP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>July 23, 2009</td>
<td>Compaction of the pavers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>July 24, 2009</td>
<td>Spreading and sweeping of joint sand stabilizer and final compaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Placement of Asphalt patch on both sides of the crosswalk in south bound lane</td>
</tr>
</tbody>
</table>

Table 4 summarizes the construction work in the south bound lane. The construction of north bound lane is not explained here because the process was similar.

In the south bound lane during maintenance, the good pavers were cleaned and reused while any bad or failed pavers were replaced with new pavers. The joint sand stabilizer was used instead of joint sand. The asphalt was cracked on the edges of the crosswalk. In order to ensure a better load transfer, the existing asphalt was replaced with new hot mix asphalt. It is 610mm wide and 102mm thick. Replacement of asphalt was done only in south bound lane which is shown in Figure 79. This asphalt was placed to prevent any future settlement.
Figure 79 Replacement of Hot Mix Asphalt

Figure 80 Vehicle in Operation After Final Completion
Figure 80 shows the vehicle in operation. This picture was taken on July 30, 2009 which is a week after construction.

After the completion of the crosswalk repair, deflection tests and a distress survey were carried out in the crosswalk.

3.2. REPAIR OF SAND SET CONCRETE BASE CONCRETE HEADER AT RING ROAD

The temporary repair work of SSCBCH at the Ring Road was carried out on November 11, 2009 and November 12, 2009. The contractor for this work was Steed and Evans who was under warranty with the University of Waterloo to repair the contract, the crew started work at 7 am. The pavers were removed only from the faulted areas, the bedding sand was replaced in those areas and the same pavers were re-installed. The geotextile underneath was showing to be damaged and the concrete base was noted in good condition.

The failure of the crosswalk was primarily due to the drainage in the crosswalk. More specifically, water remained on this crosswalk as it was the low point of the intersection. Thus despite of having two catch basins located in the intersection, due to the elevation the water remained on the SSCBCH crosswalk. Thus, over time the crosswalk began to fail due to its continuously saturated state. A new asphalt batch was placed adjacent to the crosswalk which would result on water being drained to the catch basin areas. The drainage problem has also been fixed before the repair of the crosswalk by regarding the asphalt section in the intersection. The following Figure 81 shows work in progress. Figure 82 shows the re-graded intersection.
Figure 81 Repair work in Progress SSCBCH

Figure 82 Re-graded with Asphalt SSCBCH
4. Performance

The overall performance of the crosswalk is analysed by different test methods. Pavement Response, Deflection test, Distress Survey and Profile are included in this section of the report.

4.1. PAVEMENT RESPONSE

The load distribution and failure modes of flexible asphalt and interlocking concrete pavement are very similar. The pavement carries load as a flexible pavement and pavement failure primarily through rutting in the layers under the block surface. The major failure modes for the asphalt and concrete base courses are fatigue cracking, rutting and low temperature cracking.

Since the fatigue cracking is a function of horizontal strain at the bottom of asphalt, horizontal strain in concrete layers and vertical compressive stresses in granular layers, pavement responses analysis included the tensile strain on the underside of the asphalt concrete base layer, tensile strain in concrete base course and the vertical compressive stress in granular subbase courses.

Trendlines of stress and strain accumulations are influenced by variations in environmental conditions i.e. temperature, rainfall and moisture.

4.1.1. Test Track

The accumulation of stress and strain in the three different crosswalk design assemblies at the Test Track in a one year period can be described as 1.5 million ESALs. Associated environmental data for the site has also been collected and is available. It is a significant observation that the trendlines of stress and strain accumulations are influenced by variations in environmental conditions i.e. temperature, rainfall and moisture. In short, to date the temperature has the strongest influence on strain.

4.1.1.1. Sand Set Concrete Base Concrete Header (SSCBCH)

Figure 83 shows the accumulation of vertical stress and moisture variation in the subbase layer in the SSCBCH from August 2007 to February 2010. It can be seen that the formation of stress is not only affected by traffic loading but also by moisture variation.
Figure 84 shows the accumulation of strain in the concrete base of the SSCBCH in the period since August 2007 is presented. It can be seen that the temperature variation has a direct impact on the formation of strain. High tensile strain is formed during the winter season when the temperature is below 0°C. As the temperature increases, the tensile strain decreases in the concrete.
4.1.1.2. Sand Set Asphalt Base Steel Header (SSABSH) and Sand Set Asphalt Base Aluminum Header (SSABAH)

SSABSH was repaired on July 2009 and was made SSABAH. However, the instrumentation was the same. The line indicates after and before the repair work. Figure 85 shows the accumulation of vertical stress and moisture variation in subbase layer of the SSABSH/SSABAH during the period from August 2007 to February 2010. It can be seen that the formation of stress is affected by moisture variation. Tensile vertical stress is observed at the top of the subbase as well as at 250 mm below in the subbase. The maximum amount of tensile stress is noted in September 2008. The earth pressure cell at the 250 mm in subbase stopped functioning after June 2008 which is why the data is not showing up in the figure.

Figure 86 shows the accumulation of strain at the bottom of the asphalt layer in the SSABSH/SSABAH in this period. It can be seen that temperature has a direct impact on the formation of strain. High compressive strains are formed during winter when the temperature is below 0°C. As the temperature increases, the tensile strain increases at the bottom of the asphalt base layer.
Figure 86 Accumulated Horizontal Strain and Temperature Variation in Base of SSABSH/SSABAH

4.1.1.3. Bituminous Set Concrete Base Concrete Header (BSCBCH)

Figure 87 shows the accumulation of vertical stress and moisture variation in subbase layer in BSCBCH. It can be seen that the formation of stress is affected by moisture variation. Tensile vertical stress is formed on the top of the subbase as well as at 250 mm below the subbase. The figure indicates that tensile stresses increases as moisture content increases.

Figure 88 shows the accumulation of strain in the concrete base of the BSCBCH crosswalk section from August 2007 to February 2010. It can be seen that temperature has a direct impact on the formation of strain. High tensile strain is formed during winter when the temperature is below $0^\circ$C. As the temperature increases the tensile strain decreases in the concrete.

At the Test Track, when the three sections are compared as shown in Figures 89 and 90, the stresses and strains are observed as follows: the maximum observed stress for all sections is measured in the SSCBCH followed by the SSABAH and the BSCBCH crosswalks. The maximum strain is observed in the BSCBCH followed by the SSCBCH and SSABSH crosswalks.
Figure 87 Accumulation of Vertical Stress in Subbase of BSCBCH

Figure 88 Accumulation of Horizontal Strain in Base of BSCBCH
Figure 89 Accumulated Vertical Stress in Subbase in All Crosswalks

Figure 90 Accumulated Horizontal Strain in Base in All Crosswalks
4.1.1.4. Sand Set Granular Base Aluminum Header (SSGBAH)

Figure 91 shows the moisture and temperature variation in the subbase during a six month period from September 2009 to February 2010. The temperature at the different depths of the subbase does not show a significant difference while the moisture variation can be seen significantly in the two different depths of the Granular base crosswalk. The moisture has dropped below 0°C during the first week of October at 375mm from the top of the subbase.

![SSGBAH-Test Track](image)

**Figure 91 Moisture and Temperature Variation in the Subbase of SSGBAH**

4.1.2. Ring Road

The accumulation of strain in the three different crosswalk design assemblies at the UW Ring Road over twenty eight months period (2,90,000 ESALs) and the respective environmental data are presented. Trendlines of strain accumulations are influenced by variations in environmental conditions i.e. temperature, rainfall and moisture.
4.1.2.1. Sand Set Concrete Base Concrete Header (SSCBCH)

Figure 92 shows the accumulation of strain in the concrete base layer of SSCBCH at the Ring Road from November 2007 to February 2010. It can be seen that temperature has direct impact on the formation of strain. High tensile strain is formed during the winter months when the temperature is below 0°C. As the temperature increases, the tensile strain decreases and the compressive strain increases. The compressive strain reached 160 microstrains when the temperature was recorded to be higher than 30°C. The tensile strain reached 82 microstrains when the temperature was just -7°C in January 2009.

![SSCBCH-Ring Road](image)

*Figure 92 Accumulated Horizontal Strain and Temperature and Moisture Variation in SSCBCH*

4.1.2.2. Bituminous Set Concrete Base Concrete Header (BSCBCH)

Figure 93 shows the accumulation of strain in the concrete base layer of the BSCBCH in the period of twenty eight months since November 20, 2007. It can be seen that temperature has direct impact on the formation of strain. High tensile strain is formed during winter when the
temperature is below 0°C. As temperature increases the tensile strain decreases and the compressive strain increases.

**Figure 93 Accumulated Horizontal Strain and Temperature and Moisture Variation in BSCBCH**

4.1.2.3. Sand Set Asphalt Base Aluminum Header (SSABAH)

Figure 94 shows the accumulation of strain at the bottom of the asphalt base layer of the SSABAH from November 2007 to February 2010. It can be seen that the temperature has the direct impact on the formation of strain. High compressive strain is formed during the winter when the temperature is below 0°C. Tensile strain forms as the temperature increases.

Figure 95 shows the strain accumulation in all test sections at Ring Road. The maximum tensile strain is observed in the SSABAH crosswalk while the maximum compressive strain is observed in BSCBCH during this period.
Figure 94 Accumulated Horizontal Strain and Temperature and Moisture Variation in SSABAH

Figure 95 Accumulated Horizontal Strain in All Crosswalk Sections
4.2. DEFLECTION TESTING

4.2.1. Portable Falling Weight Deflectometer (PFWD)

Deflection measurement techniques are widely used for the structural evaluation of pavement. Portable Falling Weight Deflectometer (PFWD) was used in the deflection testing of the crosswalk section. The PFWD is a dynamic impact type device. In order to simulate a load impulse similar to traffic loading, a weight is dropped on a loading plate in contact with the road. The deflection is measured by geophones located at different distances from the loading system. For this study, the CPATT Dynatest 3031 Light Weight Deflectometer (LWD) has been selected. The LWD is a light, portable device that creates a non-destructive shock-wave through the soil as a result of the impact of a falling mass (10, 15, or 20 kg) from a variable drop height (100 mm to 850 mm). The impact force is transmitted to the underlying surface through a 100, 200 or 300 mm diameter loading plate. Figure 96 shows the different parts of the Dynatest 3031. The LWD 3031 records force, pressure, elastic modulus and deflection with respect to time which are stored automatically in a Personal Digital Assistant (PDA). A Personal Digital Assistant equipped with the LWD 3031 software is used to record the stress and deflection that are measured by the sensors. The program calculates the surface elastic modulus using the following equation-3:

$$E_0 = \frac{f \cdot (1 - \nu^2) \cdot \sigma_0 \cdot a}{d_0}$$

(Equation-3)

where

- $f$ is a factor that depends on the stress distribution,
- $\nu$ is the Poisson’s ratio of the material,
- $\sigma_0$ is the applied stress at surface,
- $a$ is the radius of the loading plate, and
- $d_0$ is the centre deflection.
The measurements were taken utilizing a 20 kg drop weight and a 300 mm loading plate. In all cases, six good measurements were taken and the average of six was used for analysis and comparison. The structural behaviour of each section is compared in terms of composite elastic modulus, Deflection.

### 4.2.1.1. Test Track

At the Test Track, five test locations were selected per section. The test points are located in two wheel paths, at the edge of pavement and at the center line of the crosswalk sections as shown in Figure 97.
All sections are compared in terms of the average deflection and the elastic modulus in Figure 98 and Figure 99 respectively. The maximum deflection is observed in the SSGBAH (459 microns) followed by SSCBCH (286 microns), the SSABAH/SSABSH (137 microns) and the BSCBCH (31 microns). The average deflection of November 2008, July 2009, September 2009, November 2009 and April 2009 is shown in Figure 100. From the Figure, it can be noted that, after the repair of the SSABAH section, the deflection has decreased. The deflection results on November 2009 are slightly less than the deflection in July 2009. This is due to the variable temperature conditions and it is notable that in July it was very wet and this high moisture could be leading to higher deflection values. And the deflection results of November 2009 and April 2009 are near. The data is tabulated in Table 5.

![Deflection-Test Track](image)

**Figure 98 Deflections observed at the Test Track in all Crosswalks.**
Figure 99 Elastic Modulus observed at the Test Track in all Crosswalks

Figure 100 Average Deflection at the Test Track
Table 6 Tabular Representation of Average Deflection Over Time in Test Track

<table>
<thead>
<tr>
<th>Test Track-CW</th>
<th>Average Deflection Nov-08</th>
<th>Average Deflection July-09</th>
<th>Average Deflection Nov-09</th>
<th>Average Deflection Sept-09</th>
<th>Average Deflection April-10</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSABSH</td>
<td>88</td>
<td>200</td>
<td>129</td>
<td>-</td>
<td>137</td>
<td>139</td>
<td>47</td>
</tr>
<tr>
<td>SSCBCH</td>
<td>54</td>
<td>144</td>
<td>267</td>
<td>-</td>
<td>286</td>
<td>188</td>
<td>109</td>
</tr>
<tr>
<td>BSCBCH</td>
<td>26</td>
<td>38</td>
<td>27</td>
<td>-</td>
<td>31</td>
<td>31</td>
<td>6</td>
</tr>
<tr>
<td>SSGBAH</td>
<td>-</td>
<td>-</td>
<td>477</td>
<td>362</td>
<td>459</td>
<td>433</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 5 shows the standard deviation of the deflection values over time. A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data are spread out over a large range of values. At the Test Track, the standard deviation of the BSCBCH crosswalk is lowest which shows that data points are close to the mean which is 31. The standard deviation of the SSCBCH crosswalk is very high, average deflection of November 2008 is 54 while the mean is 188.

4.2.1.2. Ring Road

At the Ring road, the test points were strategically selected to measure the deflection. For this reason the SSCBCH has five test sections in the wheel paths, at the edge of pavement and at the center line of the crosswalk, the BSCBCH has four test sections which does not include centre of the crosswalk due to the geometrics in that particular crosswalk, and the SSABAH and the SSGBCH has six test sections; one additional test point in the bus bay area. The schematic description of test points is provided in Figure 101.
The maximum deflection is observed in the SSGBCH crosswalk (206 microns) followed by the SSABAH crosswalk (162 microns), the SSCBCH crosswalk (100 microns) and the BSCBCH crosswalk (28 microns). All sections are compared in terms of elastic modulus and average deflection from Figure 102 to Figure 105. It was inconvenient to show all the crosswalk section of Ring Road in one plot due to differing test sections; so it is provided in separate graphs.

Figure 102 Elastic Modulus and Deflection in SSABAH at the Ring Road

Figure 103 Elastic Modulus and Deflection in SSCBCH at the Ring Road
The average deflection in November 2008, July 2009, November 2009 and April 2010 are shown in Figure 106. The deflection results in November 2009 are slightly less than the deflection in July 2009. This is due to the variable temperature conditions and other factors. The deflection
result for SSABAH in April 2010 is higher than in November 2009. The data is tabulated in Table 6.

**Average Deflections-Ring Road**

<table>
<thead>
<tr>
<th>Ring Road-CW</th>
<th>Average Deflection Nov-08</th>
<th>Average Deflection July-09</th>
<th>Average Deflection Nov-09</th>
<th>Average Deflection April-10</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSABAH</td>
<td>136</td>
<td>161</td>
<td>115</td>
<td>162</td>
<td>144</td>
<td>22</td>
</tr>
<tr>
<td>SSCBCH</td>
<td>87</td>
<td>111</td>
<td>110</td>
<td>100</td>
<td>102</td>
<td>11</td>
</tr>
<tr>
<td>BSCBCH</td>
<td>37</td>
<td>38</td>
<td>27</td>
<td>26</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>SSGBCH</td>
<td>163</td>
<td>209</td>
<td>201</td>
<td>206</td>
<td>195</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 6 also shows the standard deviation of the deflection values over time at the Ring Road. A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data are spread out over a large range of values. At the Ring Road, the standard deviation of the BSCBCH crosswalk is lowest which shows that data points are close to the mean which is 32. The standard deviation of the all other crosswalk at Ring Road is less in comparison to the deviation observed in the Test Track.
4.2.2. Falling Weight Deflectometer (FWD)

The Falling Weight Deflectometer (FWD) is a nondestructive deflection testing device for use in pavement structural evaluation. The FWD is a readily available, industry accepted testing instrument that measures the pavement response (i.e., deflection) to a load that simulates the in-service truck loads applied to the pavement. The FWD applies a dynamic load through a circular plate that is lowered to the pavement surface. Sensors in contact with the surface measure the downward deflection of the pavement surface. The use of a FWD enables the engineer to determine a deflection basin caused by a controlled load.

FWD testing was carried out in the CPATT Test Track-Crosswalks on September 16, 2009 with the help of Stantec Consulting Limited. Six drops were carried out at the edge of the crosswalk with three different loadings. Figure 107 shows the test being done in Sand Set Granular Base (SSGBAH) crosswalk design.

Figure 107 FWD Testing on SSGBAH
The Load Transfer Efficiency (LTE) is a useful tool for determining how well the load is being carried across a joint or in this case the load that is being transferred from the asphalt section to the crosswalk section. The LTE is the ratio of unloaded deflection to the loaded deflection, which is given by:

$$\text{LTE} \% = \frac{D_u}{D_l} \times 100$$ (Equation-4)

Where, LTE= Load Transfer Efficiency (percentage)

$D_u$= Unloaded deflection (mils)

$D_l$= Loaded Deflection (mils)

Table 7 below shows the Load transfer efficiency for each crosswalk.

<table>
<thead>
<tr>
<th>Drop ID</th>
<th>Test Type</th>
<th>D2 (+300 MM)</th>
<th>D9 (-300 mm)</th>
<th>LTE (%)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Leave</td>
<td>16.83</td>
<td>12.18</td>
<td>72.4</td>
<td>SSGBAH</td>
</tr>
<tr>
<td>6</td>
<td>Leave</td>
<td>5.71</td>
<td>7.25</td>
<td>100.0</td>
<td>SSCBCH</td>
</tr>
<tr>
<td>7</td>
<td>Leave</td>
<td>18.34</td>
<td>14.69</td>
<td>80.1</td>
<td>SSABAH</td>
</tr>
<tr>
<td>8</td>
<td>Leave</td>
<td>5.99</td>
<td>7.75</td>
<td>100.0</td>
<td>BSCBCH</td>
</tr>
</tbody>
</table>

Figure 108 shows the deflection basin of each crosswalk. The BSCBCH and SSCBCH LTE is 100% which is maximum, it indicates that the load is being transferred across the joints. In the case of the SSGBAH and SSABAH crosswalks, the LTE is still above 70% which is an effective load transfer across the joints, indicating that they are performing in a good state at the present time. This analysis would also be consistent with the observed distress evaluations. In short, this analysis is complimentary to the distress analysis as it further indicates that the BSCBCH and SSCBCH are exhibiting the best performance at this point in time.
4.3. PAVEMENT DISTRESS CONDITION EVALUATION

Distress condition surveys were carried out in accordance with the Interlocking Concrete Block Pavement Distress Guide developed by ICPI (ICPI, 2008). The guide is based on the Pavement Condition Index (PCI) methodology and was modeled on the U.S. Army of Corps of Engineers MicroPAVER distress guide as published by ASTM. The PCI is a numerical indicator that evaluates the present condition of the pavement based on the surface distress. The type and severity of pavement is assessed by visual inspection of each crosswalk section surface condition of the pavement. The PCI does not measure the structural capacity nor does it provide direct measurement of skid resistance or roughness. The structural capacity of each section is evaluated by measuring strains, stresses, temperature and moisture at different locations in the pavement which is discussed in previous section.

The following distresses are measured and evaluated for each crosswalk section. The individual type of damage is rated separately with both degree and extent of the damaged being assessed. The degree of distress is rated high, medium, or low based on PCI numerical indicator. The PCI is calculated by using ICPI spreadsheet.

- Damaged Pavers
- Depressions
Edge Restraint
- Excessive Joint Width
- Faulting
- Heave
- Horizontal Creep
- Joint Sand Loss/Pumping
- Missing Pavers
- Patching
- Rutting

The survey was carried out in March 2010. Not all the distresses are found in the crosswalks of this research project to date. Out of eleven distresses horizontal creep, missing pavers and patching are not identified. Faulting and Heaving were identified in the last progress report for SSCBCH at Ring road, but since this crosswalk was temporarily repaired, they were not present this time. The summary of the PCI of all the section including PCI rating, pavement age and ESAL according to the survey conducted in March 2010 are shown in the table below.

Table 9 Summary of Pavement Condition Evaluation in Test Track and Ring Road Sections

<table>
<thead>
<tr>
<th>Location</th>
<th>Section</th>
<th>PCI</th>
<th>Type of Traffic</th>
<th>PCI Rating</th>
<th>Pavement age</th>
<th>Total ESAL</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Track</td>
<td>SSCBCH</td>
<td>47</td>
<td>Dynamic</td>
<td>Fair</td>
<td>32 months</td>
<td>3,875,000</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>SSABAH</td>
<td>59</td>
<td>Dynamic</td>
<td>Good</td>
<td>32 months</td>
<td>3,875,000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>BSCBCH</td>
<td>85</td>
<td>Dynamic</td>
<td>Excellent</td>
<td>32 months</td>
<td>3,875,000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SSGBAH</td>
<td>46</td>
<td>Dynamic</td>
<td>Fair</td>
<td>7 months</td>
<td>875,000</td>
<td>4</td>
</tr>
<tr>
<td>Ring road</td>
<td>SSCBCH</td>
<td>60</td>
<td>Accelerating turning</td>
<td>Good</td>
<td>32 months</td>
<td>290,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>BSCBCH</td>
<td>73</td>
<td>Static</td>
<td>Very good</td>
<td>32 months</td>
<td>290,000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SSABAH</td>
<td>67</td>
<td>Static</td>
<td>Good</td>
<td>32 months</td>
<td>290,000</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>SSGBCH</td>
<td>71</td>
<td>Static, Accelerating turning</td>
<td>Very good</td>
<td>32 months</td>
<td>290,000</td>
<td>2</td>
</tr>
</tbody>
</table>
The BSCBCH at Test Track is showing the best performance as compared to all the other crosswalks at Test Track. This is also the case at the Ring Road. The PCI of SSCBCH at Ring Road has increased after the temporary repair by University of Waterloo. The PCI vs. time for the period of July 2008 to April 2010 is as shown in the Figures 109 and 110 below. It is expected that a minimum level of service would be at a PCI level of 40 as noted on both Figures. In Figure 109, the vertical line on July 2009 denotes that the crosswalk SSABSH was repaired to be SSABAH and SSGBAH was a new construction.

Figure 109 Pavement Condition Index of Test Track Over Time
Comparing the PCI over time in both the locations, the visual distresses in the Test Track has increased significantly than in the Ring Road. This is due to the frequent movement of heavy construction equipment running in the Test Track in the summer of 2009, for the construction of new landfill site.

4.4. PROFILE

The CPATT SurPRO 2000 is a Class 1 multipurpose walking profiler manufactured by ICC as shown in Figure 111. The unit operates on a battery, two inertial inclinometers and an optical encoder. Data is collected by rolling the profiler at a constant speed along a line of interest. Inclinometers operate under the same principles as accelerometers; however, they are more sensitive to vibrations and are able to compute the angle of the profiler’s inclination. Using the angle of inclination and distance travelled, the SurPRO 2000 calculates elevation changes with respect to the starting elevation.

The CPATT SurPRO was calibrated prior to starting a survey. Longitudinal roughness profiles were taken in the left and right wheel paths and transverse profile were taken of each crosswalk as shown in the figure below. Prior to testing each crosswalk was inspected to ensure that they were free of any loose debris and profiling lines were marked with spray paint to help in reducing the meandering by operators. The test area is shown in the Figure 112. The profile of

![Figure 110 Pavement Condition Index of Ring Road Over Time](image-url)
Test Track was surveyed on November 7, 2009 and the profile of the Ring Road crosswalks were taken on November 8, 2009.

Figure 111 SurPro 2000

Figure 112 Test Section in the Crosswalk for SurPRO
*RWP: Right wheel path, *LWP: Left wheel path, * Transverse profile was taken 0.4m from the header of the crosswalk.

The sampling interval of 20mm was used to get the profile. The data was collected at speeds below 3 km/h. The device was aligned with the starting line and slowly accelerated to avoid erroneous readings and gradually brought to a complete stop at a point beyond the end mark. Three runs were taken at each profile. The analysis of the data was done using ProVAL 2.7 software. The report of each profile is shown below. In the following profiles it should be noted that SurPRo operates in closed loop survey. The red marks are the start and end of the loop.

4.4.1. Test Track

Figure 113 to 116 shows the profile of north edge and south edge with respect to the centerline of the BSCBCH, SSABAH, SSCBCH and SSGBAH. The measured Profile for each crosswalk is all parallel to each other in all the profiles, so it is very similar. The south lane which has loaded vehicles exhibits more rutting as compared to the North lane. However, there is one exception as the SSGBAH has more rutting in the north lane as opposed to the south lane. The right part of the figure is Northbound and the left part is Southbound.

![Figure 113 Transverse Profile of BSCBCH at Test Track](image-url)
Figure 114 Transverse Profile of SSABAH at Test Track

Figure 115 Transverse Profile of SSCBCH at Test Track
Figure 116 Transverse Profile of SSGBAH at Test Track

Figure 117 represents the longitudinal profile of the right wheel paths of all the crosswalks in Test Track. It can be observed that there is more rutting in the SSCBCH crosswalk followed by the SSABAH crosswalk. This is also noted and consistent with the distress survey that are presented earlier in this progress report. The BSCBCH shows less rutting in comparison to the others.
Figure 117 Longitudinal Profile at the Right Wheel Path of all Crosswalks at Test Track

Figure 118 represents the longitudinal profile of the left wheel paths of all the crosswalks at Test Track. It can be observed that there is crack formation in the left wheel path of BSCBCH. High rutting is observed in the SSGBAH.

4.4.2. Ring Road
Figure 119 to 122 shows the profile of the north edge and the south edge with respect to the centerline of the BSCBCH, SSABAH, SSCBCH and SSGBAH. In Figure 120 and 122, it is observed that more rutting is observed on the west side of the crosswalk as compared to the east side of the crosswalk. Similarly, in Figure 121, the south section has more rutting as compared to the north section.

Figure 119 Transverse Profile of BSCBCH at Ring Road

Figure 120 Transverse Profile of SSABAH at Ring Road
Figure 121 Transverse Profile of SSCBCH at Ring Road

Figure 122 Transverse Profile of SSGBCH at Ring Road

Figure 123 represents the longitudinal profile of left wheel paths of all the crosswalks in Test Track. It can be observed that there is more rutting in the SSABAH crosswalk followed by the
SSGBCH crosswalk. The BSCBCH crosswalk shows less rutting in comparison to the others. The longitudinal profile of the SSCBCH was not taken due to maximum heaving, rutting and depressions along the path, which prevented carrying out SurPRO survey.

![Figure 123 Transverse Profile of SSABAH at Ring Road](image)

Figure 123 Transverse Profile of SSABAH at Ring Road

Figure 124 represents the longitudinal profile of the right wheel paths of all the crosswalks at Ring Road. It can be observed that rutting is seen in the SSGBCH section followed by the BSCBCH and the SSABAH crosswalks in the right wheel paths.

![Figure 124 Transverse Profile of SSABAH at Ring Road](image)
### 4.5. SUMMARY

Table 10 Summary of Overall Observation at Test Track

<table>
<thead>
<tr>
<th>Tests Conducted</th>
<th>Location- Test Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSABAH</td>
</tr>
<tr>
<td>ESAL</td>
<td>3.75 million</td>
</tr>
<tr>
<td>Pavement Condition Index</td>
<td>Nov-09</td>
</tr>
<tr>
<td></td>
<td>Apr-10</td>
</tr>
<tr>
<td>Deflection</td>
<td></td>
</tr>
<tr>
<td>PFWD(average Deflection)</td>
<td>Apr-10</td>
</tr>
<tr>
<td>FWD</td>
<td>Load transfer Efficiency (%)</td>
</tr>
<tr>
<td>Profile</td>
<td>Nov-09</td>
</tr>
</tbody>
</table>
### Table 11 Summary of Overall Observation at Ring Road

<table>
<thead>
<tr>
<th>Tests Conducted</th>
<th>Location- Ring Road</th>
<th>SSABAH</th>
<th>SSCBCH</th>
<th>BSCBCH</th>
<th>SSGBCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESAL</td>
<td></td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
</tr>
<tr>
<td>Pavement Condition Index</td>
<td>Nov-09 67</td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
</tr>
<tr>
<td></td>
<td>Apr-10 67</td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
<td>290,000</td>
</tr>
<tr>
<td>Deflection PFWD (average Deflection)</td>
<td>Apr-10 162 microns</td>
<td>162 microns</td>
<td>100 microns</td>
<td>26 microns</td>
<td>206 microns</td>
</tr>
<tr>
<td>Profile</td>
<td>Nov-09</td>
<td>The profile of the crosswalks shows that there is more rutting in SSABAH which is followed by SSGBCH. BSCBCH is the better performing crosswalk according to the profile information.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td>Followed by SSCBCH, this crosswalk is good for City road condition, in the heavy loads condition like in Test Track, this crosswalk was repaired.</td>
<td>Followed by BSCBCH, this crosswalk was repaired and that is why it is performing better at this stage.</td>
<td>Low deflection i.e. more stiff, similar performance as of Test Track</td>
<td>Unlike Test Track, this crosswalk is performing better</td>
<td></td>
</tr>
</tbody>
</table>
6. Overview, Observations and Recommendations

6.1. OVERVIEW

- Eight test sections were built at two sites in Waterloo, Ontario to assess the structural performance of four different interlocking concrete pavement crosswalk design assemblies under two different loading scenarios.
- Six sections are instrumented with mechanical and environmental sensors whereas aggregate base section on the Ring Road and Test Track has only environmental sensors.
- The pavement behaviour under 3,750,000 ESALs repetitions at the Test Track site and under 290,000 ESALs on the Ring Road site is studied. The CPATT Test Track encounters heavy truck loading primarily loaded garbage trucks with maximum load up to 56,000 kg (6 axles) while the UW Ring Road traffic is similar to a typical urban road with approximately 10% truck and 5% bus traffic.

6.2. OBSERVATIONS

- At the Test Track, the stresses and strains are observed as follows: the maximum observed stress for all sections is measured in the asphalt base section (SSABSH) followed by bituminous set concrete base (BSCBCH) and sand set concrete base (SSCBCH) crosswalks. The maximum strain is observed in the bituminous set concrete base crosswalk (BSCBCH) followed by sand set concrete base (SSCBCH) and sand set asphalt base (SSABSH) crosswalks. Since the maximum strain and stress values are well below the allowable strain and stress from typical models, there is no indication at this time of unserviceable fatigue cracking and rutting in the sections.
- At the Ring Road, the strains are observed as follows: Maximum observed tensile strain for all test sections is found in the SSABAH section followed by the BSCBCH and the SSCBCH crosswalks. The maximum tensile strain has not exceeded the maximum allowable strain. Therefore no unserviceable fatigue cracking has occurred in the sections in this period. It is observed that, the lowest performance is on the SSCBCH crosswalk which was due to inadequate surface drainage design which caused severe ponding of.
surface water runoff on this crosswalk in the spring. However, it has been repaired temporarily in November 2009.

- According to the deflection survey, the maximum deflection is observed in SSGBCH/SSGBAH at both the location. The SSCBCH crosswalk has the second highest deflection at the Test Track and third in Ring Road. The SSABAH is second highest in the Test Track and third at the Ring Road. While the BSCBCH has the highest stiffness and lowest deflection in both the sections. All the deflections observed in the crosswalk are less than a half a mm. The deflections for the crosswalks at both Test Track and Ring Road are listed below.

<table>
<thead>
<tr>
<th>Crosswalk Assembly</th>
<th>Test Track Deflection (mm)</th>
<th>Ring Road Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSCBCH</td>
<td>0.232</td>
<td>0.013</td>
</tr>
<tr>
<td>BSCBCH</td>
<td>0.005</td>
<td>0.011</td>
</tr>
<tr>
<td>SSABSH/SSABAH</td>
<td>0.049</td>
<td>0.026</td>
</tr>
<tr>
<td>SSGBAH/SSGBCH</td>
<td>0.097</td>
<td>0.043</td>
</tr>
</tbody>
</table>

- According to PCI rating, the BSCBCH is performing the best at both sites. The PCI of BSCBCH is seen to be consistent after 85 for Test Track and 73 for Ring Road. The Ring Road assembly with only 300,000 ESALs has less PCI then the one at Test Track assembly with 3.5 million ESAL. This is due to different traffic loading and speed condition. At Test Track we have uniform speed of 70 km/hr and at Ring Road there is static traffic, slow moving and accelerating which resulted in causing more distress than in Test Track section.

SSCBCH at the Ring Road and the SSABAH at the Test Track are rated good. It should be noted that the SSABAH was repaired in July, 2009. The maximum deformation, rutting and depression are observed in the SSCBCH section at the Ring Road site and in Test Track. The SSGBCH section at the Ring Road is performing the second best followed by the SSABAH and the SSCBCH sections.
<table>
<thead>
<tr>
<th>Location</th>
<th>Crosswalks</th>
<th>PCI</th>
<th>PFWD (microns)</th>
<th>FWD (LTE%)</th>
<th>Rutting</th>
<th>Rank</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Track</td>
<td>BSCBCH</td>
<td>85</td>
<td>31</td>
<td>100</td>
<td>Minimal amount of rutting</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSCBCH</td>
<td>47</td>
<td>26</td>
<td>100</td>
<td>25mm to 30mm rutting in the wheel paths of southbound lane</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSABA</td>
<td>59</td>
<td>137</td>
<td>80.1</td>
<td>20mm rutting in southbound lane</td>
<td>2</td>
<td>After repair</td>
</tr>
<tr>
<td></td>
<td>SSGBA</td>
<td>46</td>
<td>286</td>
<td>72.4</td>
<td>20mm rutting in all wheel paths</td>
<td>4</td>
<td>Pavement age is six months, very high rutting is seen which is the early sign of failure.</td>
</tr>
<tr>
<td>Ring Road</td>
<td>BSCBCH</td>
<td>73</td>
<td>26</td>
<td>Minimal amount of rutting</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSCBCH</td>
<td>60</td>
<td>100</td>
<td>Rutting is low but depression is 25mm</td>
<td>4</td>
<td>PCI increased after temporary repair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSABA</td>
<td>67</td>
<td>162</td>
<td>20mm rutting in the bus park</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSGBCH</td>
<td>71</td>
<td>206</td>
<td>Minimal amount of rutting</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13 Ranking of the Crosswalks According to the Performance
6.3. RECOMMENDATIONS

- Additional monitoring of pavement performance is needed to observe longer term trends.
- Based on review of the data and conservative engineering judgment, the recommended maximum lifetime 80 kN equivalent single axle loads are in Table 13 below. These are based on a PCI of 60 as the lowest acceptable condition and the basis for rehabilitation, as well consideration of deflections and load transfer:

<table>
<thead>
<tr>
<th>Crosswalk Assembly</th>
<th>ESALs/PCI</th>
<th>Maximum recommended lifetime design ESALs, millions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jun-09</td>
<td>Nov. 2009</td>
</tr>
<tr>
<td></td>
<td>Test track</td>
<td>Ring Road</td>
</tr>
<tr>
<td>BSCBCH</td>
<td>240,000/100</td>
<td>19,000/100</td>
</tr>
<tr>
<td>SSCBCH</td>
<td>240,000/68</td>
<td>19,000/44</td>
</tr>
<tr>
<td>SSABAH</td>
<td>240,000/61</td>
<td>19,000/75</td>
</tr>
<tr>
<td>SSGBCH</td>
<td>No section</td>
<td>19,000/82</td>
</tr>
</tbody>
</table>

*Repaired November 2009 **Rehabilitated July 2009

The crosswalk SSABSH at Test Track failed and was rehabilitated on July 2009. During this process Steel Header was replaced by Aluminum Header. This failure of crosswalk was recognized as construction deficiency so it was not considered in determining the lifetime design ESAL. It should be noted that there is heavy channelized loading in the Test Track in the case of SSGBCH.

In addition to all the comments, one of the important points to consider is, the quality of workmanship in the construction of the crosswalks for this research purpose was excellent.
References


“Pavement Analysis.” Elsevier.

Appendix A: Pictures of Test Track Crosswalks

Figure 125 Rutting in Sand Set Concrete Base Concrete Header

Figure 126 Sand Set Concrete Base Concrete Header at Test Track
Figure 127 Rutting in the Southbound Wheel path in Sand Set Granular Base Aluminum Header

Figure 128 Sand Set Granular Base Aluminum Header
Appendix B: Pictures of Ring Road Crosswalks

Figure 129: Bituminous Set Concrete Base Concrete Header at Ring Road

Figure 130: Rutting in the bus park of Sand Set Asphalt base Aluminum header at Ring Road
Figure 131 Distress Survey in Sand Set Concrete Base Concrete Header

Figure 132 Depression in Sand Set Concrete Base Concrete Header
Figure 133 Deflection Survey in Sand Set Granular Base Concrete Header at Ring Road

Figure 134 Clearing the debris before survey in Sand Set Granular Base Concrete Header