Effective pavement design involves the consideration of traffic loadings, subgrade soil conditions, costs and various other factors. Although the majority of paved roads constructed in Canada are asphalt concrete (flexible) pavement structures, Portland cement concrete or "PCC" (rigid) pavement products can provide various cost and technical benefits. As PCC pavements are used frequently throughout the United States, they were included in the US Long Term Pavement Performance (US-LTPP) experiment to provide a better understanding of how these pavements perform and how to better design and construct them to reduce costs and prolong pavement life.

With increasing traffic volumes and the need for innovative rehabilitation and repair of the aging transportation infrastructure, the growth of the concrete pavement product usage in Canada has been continuous over the past decade. To further the dissemination of PCC pavement technology, this technical brief was developed with two main objectives. First, a brief overview of the types of PCC pavements available is provided. Second, some of the performance results observed to date concerning PCC pavements in the US-LTPP experiment are provided, as well as various Canadian case studies.

BACKGROUND

Flexible vs. Rigid

The two main types of pavement structures are flexible and rigid as shown in Figure 1. In terms of structural characteristics, these pavement types are very different. Flexible pavements consist of asphalt layer(s) over granular base and subbase, over the subgrade. The flexible pavement structure relies on the asphalt, base and subbase layers to transfer the applied load. As noted in Figure 2, the applied load of a vehicle is distributed through each layer of the pavement structure. Consequently, each layer is important to the structural integrity of the pavement. Bases and subbases must be tested to ensure that the materials meet the gradation requirements and other required properties. The subgrade type and strength are also an important factor to determining the required thickness of the layers in the pavement structure. Overall, the thickness of the flexible pavement layers is determined according to the applied traffic loads and subgrade soil conditions.

Conversely, rigid pavements do not require a base or subbase(s) for structural support. Furthermore,
the subgrade has a minor impact on the overall thickness in terms of structural design but is a consideration for drainage. Proper design and construction of rigid pavements are related to uniform support. As noted in Figure 2, the applied load is transferred across the rigid structure so that only a small bearing stress is applied to the underlying foundation. Bases or subbases provide a working platform during construction. A permeable subbase is often used under a rigid structure for drainage purposes and can be either stabilized or unstabilized. If a rigid pavement is being constructed over poor subgrade materials, it is generally desirable to use subgrade stabilization in expansive soils or install subdrains to eliminate or reduce subgrade moisture levels.

**Types of Concrete Pavements**

There are four main types of concrete pavements. These include: jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRPC), continuously reinforced concrete pavements (CRCP) and prestressed concrete pavements.

The JPCP is the most commonly constructed pavement in Canada. These pavements may be either doweled or undoweled and have closely spaced contraction joints. The undoweled type of JPCP relies on aggregate interlock for load transfer. The aggregate interlock or shear interaction of the aggregate particles transfers the load across the joints. These

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**Figure 1: Typical Flexible and Rigid Pavement Layers**

![Flexible and Rigid Pavement Layers Diagram](image)

- **Rigid Pavement Structure**
- **Flexible Pavement Structure**

**Figure 2: Typical Load Distribution for Flexible and Rigid Pavement Layers**

![Load Distribution Diagram](image)

- **Rigid Pavement Structure**
  - Pressure < 0.2 MPa
- **Flexible Pavement Structure**
  - Pressure = 2.0 MPa
types of pavements are most effective with short joint spacing and are suitable where there are less than 80 – 100 trucks per day. In general, if the thickness is 200 mm or more, dowels should be used. If the design thickness is less than 175mm then dowels are not required, as there will not be sufficient truck volume to cause faulting. Design thickness between 175 and 200 mm fall within a “gray zone” and may or may not require dowels depending on several factors such as, amount of trucks, traffic pattern (channelized or non channelized) and speed. Doweled JPCP generally has a joint spacing of 4.5 m to minimize transverse slab cracking.

JRPC usually contains a steel rebar mesh, which is designed to control the natural crack progression. Joint design spacing is generally larger than the JPCP. Based on the high initial construction cost and longer slab lengths, which can cause potential problems in colder climates, these pavements tend not to be constructed in Canada.

CRCP pavements contain continuous steel reinforcement in the longitudinal direction to eliminate joints. The steel is designed to provide load transfer and it is engineered so that transverse cracks develop at short intervals. The initial construction costs of CRCP’s are high due to the amount of steel within the structure and are not commonly used in Canada. However, CRCP’s are frequently used in the United States and in Europe on high volume facilities.

The fourth type of rigid pavement is the prestressed or post tensioned concrete pavement. These concrete pavements tend to be placed in specialized locations and are predominantly used at airports. Speed of placement is the key reason these pavements are chosen for use at airports. Due to the logistics of transporting and placing these panels, they are not commonly used on highways, as the construction procedure is not as efficient as a slipform operation.

Concrete Pavement Products

In addition to utilizing the conventional concrete pavements for new highway construction, there are several other concrete pavement products used for new construction, rehabilitation and maintenance purposes. Concrete products that have been used in Canada include: three types of whitetopping (WT) – conventional overlay, concrete inlay and ultra-thin whitetopping (UTW); roller compacted concrete (RCC) and interlocking concrete block pavements. As a future C-SHRP technical brief will concern UTW and RCC pavements in more detail, these relatively new technologies are only briefly introduced below.

Whitetopping involves placing more than 100 mm of concrete directly on an existing flexible pavement (overlay) or in a trench milled out of an aged flexible pavement (inlay). The concrete thickness is calculated similar to a new pavement structure on an asphalt-stabilized base assuming that it is not bonded to the existing flexible pavement. Whitetopping requires minimal pre-overlay treatment and provides improved structural capacity and functional condition of the highway. Whitetopping has also been shown to mitigate reflective cracking, resist rutting and provide good skid resistance, while requiring low maintenance with no seasonal weakening. It is particularly successful in cases where rutting has occurred on high volume facilities with heavy truck traffic. Some examples of the use of WT in Canada are concrete inlays placed at an intersection in Windsor, Ontario and at truck scale in Amherst, Nova Scotia.

Ultra-thin whitetopping is a composite pavement consisting of a thin concrete overlay or inlay of 50 to 100 mm in thickness. Specific steps are taken to bond the new concrete to the existing flexible pavement and to saw short joint spacing (0.6 m to 1.8 m). This short joint spacing is designed to allow the slab to deflect rather than bend, thus reducing slab stresses. Some of the benefits of UTW include the ability to utilize local aggregates and ready mix plants. Local contractors can be trained to construct UTW, as it does not require special paving equipment and can be utilized as a fast track construction choice allowing for opening up to traffic in 24 hours or less. UTW has been utilized in several locations in Ontario (i.e. Mississauga, Brampton, Hamilton and Ottawa) and in Vancouver, BC.

Roller Compacted Concrete is a zero slump concrete mixture that is placed and compacted with the same equipment that is used to place flexible pavements. It has an exposed surface layer and is very effective in heavy industrial handling facilities such as logging and container yards, but it is also used on haul roads, highways, roadways, subdivisions, parking lots and loading yards. The construction procedure does not require forms and this feature allows for quick, high volume construction with minimal labor. The City of Edmonton has used RCC with an asphalt overlay at a
number of major intersections and a public road leading to the Clover Bar Waste Management Center. Some other highway and street applications are as follows: climbing lane in Fort McMurray, AB; subdivision arterial roadways and streets in Edmonton and St. Albert, AB and Richmond, BC; and intersections in Terrace, BC and Calgary, AB. An RCC street was also constructed in Montreal, QC in the summer of 1999.

Finally, interlocking concrete block pavements may also be used in places where construction must occur over soft ground or land that has been reclaimed from beneath water. They are also used over utility cuts in various urban cities and on industrial pavements such as intermodal transfer facilities, tidewater terminals and log sort yards. If large settlements occur, the blocks can be picked up and replaced as required. A recent study in North Bay, Ontario showed that concrete pavers placed on streets and walkways were cost effective over a 40 year life cycle and the user delay costs associated with repairs were postponed as the pavers lasted longer than asphalt.

Components of Concrete Pavements

In order to achieve an effective rigid pavement, it is necessary to examine the important design elements. Figure 3 depicts the basic components in a concrete pavement. For detailed descriptions on the various components, refer to the American Concrete Pavement Association (ACPA) website referenced at the end of this document. The following is a brief discussion on the importance of some of these factors in the design of rigid pavements for use in Canada.

Joints

Pavement joints are a major component in rigid pavement design. They are engineered to control the natural transverse and longitudinal cracking from internal distresses. Natural crack development usually occurs within the first 12 – 24 hours and can be largely attributed to volume loss and thermal contraction. Other factors such as temperature gradients, moisture gradients, thermal cycles and loading can occur sometime after 12 hours and may take months to appear. The purpose of joint design is to provide plains of weakness in the slab to control the location of the cracks. Other functions of joints include dividing the pavement into construction lanes or increments, accommodating slab movements, providing load transfer and a uniform sealant reservoir.

The four general types of joints include: transverse contraction joints which are perpendicular to the centre line of the pavement; transverse construction joints installed at the end of a day’s paving or during an extended interruption; longitudinal joints typically at the centre line or at the lane edge; and expansion or isolations joints placed to isolate a more rigid structure e.g. manhole or pavement movement on a different axis. Joint spacing should be short, uniform, perpendicular, simple and practical. A joint plan should be designed so that existing joints or cracks are matched to new joints and the joint must be placed at the appropriate time.

Concrete Materials

Concrete is a mixture of aggregates, cement, water and admixtures. The aggregates represent approximately 60 – 75 % of the mix while the remaining 25 – 40 % is the paste, composed of the cement, water, air and admixtures. The selection of appropriate cement type, admixtures and aggregate gradation is extremely important for providing adequate strength and good resistance to in-service pavement conditions. In particular, air-entraining agents are extremely important in Canada. This admixture improves workability, reduces segregation and enables earlier finishing in fresh concrete. In hardened concrete, it increases freeze thaw resistance, improves scaling resistance to de-icers, improves sulfate action and provides improved water tightness. Refer to the engineering bulletin “Design and Control of Concrete Mixtures” for a more comprehensive discussion of concrete mixtures including air entrainment, other admixtures and supplementary cementing materials (SEM).
**Surface Texture and Smoothness**

When a pavement is evaluated in terms of safety, surface texture or frictional properties along with smoothness are important characteristics. The selection of surface texture for a given project should be based on site conditions, such as climate; pavement use, speed limit, cost and surrounding land use. A detailed evaluation of surface textures can be found through the ACPA. Surface texturing is also performed on existing in-service roads when the frictional properties fall below specified limits by diamond grinding or shot blasting the surface of the concrete pavement.

Smoothness is an important parameter in terms of pavement serviceability. Smoothness governs the pavement-vehicle-human interaction and is largely dependent on proper design and construction. Similar to flexible pavements, concrete pavements are constructed to meet smoothness requirements and can be checked with profilographs or other devices.

**Thickness Design**

The thickness of the pavement structure is determined largely from estimated traffic loading and frost protection where appropriate. As noted earlier, the subbase provides a working platform for concrete paving operations. Typical concrete pavement thicknesses are provided in Table 1.

**Table 1: Typical Designs**

<table>
<thead>
<tr>
<th>Object</th>
<th>Typical Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidewalks</td>
<td>100 mm – 125 mm</td>
</tr>
<tr>
<td>Driveways</td>
<td>100 mm – 125 mm</td>
</tr>
<tr>
<td>Parking Lots</td>
<td>100 mm – 125 mm</td>
</tr>
<tr>
<td>Streets / Access Roads</td>
<td>150 mm – 200 mm</td>
</tr>
<tr>
<td>Secondary Highways</td>
<td>150 mm – 200 mm</td>
</tr>
<tr>
<td>Major Highways</td>
<td>200 mm – 250 mm</td>
</tr>
<tr>
<td>Major Freeways</td>
<td>Over 250 mm</td>
</tr>
</tbody>
</table>

**Concrete Production and Construction**

Concrete in Canada is produced for delivery by central mix or ready mix operations. Central mix operations involve charging batched ingredients into a stationary mixer set up close to the job site. Conversely, ready mix concrete is batched directly into the transporting truck and is mixed in transit from the plant to placement location.

In terms of placing a concrete pavement, slip form paving and fixed form paving are available. Slip form paving is used for almost all highway concrete paving operations. The slip form consolidates, geometrically

![Figure 4: Slip Form Paving Operation](image-url)
shapes, and surface finishes the concrete mass by “slipping” or pulling the forms continuously as shown in Figure 4. Some of the advantages of this method include the use of low slump concrete, which enables high production paving and the ability to easily produce a very smooth riding surface. Fixed form operations utilize paving forms that hold the concrete in place at the required grade and alignment. While slip form paving is generally faster and produces a smoother surface, fixed form paving has lower mobilization costs and the ability to construct in tight areas where clearance is required such as intersections, multiple change widths, blockouts and critical staging areas.

**Curing and Saw/Seal Operations**

Curing ensures that adequate moisture is available for the hydration process and is very important to performance of the rigid pavement. Hydration is the chemical reaction between cement and water, which results in strength gain within the concrete. The process is temperature sensitive so it is necessary to provide protection to ensure that hydration is continuous, especially when temperatures fall below five degrees Celsius (5°C). Curing compounds are the most common choice for pavements and they are selected based on the ease and speed of application.

A saw and seal operation is an important part toward ensuring the joints are placed properly in the concrete. Two types of cuts are constructed; the initial saw cut and the widening or reservoir cut. The purpose of the initial saw cut is to create a plane of weakness to control the location of cracking in the slab. The saw cuts should be done as soon as the concrete slab will support saw equipment without undue raveling. The widening cut is necessary to shape the joint for the sealant material and this cut can be made at the time of the initial saw cut with the use of a special blade.

The joint sealant materials are either formed in place or preformed. Long term performance of formed in place materials depends on the adhesion to the joint face. Proper cleaning prior to the installation combined with the shape factor or reservoir width and depth are required for optimal performance. Preformed materials are manufactured in a variety of different shapes and sizes and depend on long term compression recovery of the seal.

**PCC PAVEMENTS IN THE US-LTPP EXPERIMENT**

The United States Long Term Pavement Performance (US-LTPP) experiment was initiated in 1987 to determine why some pavements last longer than others through an a comprehensive 20-year study of more than 2,400 in-service asphalt and Portland cement concrete pavements across the U.S. and Canada. In 2000, the Federal Highway Administration (FHWA) released a document entitled “Key Findings from LTPP Analysis 1990-1999” to highlight some of the key findings from LTPP data analysis completed from 1990 to 1999. A selection of the performance results observed with the PCC pavements within that report are provided below.

**Effect of Structural Features Toward Performance**

LTPP data analysis has identified a number of construction and design related parameters that contribute to performance. First, a strong relationship was observed between the rate of increase of pavement roughness and increased joint faulting. By using dowels, 50% less joint faulting was observed at various test sites, thus reducing the progression of roughness. In areas with wet or freeze climates, dowels appeared to negate the effects of cold temperatures and moisture that often cause erosion of the subgrade and pumping of fines.

Proper drainage was also observed as a critical parameter toward both roughness and joint faulting in cases of undoweled pavements. Undoweled JPCP with good drainage (i.e. higher AASHTO drainage coefficients) displayed lower roughness than those with poor drainage.

Faulting of undoweled JPCP was also reduced by widening the PCC slabs by 0.6 m. Thus reducing the critical deflections at the slab corners under heavy traffic loading. Transverse cracking was also reduced. However, no increase in faulting was observed with conventional width JPCP incorporating dowels when compared to widened JPCP slabs with dowels.

The use of skewed joints was also investigated. While the LTPP data showed that skewing joints was helpful in reducing faulting for undoweled JPCP no significant improvement was observed with doweled joints. In terms of joint spacing, results to date con-
firm conventional wisdom that longer joint spacing increases the percentage of slabs with transverse cracking and faulting. With regard to joint sealing, results to date indicate that sealed joint sections perform better than unsealed sections, which contain significantly more debris and exhibit more spalling than sealed joints.

Finally, mechanistic transverse cracking models developed with LTPP data displayed a strong correlation between increased slab thickness and reduced transverse cracking. However, the data show that poor joint load transfer cannot be simply solved by increasing slab thickness. Additional analysis of this data is expected as more data is collected.

**Design**

A major input to PCC pavement design is the elastic modulus of the subgrade reaction, or “k-value.” The k-value may be determined through correlation with soil tests, backcalculation with falling weight deflectometer (FWD) data, and plate bearing tests. LTPP data confirmed that the k-values backcalculated from FWD tests exceeded plate-load k-values by a factor of 2, thus validating a conventional rule used by designers.

**Effect of Initial Smoothness**

Analysis of roughness data indicated that PCC pavements generally start with greater as-constructed roughness (i.e. lower smoothness) compared to asphalt pavements, however, they develop subsequent roughness more slowly than asphalt pavements, particularly at higher traffic loads. Furthermore, data analysis indicated that average roughness over time for JPCP and CRCP depends greatly upon initial smoothness. Smoother construction resulted in smoother pavements over time.

**EXAMPLE CANADIAN CONCRETE PAVEMENT PROJECTS**

With increased demand for innovative solutions to repair the aging infrastructure, there has been a growth in the use of concrete pavement products in Canada. This is evidenced by the recent construction of JPCP structures on Highway 407 in Toronto, ON, Autoroute’s 40 and 15 in Montreal, QC, Autoroute 440 in Laval, QC, Highway 104 in NS and several other roads in Windsor, ON and Winnipeg, MB.

**Highway 407, Ontario**

Highway 407 is an express toll route located in Toronto, ON. It is a 69 km, 6-lane divided highway. The selected design was a JPCP consisting of 280 mm concrete over 100 mm asphalt treated open graded drainage layer (OGDL) and 200 mm granular base (Modified Granular A). The flexural strength was designed at 5 MPa at 28 days and dowels were placed at transverse contraction joints. This design was selected because the private consortium that won the bid to design and build this road felt that concrete pavement was the most effective design based on both technical and cost considerations. An overhead view of Highway 407 is shown in Figure 5.

**Highway 104, Nova Scotia**

The Nova Scotia Department of Transportation and Public Works (NSTPW) undertook a study to evaluate flexible and rigid pavement structures on a portion of the Trans-Canada Highway (Highway 104) near Oxford. A five year study was completed on two adjoining pavement structures, one flexible and one rigid.
constructed in 1994 to compare their performance based on a number of criteria. The flexible structure was designed as follows: 38 mm Type Special C asphalt; 114 mm Type Special B asphalt; 150 mm of Type 1 gravel; and 420 mm of Type 2 gravel over 300mm of Class E gravel. Compaction records from three test sites showed the following ranges: 46 to 49 mm Type C Asphalt, 114 to 127 mm Type B Asphalt, 224 to 302 mm Type 1 Gravel, 499 to 650 mm Type 2 Gravel, and 300 mm Class E Gravel. Similarly, the JPCP structure was designed as a 250 mm doweled pavement on 150 mm granular base. Due to contamination of the 150 mm of granular material during the spring thaw the design was modified to 100 to 330 mm of granular base under the concrete pavement. Cores and compaction records showed the pavement varied in thickness from 253 mm to 280 mm and the new subbase varied from 250 to 330 mm over the contaminated 150 mm modified Class B granular. Both structures included a geotextile. The two sections were evaluated in terms of surface distress, profile ride index, riding comfort index, surface friction and roadside noise level. Evaluations were performed by NSTPW over a five-year period. Table 2 summarizes the results based on the five evaluation parameters.

Overall the results presented in Table 2 indicate that both pavements at five years have performed well. After five years of service, the JPCP has a superior profile ride index (6.8 versus 16.2), riding comfort index (7.4 versus 6.9) and friction numbers (60 versus 48). Little difference was noted between roadside noise levels (89 dBA concrete versus 87 dBA asphalt) and the surface distresses observed. Based on these findings, the report states the department should consider utilizing concrete in another paving project as no major defects were observed.

### Autoroute 13, Quebec

Ministère des Transports du Québec (MTQ) has been the most active provincial department in constructing concrete highways in recent years. Since 1994 MTQ has placed over 317,600 cubic metres of concrete pavement or approximately 145 kilometres of 2-lane highway. In 2000, 10 km of JPCP was constructed on Autoroute 13 in Laval, QC. The 270 mm thick pavement included three 3.65 m lanes with 3.0 m concrete shoulders on each side. Transverse joints were spaced at 5 m intervals with 35 mm dowel bars

### Table 2: Highway 104 Pavement Comparison

<table>
<thead>
<tr>
<th>Surface Distress Survey 1999</th>
<th>Flexible Structure</th>
<th>Rigid Structure</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Minor rutting, minor raveling with a few raveled areas, slight to moderate flushing, poor longitudinal joints, longitudinal cracking throughout pavement but mainly on shoulders, settlement of asphalt due to erodible base, settlement of fill at abutments adjacent to bridge</td>
<td>Minor edge damage due to plow, minor spalling portion of some slabs, some sporadic aggregate pop-outs, settlement at two culverts, diagonal crack in two slabs over culvert, minor loss of joint sealant, settlement of shoulder gravel in some locations</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>Profile Ride Index</td>
<td>4.2</td>
<td>7.2</td>
<td>11.2</td>
<td>13.3</td>
<td>16.2</td>
<td>4.1</td>
<td>4.8</td>
<td>7.1</td>
<td>6.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Riding Comfort Index</td>
<td>7.9</td>
<td>6.9</td>
<td>7.2</td>
<td>6.6</td>
<td>6.9</td>
<td>7.5</td>
<td>6.4</td>
<td>7.8</td>
<td>7.3</td>
<td>7.4</td>
</tr>
<tr>
<td>Friction Number (British Pendulum Test)</td>
<td>68</td>
<td>56</td>
<td>53</td>
<td>65</td>
<td>48</td>
<td>84</td>
<td>71</td>
<td>70</td>
<td>68</td>
<td>60</td>
</tr>
<tr>
<td>Noise Levels (dBA at Shoulder)</td>
<td>89</td>
<td>87</td>
<td>88</td>
<td>93</td>
<td>87</td>
<td>93</td>
<td>89</td>
<td>90</td>
<td>96</td>
<td>89</td>
</tr>
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</table>
used for improved load transfer. A ternary blended cement consisting of fly ash, silica fume and type 10 cement was used during construction on an experimental basis. The concrete produced using this blended cement performed very well during construction and will provide more durable concrete due to the lower permeability of this value-added product. Another innovation in this project included the construction of a two-kilometre test section of continuously reinforced concrete pavement (CRCP). As previously mentioned, this type of pavement utilizes steel reinforcing to eliminate the need for joints in the pavement. Transverse shrinkage cracks develop at close intervals and are held tightly together by 20 mm longitudinal reinforcing steel spaced 250mm apart and 90 mm from the top of the concrete surface. This maintains a high degree of load transfer. The longitudinal bars were supported by 20 mm skewed transverse steel bars. Surface texture consisted of turf drag with transverse random tining on both sections.

**National Research Council Fuel Study**

Finally, a study performed by the National Research Council of Canada (NRC) on the ‘Effect of Pavement Surface Type on Fuel Consumption’ concluded that the concrete pavement had a superior ride compared to the asphalt pavements studied. In the section concerning road roughness, the report noted the IRI data collected over four seasons indicated that on the smooth sections, the asphalt pavements had the highest amount of seasonal change, and the concrete pavement (QC Highway 440) IRI was the most stable of all pavements throughout all seasons.

**SUMMARY**

Canadian roads are aging and require timely and cost effective renovation, repair and good management. Concrete pavement products can provide innovative solutions in terms of both technical and cost efficiencies. This technical brief provides a broad summary of the concrete pavement products available today, as well as some initial performance results observed by the US Long Term Pavement Performance (US-LTPP) experiment along with various examples of typical designs used in Canada. The information presented can assist pavement designers to ensure the most appropriate pavement strategy is selected when designing new highways or rehabilitating old ones.
REFERENCES


Nova Scotia Department of Transportation and Public Works, Highway 104 Cumberland County, Year 5 of a 5 Year Study Asphalt Pavement and Portland Cement Concrete Pavement, October 1999.


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