PORTLAND CEMENT ASSOCIATION

5420 Old Orchard Road
Skokie, Illinois 60077-1083
VOICE 847.966.6200 FAX 847.966.8389
INTERNET www.portcement.org

RESEARCH & DEVELOPMENT INFORMATION

Roller Compacted Concrete Pavements—A Study of Long Term Performance

By Robert W. Piggott, P.E.

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Robert W. Piggott, P.Eng.

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Appendices

Objectives of the Study

1. **Review literature on the subject of the long term performance of Roller Compacted Concrete pavements.**

2. **Inspect Roller Compacted Concrete pavements in United States and Canada that have been in service for at least three years and report on their condition.**

1.0 Introduction

*(It should be noted that Roller Compacted Concrete (RCC) for pavements is different than RCC for dams and dam overtopping protection. The main differences are aggregate size and gradation, water and cementitious materials contents, and the method of placing the RCC mixture. This study deals **only** with RCC for pavements).*

Well over one hundred roller compacted concrete (RCC) pavement projects have been constructed in North America in the past twenty-four years. Very little has been written about the performance of these pavements after several years of service.

This report addresses the long term performance of RCC pavements under various loading applications and climatic conditions. The study was carried out in 1998. Only projects that have been in service for at least three years were considered for inclusion in the report. A total of 34 RCC pavement projects were inspected throughout the United States and Canada. Many of the projects had similar applications or similar performance. Of the 34 projects, a synopsis of 18 projects, representing a variety of applications, loading and climatic conditions are included in this report.

The oldest pavement that was studied is a log sorting yard on Vancouver Island, British Columbia, Canada, which was built in 1978. The most recent project is the street reconstruction program in Fort St. John, British Columbia, Canada, started in 1995.

The selected projects span a range of pavement applications, such as intermodal container terminals, log and lumber storage areas, military facilities, wood chip and coal storage areas, composting areas, warehouse floors and roads. There is considerable potential for the expanded use of RCC paving for streets and highways. Six road projects that have exhibited good performance are listed in Appendix A.

A few of the projects in the study included a thin layer of asphalt 37 mm to 50 mm (1½ in. to 2 in.) thick, usually applied at the time of construction. This was done to improve rideability and provide a protective covering against possible freeze/thaw damage to the RCC surface.

The number of RCC pavement projects in North America is estimated at more than 140. The equivalent of over 3,000,000 m^2 (3,200,000 yd^2) of RCC pavement have been built, or 750 single lane kilometers (465 miles) of road 200 mm (8 in.) thick.[16] The use of RCC for road and street paving is increasing as smoothness and durability properties improve.

2.0 Background and Literature Review

While Roller Compacted Concrete for pavements has been in recent use in North America since the early 1970's, it is reported by the Seattle District Office of the U.S. Army Corps of Engineers that an RCC runway was built at Yakima, WA circa 1942.[1] A form of RCC pavement was apparently built in Sweden as early as the 1930's.[1]

Cement-treated base (CTB) was used for several years in the late 1960's in the Oregon logging industry, but a protective asphalt surface was always applied. The cementitious base was designed to carry the logging equipment loads, but the asphalt surface was vulnerable to damage from heavily loaded tires in hot summer temperatures. The asphalt was also damaged by spilled fuel, hydraulic fluid leaks and gouging of the surface from equipment forks.

Cement-treated base with an asphalt overlay was designed for a log sorting yard on Vancouver Island, British Columbia in 1976.[3]. The suggestion was made to try increasing the cement content of the soil-cement from 6% to 12% by weight, making it stronger and probably more resistant to freeze/thaw damage. The asphalt overlay was delayed until the performance of the "strong CTB" could be assessed. The exposed cementitious pavement was so successful that the asphalt layer was never applied. Thus was born what we now call "Roller Compacted Concrete".

The advantages of a cementitious paving material for forest industry applications quickly became apparent. It was not affected by spillage of petroleum products, could not be easily damaged by equipment and offered much faster operating speeds, with reduced equipment maintenance, than gravel surfaced sites. Word spread quickly and by the end of the decade over a dozen RCC log sorting yards were in place. Today, RCC is included as one of the initial design options in nearly every heavy duty pavement project in the United States and Canada.

Heavy loads on pavements are not limited to the forest industry. Port authorities and transportation companies also looked at this innovation for heavily loaded pavements.[4] RCC pavements in the transportation and commodity handling industry are now in service in Vancouver, Boston, Tacoma, Houston and Denver, to name only a few.

In the mid-1980's, when RCC paving use was expanding in the transportation industry, engineers at the United States Army Corps of Engineers (USACE) expressed interest in the applicability of RCC pavements to their installations in the United States and overseas.

One of the first RCC pavements built by USACE was a test road for tanks at Fort Lewis, Washington, in 1984.[6] Following an evaluation period, the test section was deemed to be a success and a storage area for rocket launch vehicles was constructed at Fort Lewis in 1985. Other equipment hardstands were built by USACE at several military facilities throughout the United States including Fort Campbell, KY, Fort Hood, TX, Fort Bliss TX, Fort Gordon, GA, Fort Drum NY.

The next logical step in the evolution of RCC paving was to try it for roads. This application introduced another variable into the construction process - rideability. Significant improvement in ride was achieved when a high density asphalt paving machine was introduced. Conventional asphalt pavers used on early RCC projects, could only compact the mixture to approximately 80% of maximum density. The high density paver however, placed the RCC mix to over 90% of final density, leaving much less work for the rollers.

As more experience was gained by RCC paving contractors in both United States and Canada, it was apparent that the high density paver produced a superior pavement. It has now become the standard RCC paving machine. In the 1990's, there are examples of exposed (unsurfaced) RCC pavements in street applications with very satisfactory rideability.[7] (Fig. 1)

Durability against freezing and thawing, and deicer salt scaling has been a concern since RCC was first introduced in 1976. When RCC samples are subjected to the standard ASTM durability tests for concrete, results show only poor durability ratings.[11] Yet results of full scale freeze/thaw testing of an RCC pavement by the Corps of Engineers,[13] as well as observations of numerous RCC pavement projects in service for many years, show that they are durable in a winter climate.

Research on the use of air entraining agents thus far has been inconclusive, since it is extremely difficult to entrain air in a typical RCC mix.[12] Of more significance to durability is the density of the in-place RCC slab, and the inclusion of supplementary cementitious materials in the mix.[13]

In more recent research on the durability of RCC paving mixes, Marchand found that good durability could be achieved using silica fume as a partial cement replacement,[10] without using any air entraining agent.

Load transfer across joints and cracks in RCC pavements was studied by Nanni [17]. He found that the load transfer efficiency (LTE) for saw cut joints was in the range of 40 to 60 percent, and increased to 60 to 90 percent for natural cracks.

Figure 1. Bighorn Ave., Alliance, NE

Since the first logging industry projects in the 1970's, applications of RCC paving technology have expanded into many other fields. These include wood chips and coal storage, operating surfaces for waste composting, military facilities, automobile and aircraft parking areas, streets and secondary highways, and high performance RCC containing silica fume.[8]

3.0 OBSERVATIONS

3.1 Surface Texture and Condition

When an RCC pavement is completed and cured, a thin layer of fine aggregate and cement paste remains at the surface. With abrasion from traffic and exposure to weathering, some of this fine surface material is worn away in the first 2-3 years of service. However, the loss of these fines to a depth of no more than 2 mm (1/16 in.) seems to be the extent of surface erosion for most of the projects that were studied, regardless of the age of the pavement. There is a remarkable similarity in surface appearance of pavements that are five years old to those that have been in service for ten years or more. The coarse aggregate at the surface remains firmly embedded in the RCC matrix. (Figs. 2 & 3)

Most owners consider this embedded coarse aggregate to be a benefit for traction, since there is as yet, no means of intentionally imparting surface texture to an RCC pavement, as is done in a conventional concrete pavement.

On the older projects, the maximum size coarse aggregate that was used in the RCC mix was 20 mm to 25 mm (¾ in. to 1 in.). In the last ten years however, tighter pavement surfaces have been achieved using a maximum coarse aggregate of 15 mm (⅝ in.). With the smaller coarse aggregate, erosion of surface fine material is considerably less than 2 mm (1/16 in.).

Where unsurfaced RCC has been used for intermodal terminals (Boston, Denver), patches of surface erosion are more extensive. Material loss to a depth of 8 mm (⅜ in.) was observed in some areas. It is important to note, however, that this condition usually occurs in patches of variable size from 1 to 9 m^2 (10 to 100 ft^2), while nearby a section of RCC surface may show a "nearly new" appearance. (Fig. 4)

The RCC surface is exposed at all of the intermodal terminals studied. No deicers are used at any of the terminal sites, although all are exposed to freeze/thaw conditions. Based on the condition of the RCC pavements at the intermodal terminals reviewed for this study, these surfaces sustain the most severe service of any RCC pavement application.

Figure 2 Surface at Fibreco Pulp Inc, Taylor, B.C. Built in 1988.

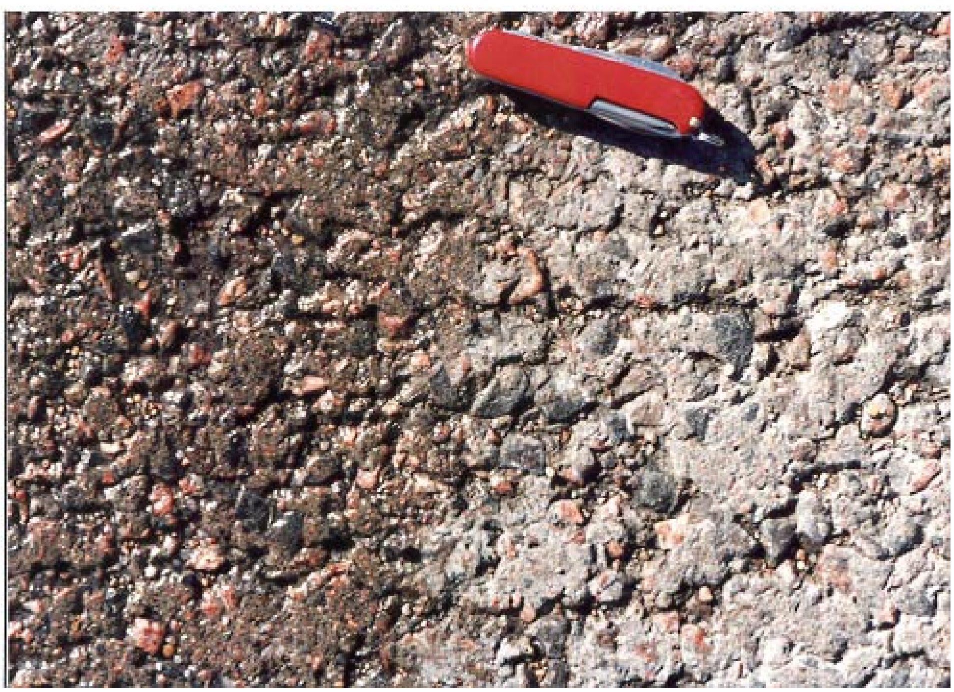


Figure 3 Surface of intermodal terminal, Denver, CO. Burlington Northern Santa Fe. Built in 1985.

Figure 4 Variation in surface texture, intermodal terminal, Denver, CO Burlington Northern Santa Fe. Built in 1985. *(Dark areas are surface moisture)*

3.2 Joints

Because joints are not built into an RCC pavement in the same way that they are constructed in a conventional concrete pavement, for the purpose of discussion in this report, transverse shrinkage cracks are referred to as "joints". "Longitudinal joints" occur between strips of pavement laid down by the paving machine, usually 3.6 m to 4.8 m (12 ft. to 16 ft.) wide. A "cold joint" or "construction joint" is the near-vertical face along the edge of a paving strip that was left by the paver at the end of a day's work. Construction on the following day usually starts at this face. Occasionally a transverse "cold joint" may occur at the end of a paving strip, when the placing sequence calls for continuation of the same strip at a later time.

As would be expected in a portland cement mixture, shrinkage cracks are common in all the pavements that were studied. In general, the cracks are transverse to the direction of paving, where the direction could be determined. The spacing of the cracks is highly variable, though seldom exceeding 20 m (65 ft.). Saw cut joints were observed at four projects - Edmonton, Fort Drum, Bighorn Ave. and the Saturn Plant roads.

Figure 5 A typical shrinkage crack. GM Saturn plant, Spring Hill TN. Built in 1988.

For reasons that could only be determined through more detailed study and a thorough sampling and testing program, some cracks are as close as 4 m (13 ft.) on a few projects. The closer crack spacing is nearly always found on the older projects that have been in service for ten years or more, and subjected to a greater number of loads. Due to the random nature of the traffic on the pavements, and the lack of available data, it was impossible to determine the magnitude or frequency of loads on the projects in the study.

There is minimal evidence of any crack sealing on most of the projects. Typically, initial shrinkage cracks are formed in the first weeks following construction, with additional intermediate cracks forming in the following months and years.

The usual answer from operators to questions about crack maintenance was that there have been no problems with the cracks in the RCC pavement, hence no need for any maintenance! Usually debris from the surface filled the cracks - fine aggregate, wood debris, coal dust, etc. (Fig. 6) In the colder climates with unsurfaced RCC pavement, there is occasional evidence of edge chipping from larger stones that become embedded in the cracks that opened up in winter. (Fig. 7) None of those interviewed indicated this to be a serious problem. Most of the cracks observed were tight and it would have been difficult to achieve penetration of the sealant in any case. (See Fig. 5) While there is minor erosion of the crack edges at the surface, at a depth of 6 mm (¼ in.) crack width is less than 2 mm (1/16 in.) in most cases.

Figure 6 Wood fibre in the shrinkage crack. Alberta Pacific Forest Industries, Athabaska, AB. Built in 1992.

On those few projects where a crack sealing program has been implemented, hot poured asphaltic sealant was usually the material of choice. At the Central Freight Inc. truck terminal at Austin, TX, a "route and seal" program was carried out 5 years after construction was completed. (Fig.8.)

Where an RCC pavement was overlaid with asphalt (Fig. 9), original shrinkage cracks in the RCC reflected through the asphalt overlay. Intentional delay of several weeks or months before applying the asphalt layer resulted in the reflection cracks being almost hairline in appearance.

Longitudinal cracking approximating the width of the paving lane was observed on nearly all pavements studied. The most serious deterioration usually occurs at these longitudinal joints, especially if they were also "cold joints" (ones that remained over night during construction). Maintenance and repair was varied. Some owners installed a partial depth cementitious patch, ranging in width from 200 mm to 600 mm (8 in. to 24 in.) wide, and 100 mm to 250 mm (4 in. to 10 in.) deep, depending on the original thickness of the pavement and the extent of the deterioration. Others patched the eroded area with asphalt, epoxy compounds or a variety of other materials. If the deteriorated joint did not hamper the operation of the facility, many owners did nothing at all by way of repair. (Fig. 10)

Saw cut shrinkage control joints were installed on portions of four of the road pavements - 112th Ave., Edmonton, Fort Drum, NY, and Bighorn Ave., Alliance, NE. and the Saturn plant roads at Spring Hill, Tenn. At spacing in the range of 6 m to 9 m (20 ft. to 30 ft.), transverse shrinkage was almost completely controlled by the saw cuts. Bituminous crack filler was used on all the joints on Bighorn Ave. Crack sealing was also observed on some of the joints at Fort Drum and the Saturn plant pavements. No sealer was observed at 112th Ave. While sealing of joints (random or saw cut) may reduce joint edge chipping, most of the unsealed joints were also in very good condition. (Fig. 5)

Longitudinal uncontrolled shrinkage cracking seems to behave in a similar manner to conventional concrete pavement. Where the street paving lane width exceeded about 3.5 m (12 ft.) on Bighorn Ave., Alliance, NE, longitudinal uncontrolled shrinkage cracks appeared near the mid-point in about 10% of the panels. It appears that longitudinal control joints in an RCC street pavement should be considered, when the panel width exceeds 3.5 m (12 ft.) for typical street paving thicknesses of 150 mm to 200 mm (6 in. to 8 in.).

Figure 7 Chipping at the edge of shrinkage cracks from incompressible debris that enters the crack in winter. Fort Drum, NY. Built in 1988.

Figure 8 Joints were routed and sealed 12 months after construction was completed. Central Freight Inc., Austin, TX. Built in 1987.

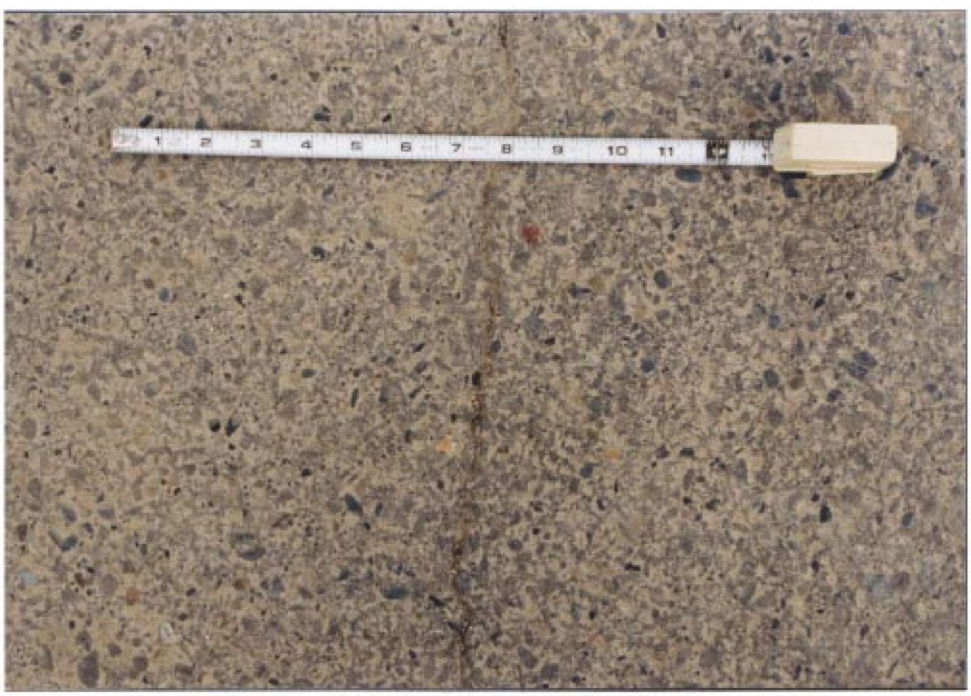


Figure 9 Reflection crack through 50 mm (2 in.) asphalt overlay. Fort St. John, B.C. Built in 1995.

3.3 Load Transfer at Joints

With the exception of one or two isolated locations, there is little evidence of "faulting" (loss of load transfer) at joints. This is one of the most surprising observations noted in this study. Of the 18 projects that were inspected, in only one case was there evidence of minor faulting. This observation is contrary to the assumption by some that there is poor load transfer across uncontrolled cracks in RCC pavements. As noted above, crack width varied from "hair line" to 6 mm (¼ in.), yet there was no differential elevation across most of the cracks.

The lack of any faulting is particularly interesting at the Port McNeill log sorting yard operated by MacMillan Bloedel Limited on Vancouver Island, British Columbia. This 300 mm (12 in.) thick pavement was built in 1978 and has been in continuous service since then. Cracking is extensive with spacing as close as 3 m (10 ft.) in some parts of the surface. Other than patching some of the cold joints, there has been very little joint maintenance done. (Fig. 10 & 11)

There is no obvious explanation for the *apparent* load transfer across the shrinkage cracks. One might speculate that few, if any, of the pavements have approached their repetitive designed loadings. While this may be true in some of the streets and military facilities that were studied, some of the older intermodal terminals and log sorting yards are more likely to be approaching, or have exceeded their designed loadings.

Further study of load transfer across saw cut joints and uncontrolled cracks may be needed.

Figure 10 A 20 year old shrinkage crack, MacMillan Bloedel Ltd. log sorting yard, Port McNeill, Vancouver Island, B.C.

Figure 11 MacMillan Bloedel Ltd. log sorting yard, Port McNeill, Vancouver Island. No faulting at the numerous cracks in the surface. Built in 1978.

3.4 Surface Smoothness

Based on the study of six road projects for this report, there is no doubt that RCC pavements can be successfully built to carry traffic on all but the highest class of multi-lane highway. While three of the six projects (Likely Road, 112th Avenue, Fort St. John streets) included an asphalt overlay to the RCC, excellent riding qualities were also achieved on the three exposed RCC pavements that were built with the high density asphalt paving machine.

The pavement on 99th Ave. in Portland, OR, is an excellent example of exposed RCC performance in an urban environment. The pavement was built in 1986 and carries commercial and bus traffic. Very little material has been eroded from the surface and the joints remain tight. There is no evidence of crack sealing. (Fig. 12)

The riding quality of the internal roads at the General Motors Saturn plant in Tennessee is also very good. (Fig. 13) The main entry road to the plant has been overlaid with 50 mm (2 in.) of asphalt, however the rest of the internal roads remain as exposed RCC pavement.

A surprising observation at the 20 year old Port McNeill log yard on Vancouver Island is the smoothness of the surface. The RCC matrix is dense with no protruding coarse aggregate as was observed at most of the other sites studied. A minor concern for the operators is the lack of traction for the log handling equipment when the pavement is dry. This is attributed to the layer of fine wood fibre dust that collects on the surface.

Figure 12 Collector class road, 99th Ave., Portland, OR. This exposed RCC pavement was built in 1986. The parking lanes on each side are asphalt pavement.

Figure 13 Internal roads at General Motors Saturn plant, Spring Hill, TN. Built in 1988.

3.5 Freeze/Thaw and Deicer Scaling Resistance

Confirming the reports of others[11], observations made in the field during this study indicate that it is possible to construct exposed RCC pavement that is durable in winter climates. RCC pavement with adequate portland cement content, that is well mixed, placed to the specified density and properly cured, appears to be resistant to the effects of freezing and thawing, and deicing salt.

All street pavements studied were at least three years old. Two of the pavements, GM Saturn Plant, TN, and 99th Ave., Portland, OR, are located in a moderate winter climate with few freeze/thaw cycles and no application of deicers.

The pavement on Likely Rd. near Williams Lake, B.C. is one of the best examples of RCC wear and durability in a winter climate. The pavement was built in 1987, however, within three years part of the original chip seal surface was worn away under heavy braking of logging trucks, leaving the RCC exposed. Though exposed to salt and sand through several winters, the surface was unaffected. In 1995 the RCC pavement was cover again, this time with 25 mm (1 in.) of asphalt. In 1998 that overlay is beginning to wear off once more, exposing the RCC base to traffic wear, sand and deicer salts for a second time. (Fig. 14)

At all of the RCC pavement sites in the cold regions of the United States and Canada, there is very little evidence of damage from freezing and thawing. Where deicers are used on exposed RCC pavement, as on Bighorn Ave. in Alliance, NE, there is no evidence of scaling.

In some cases salt may be tracked onto a storage area surface from adjacent roads such as at Gro-Bark Organics in Ontario, Bullmoose coal storage in B.C. and Fort Drum, New York. At these locations as well, the RCC pavement is performing as designed with no indication of scaling.

Figure 14 RCC is once again exposed on Likely Rd., Williams Lake, B.C. Built in 1987.

4.0 CONCLUSION

This study deals only with Roller Compacted Concrete (RCC) that is used in pavement applications. RCC for dams is an entirely separate field of RCC technology.

RCC has been used for pavements in the United States and Canada since the mid-1970's. Well over 3,000,000 m^2 (3,200,000 yd^2) have been built to date, the equivalent of more than 750 single lane kilometers (465 miles) of road 200 mm (8 in.) thick.

From more than 140 RCC pavement projects built to date, thirty-four in United States and Canada were inspected. Eighteen were selected for inclusion in this report. They represent a cross-section of RCC pavement applications currently in use. The oldest pavement was placed into service in 1978, while the most recent has been in use since 1995. The projects selected include roads, military facilities, a log sorting yard, storage areas, intermodal terminals and compost facilities.

The quality of RCC pavement construction in terms of smoothness, jointing and durability has greatly improved since the first projects were built in the 1970's. The introduction of high density asphalt paving machines to place and compact the RCC mixture has been the single most significant factor to influence RCC pavement construction. Since the early 1990's, RCC pavements with riding qualities equal to new concrete or asphalt pavements have been built. Six of the projects included in this report are road pavements.

Freeze/thaw resistance and deicer scaling resistance of RCC pavements have been a concern for many specifiers. While no reliable laboratory test is available to measure the durability of an RCC mix, experience in the field has shown that durable RCC pavements can be built. To resist damage from freezing and thawing, and deicers, the paving mixture must have adequate cementitious content and use sound aggregates. The ingredients must be well mixed and placed to the specified density, and be properly cured. From observations made in this study, in the first two to four years of service, some minor loss of fine aggregate from the surface occurs, leaving the coarser particles exposed. This loss of surface material then seems to stop and there is little change in the pavement thereafter.

The most severe service, both from traffic loading and freeze/thaw cycles, occurs at intermodal terminals, such as Conley and Moran Terminals at Boston, and the Burlington Northern Santa Fe Intermodal Terminal at Denver. At some areas of these terminals the coarse aggregate is exposed to a depth of 8 mm (⅜ in.). This surface condition seems to be of little concern to the operators.

Of greater concern however, is deterioration at longitudinal cold joints where construction stopped for the day. Insufficient compaction along this joint leads to loss of material due to weathering and traffic. This area has required the most maintenance. Repair materials included concrete, asphalt and other patching products.

There is very little evidence of structural failure in the pavements that were studied. This may be due in part to the high strength that is achieved as RCC ages. Core samples taken eight years after construction at a log sorting operation on Vancouver Island showed compressive strengths of 40 MPa (5880 psi).[3] It is also possible that some pavements have not received the loadings anticipated in the original design.

The Vancouver Island log sorting area operated by MacMillan Bloedel Ltd. is an good example of an RCC pavement that has been in continuous service for over twenty years and now exhibits extensive cracking (Figure 11). The cracking has had minimal effect on the operation of the log sorting yard and the pavement is still performing its original function. The operators report continued satisfaction with the RCC pavement.

Saw cut control joints were found on four projects, 112th Street in Edmonton, Alberta, Bighorn Ave. in Alliance, Nebraska, Fort Drum, New York and the General Motors Saturn plant roads at Spring Hill, Tennessee. Shrinkage was accommodated on all the other pavements through uncontrolled cracking. Where wood chips, coal, compost or logs are stored, debris from these materials fills the cracks, inhibiting moisture penetration. Very little routine crack sealing has been done as a general maintenance procedure on any of the projects studied. However one project, Central Freight Inc. at Austin. Texas, carried out a "route and seal" program on cracks five years after the pavement was completed in 1987. All the cracks there are in good condition.

The virtual absence of faulting at both transverse and longitudinal cracks is a surprising observation that came out of the study. Even at cracks up to 4 mm (3/16 in.) wide, where there is unlikely to be any load transfer, no faulting was evident. Where crack width was less than 2 mm (1/16 in.) some load transfer through aggregate interlock may be occurring. In some cases it is probable that the magnitude and frequency of loading has been below design values, resulting in reduced fatigue of the RCC pavement slab.

While several operators acknowledged that an RCC pavement is not of the high quality provided by conventional concrete, nearly all agreed that RCC is an adequate pavement option, considering the lower initial cost. Although information on pavement costs is not included in this study, it was apparent from conversations with facility operators, that the lower initial cost of an RCC pavement, compared to asphalt and conventional concrete, was a major consideration in the final selection of the pavement structure. Cost comparisons always vary depending local economics, however RCC pavement of equal design, is usually lower in first cost than conventional concrete, and often very close in first cost to a flexible pavement.

Appendix A

Detailed Project Reports

This appendix contains detailed reports on eighteen RCC pavement projects. Although thirty-four RCC projects in the United States and Canada were inspected, those included in this appendix represent a range of the most prominent applications, some of which have been in service since the late 1970's.

The amount of information contained in each report necessarily varies, depending on the age of the facility, and the availability of data from the contractors, consultants and owners, some of whom are no longer in business.

The detailed project reports have been subdivided into three broad classifications:

TERMINALS - These are intermodal facilities where goods are stored and transferred between ship, truck and rail for further distribution.

Burlington Northern Santa Fe Intermodal Terminal - Denver, CO
Conley Terminal - Massachusetts Port Authority, Boston, MA
Central Freight Terminal - Austin, TX
Lynnterm Terminal Warehouse - North Vancouver, B.C.

STORAGE AREAS - Projects in this group include wood chip storage for the pulp and paper industry, a log sorting yard, compost processing facilities, coal storage and military equipment hardstands.

Log sorting yard - MacMillan Bloedel Ltd., Port McNeill, B.C.
Coal storage - Bullmoose Mine, Teck Corporation, Tumbler Ridge, B.C.
Vehicle hardstands - U.S. Army, Fort Lewis, WA
Vehicle hardstands - U.S. Army, Fort Drum, NY
Wood chip storage - Fibreco Pulp Inc., Taylor B.C.
Compost processing - Gro-Bark Organics Inc., Hornby, ON
Wood chip storage - Alberta Pacific Forest Ind. - Athabaska, AB
Compost processing - City of Vancouver, B.C.

ROADS - Included in this group of projects are municipal streets, a secondary highway and internal industrial roads.

Secondary provincial highway - Likely Rd., Williams Lake, B.C.
Municipal road - 99th Ave., Portland OR.
Industrial roads - General Motors Saturn Plant, Spring Hill TN
Municipal road - 112th Ave., Edmonton, AB
Municipal road - Alliance, NE
Municipal roads - Fort St. John, B.C.

Project Summary Table

Project I.D.	Location	Use	Year	Area/Length	Thickness	Surface	Remarks
TERMINALS							
Burl. Northern Santa Fe	Denver Colo.	Containers	1986	105,350 m^2	375 & 500 mm	Exposed	
MASSPORT Terminal	Boston Mass.	Containers	1986/7	65,000 m^2	450 mm	Exposed	
Central Freight	Austin Texas	Truck Terminal	1987	58,500 m^2	175 & 200 mm	Exposed	
Lynnterm Terminal	Vancouver B.C.	Storage warehouse	1989-95	35,100 m^2	350 & 425 mm	Exposed	3 projects: 1989/93/95
STORAGE							
Log sorting yard	Pt. Mcneill B.C.	Log sorting	1978	24,000 m^2	300 mm	Exposed	
Bullmoose Mine	Tumbler Ridge B.C.	Coal storage	1982/3	19,000 m^2	225 mm	Exposed	
Fort Lewis	Fort Lewis Wash.	Equipment parking	1985	20,900 m^2	213 mm	Exposed	
Fort Drum	Fort Drum N.Y.	Equipment parking	1988	360,000 m^2	250 mm	Exposed	
Fibreco Pulp Incorp.	Taylor, B.C.	Wood chips	1988-95	17,000 m^2	300 mm	Exposed	Orig. project & expansion
Gro-Bark Organics Inc.	Hornby, Ontario	Compost	1990	24,000 m^2	200 mm	Exposed	
Alberta Pacific Ind.	Athabaska, Alberta	Wood chips	1992/3	117,000 m^2	200-350 mm	Exposed	
Vancouver compost	Delta, B.C.	Compost	1995	18,000 m^2	200 & 250 mm	Exposed	
ROADS							
Likely Road	Williams Lake, B.C.	Secondary Hwy.	1987	1.5 km (1 lane)	213 mm	25 mm overlay	
99th Avenue	Portland, Oregon	Collector street	1985	305 m (2 lanes)	200 mm	Exposed	
Gen. Motors Saturn Plant	Spring Hill, Tenn.	Roads & parking	1988	29 km (2 lanes equiv.)	150/200/250 mm	Exposed	3.2 km asphalt overlay
112th Avenue	Edmonton, Alberta	Collector street	1992	550 m (2 lanes)	200 mm	75 mm overlay	150 mm CTB
Bighorn Avenue	Alliance, Neb.	Residential street	1994	400 m (2 lanes)	150 mm	Exposed	
Municipal streets	Ft. St. John, B.C.	Resid./Collector Rds.	1995/96/97	2740 m (2 lanes)	225 mm	50 mm overlay	Part of long term prog.

Terminals

Figure 15 Intermodal Terminal, Burlington Northern Santa Fe RR., Denver, CO

Owner: Burlington Northern Santa Fe Railroad
Engineer: Centennial Engineering Inc., Arvada, CO
Location: Denver, Colorado
Type of Use: Truck/rail Intermodal Container Terminal
Contractor: Peltz Companies, Alliance, NE
Year Built: 1986
Thickness: 375 mm & 500 mm (15 in. & 20 in.)
Area: 105,350 m^2 (126,000 yd^2)

Traffic on this pavement involves the transfer of loaded containers from rail cars to highway trucks for local distribution. No loading information is available since container weights are highly variable. A straddle crane spans the rail track and a truck lane on each side of the track. Estimated working load of the crane wheel assemblies on one side is 25,000 kg (55,000 lbs.).

Prior to construction, the site was a swampy area. The water table remains near the surface today. A subbase of approximately 600 mm (24 in.) of pit run gravel was placed prior to RCC construction. Maximum coarse aggregate size in the RCC mix was 20 mm (¾ in.), with maximum 5% passing the 75μm (#200) screen.

The pavement was built in lanes 6.4 m (21 ft.) wide using a high density asphalt paver. Most of the area was 375 mm (15 in.) thick, consisting of a 225 mm (9 in.) base layer and 150 mm (6 in.) top layer.

As with most of the RCC pavements studied, transverse shrinkage crack spacing is highly variable, a few are as close as 6 m (20 ft.), with the occasional crack at 30 m (100 ft.) away from the next. Most are tight, though minor edge breakdown is beginning to show up in a few areas. According to the terminal manager, very little regular maintenance is done. Longitudinal joints are showing more deterioration with edge breakdown widening some sections to 100 mm (4 in.). There is no settlement (faulting) across any of the shrinkage cracks or longitudinal joints. One panel approximately 4.5 m (15 ft.) square has lifted about 75 mm (3 in.) at one corner. There is no obvious explanation for this occurrence.

For reasons that are unclear, transverse saw cuts, 75 mm (3 in.) deep, at approximately 150 m (500 ft.) centers, were made in the RCC surface 12 months after the project was completed. Bituminous joint filler was installed over foam backer rod. Most of the joint material is not functioning now. The surface exhibits the typical discontinuous short shallow surface cracks, 100-150 mm (4-6 in.) long, often seen in RCC pavements. *There is no evidence that these cracks are having any negative effect on the performance of the pavement.*

Figure 16 Closeup of the RCC surface. Built 1986.

Terminals

Figure 17 Conley Terminal, Boston, MA. Built 1986.

Owner: Massachusetts Port Authority (MASSPORT)
Engineers: Whitman & Howard Inc.
Location: Conley Terminal, South Boston, MA
Type of Use: Ship/truck/rail Intermodal Terminal
Year Built: 1986/87
Contractor: J.F. White Contracting Co., Newton, MA
RCC Subcontractor - Jack Cewe Ltd., Vancouver, B.C., Canada
Thickness: 450 mm (18 in.)
Area: 65,000 m^2 (77,750 s.y.)

Conley Terminal is one of two RCC paved intermodal facilities administered by the Massachusetts Port Authority. Moran Terminal, built in 1987, is the name of the other terminal. Conley Terminal , the older of the two, was constructed in three phases starting late in 1986 and completed in 1987. Only the Conley Terminal was inspected for this report. MASSPORT officials commented that the Moran Terminal RCC pavement is in better condition than the Conley Terminal pavement.

The RCC was constructed in three lifts to a total depth of 450 mm (18 in.). There is a 200 mm (8 in.) compacted granular base under the RCC. Lift thickness varied in the multi-layer construction. Part of the pavement was built in three 150 mm (6 in.) layers, while in other areas the bottom lift was 225 mm (9 in.) thick, followed by two 112 mm (4 ½ in.) layers.

The RCC mix in the first phase contained 356 kg/m^3 (600 $lbs./yd^3$) of portland cement, and

72 kg/m^3 (120 lbs./yd^3) of fly ash. In the second and third phases, the portland cement content was adjusted to 296 kg/m^3 (500 lbs./yd^3) and fly ash added at the rate of 59 kg/m^3 (100 lbs./yd^3) Maximum size coarse aggregate was 20 mm (¾ in.). The specified 28 day flexural strength of 4.8 MPa (700 psi) was achieved.

In 1993, PCS/Law Engineering of Beltsville, Maryland, prepared an RCC Pavement Repair Plan for the Conley Terminal that addressed three areas of distress: longitudinal joint deterioration, surface deterioration and patch deterioration at transverse construction joints. The permanent repairs have not been made, however temporary patches with hot mix asphalt have been applied to the worst eroded cracks and cold joints. Observations made during the 1998 inspection confirm that longitudinal joint deterioration continues to occur.

In areas where transverse shrinkage has occurred, crack width is highly variable. Some cracks remain tight, showing some minor edge break off, while in a few areas, the shrinkage cracks have opened to 6 mm (¼ in.). There is no evidence of a regular crack sealing program, though there are indications of some crack filling that was done in the past. Concrete has been used for reinstatement of the slab where utility cuts or joint repairs have been made. It is also reported that delamination of the RCC layers has been found during repair operations.

Away from longitudinal construction joints and the transverse shrinkage cracks, the RCC surface shows only minor erosion to a maximum depth of approximately 6 mm (¼ in.) in a some areas. The surface erosion is not uniform over the entire pavement however. At least 75% of the paved surface exhibits the typical loss of fine material that was observed on nearly every RCC pavement inspected in this study.

At the Moran Terminal, more extensive repairs to cold joints were carried out in 1996. The top layer was saw cut and removed for a width of approximately 450 mm (18 in.) on each side of the joint. Load transfer dowels were installed and the pavement reinstated with 27.5 MPa (4000 psi) conventional concrete. Approximately 1370 m (4500 ft.) of cold joints were repaired in this manner. MASSPORT officials report that the Moran Terminal repair is performing well.

Figure 18 Typical condition of the RCC surface at Conley Terminal, Boston, MA

Terminals

Figure 19 RCC truck terminal pavement at Austin, TX is in excellent condition after eleven years of service.

Owner: Central Freight Lines, Austin, Texas
Engineer: MLA Engineers, Austin, Texas
Location: Austin, TX
Type of Use: Truck Terminal
Contractor: Peltz Companies, Alliance, NE
Year Built: 1987
Thickness: 175 mm (7 in.) in storage areas (75%), 200 mm (8 in.) traveled areas (25%)
Area: 58,500 m^2 (70,000 yd^2)

OBSERVATIONS
Terminal management is very satisfied with the RCC pavement performance. There has been some loss of surface fine material leaving the coarse aggregate exposed to a depth of up to 6 mm (¼ in.) in less than 10 % of the area.

Longitudinal joints are less than 6 mm (¼ in.) wide, spaced at approximately 4.3 m (14 ft.), corresponding to the paver width. Spacing of the transverse shrinkage cracks is variable, some as close as 7 m (23 ft.), and others up to 15 m (50 ft.) apart. The average spacing is 9 m (30 ft.). A "route and seal" program of crack maintenance was carried out about 5 years after construction. All transverse cracks are tight and there is no evidence of faulting anywhere.

Though the pavement is in constant use, especially at loading bays, there is no evidence of distress due to wheel loads or trailer dolly pads. Compressive strength tests during construction averaged

25 MPa (3625 psi). Cementitious content of the mix was 150 kg/m^3 (250 lbs./yd^3) portland cement, and 150 kg/m^3 (250 lbs./yd^3) of fly ash. Maximum aggregate size was 20 mm (¾ in.) Due to the urgency to put the terminal into service, very little curing was done. No gravel base was used, however 300 mm (12 in.) of the clay subgrade was stabilized with lime.

Figure 20 Shrinkage crack and surface condition, Central Freight Terminal, Austin, TX. Built in 1987.

Terminals

Figure 21 The RCC operating surface inside the warehouse where baled pulp bundles are stored.

Owner: Port of Vancouver - Operating tenant: Western Stevedoring
Engineer: 1989 project - Westmar Consultants Ltd., Vancouver
1993 & 1995 projects - Jack Cewe Ltd., Vancouver
Location: North Vancouver, British Columbia, Canada
Type of Use: Warehouse storage of baled pulp
Contractor: Jack Cewe Ltd., Vancouver, B.C.
Year Built: 1989, 1993, 1995
Thickness: Variable: 350 mm & 425 mm (12 in. & 15 in.)
Area: 35,100 m^2 (42,000 yd^2)

This is a dockside facility that ships finished lumber and bundles of baled pulp used in paper manufacturing. The pulp bales are stored under cover in warehouses with RCC paved floors. Rubber tired loaders transfer the pulp bales from rail cars to the warehouse prior to ship loading. Wheel loads are concentrated on the drive axle, and the lightly loaded steering axle. Following the success of the first RCC floor built in 1989, two additional RCC warehouse floors were built in 1993 and 1995.

There has been some erosion of fines from parts of the RCC surface on the oldest pavement, approximately 6 mm (¼ in.). This condition now appears to have stabilized. Transverse shrinkage cracks have typical spacing of approximately 15 m (50 ft.). No sealing of the transverse cracks has been done. In some areas the longitudinal construction joints have sustained some erosion to a maximum width of about 150 mm (6 in.) and depth of 37 mm (1½ in.). The problem areas have been successfully patched with portland cement mortar.

There is no evidence of faulting at the transverse shrinkage cracks, however there are a few isolated locations of faulting along longitudinal construction joints.

The operators express thorough satisfaction with the performance of the RCC warehouse floors.

Figure 22 Operating surface of the warehouse floor, Lynnterm, North Vancouver, B.C. Built in 1989.

Storage

Figure 23 Log sorting yard, Port McNeill, B.C.

Owner: MacMillan Bloedel Limited
Engineer: Yule, Bloomfield Consultants
Location: Port McNeill, B.C. (Vancouver Island)
Type of Use: Log Sorting Yard
Contractor: Jack Cewe Ltd.
Year Built: 1978
Thickness: 300 mm (12 in.)
Area: 24,000 m^2 (28,700 yd^2)

This pavement is in good condition, considering that this log sorting area has been in continuous operation for twenty years. Snow is common in this area of the British Columbia coast, with frequent cycles of freezing and thawing. Frost penetration is approximately 300 mm (12 in.)

Unlike most other heavy duty RCC pavements observed in this study, there has been practically no loss of fine material from the surface. All of the coarse aggregate remains firmly embedded in the matrix. The pavement surface is very smooth, resulting in occasional equipment traction problems.

There is considerable cracking over the entire area, spaced at an average of 6 m (20 ft.) in any direction, and as close as 3 m (10 ft.) in a few areas. Deterioration of the longitudinal construction joints has been the most significant maintenance problem. This is not surprising since construction techniques were still evolving at this early stage of RCC pavement development in 1978. Approximately 25% of the longitudinal joints have been repaired by partial removal of the surface to a depth of 150 mm (6 in.), and replaced with conventional concrete. Performance of the concrete repairs has been satisfactory.

Most of the cracks exhibit typical edge breaking at the surface, resulting in a top width of 100 mm (4 in.) in some places. All of the cracks are filled with wood debris. No faulting was observed.

The extensive cracking of this twenty year old pavement may be due to one or more of the following conditions -

(1) The pavement may be near, or have exceeded the design life in frequency and magnitude of axle loads. No accurate load data over the life of the pavement is available.

(2) Loss of subgrade support during spring thaw, when the subgrade is saturated, may also be a factor in cracking.

(3) No doubt some of the cracking is due to typical concrete shrinkage early in the service life of the pavement.

At the present time, a log stacker (59,000 kg, 130,000 lbs. capacity) operates on the surface, as well as two smaller loaders (22,000 kg, 50,000 lbs. capacity).

The operators report that they are very satisfied with the performance of the RCC pavement.

Figure 24 Though cracking of the surface is extensive, the log sorting yard continues in full operation after 20 years.

Storage

Figure 25 Coal is stored on the RCC surface prior to shipment by rail to offshore markets.

Owner: Bullmoose Coal Company
Engineer: Gordon Spratt & Associates, Vancouver, B.C.
Location: Tumbler Ridge, B.C., Canada
Type of Use: Storage of processed coal
Contractor: Peter Kiewit & Sons Co. Ltd., Vancouver, B.C.
Year Built: 1982/83
Thickness: 225 mm (9 in)
Area: 19,000 m^2 (22,700 yd^2)

This coal storage area in the northern area of British Columbia, was one of the first exposed RCC pavements to be built in a severe winter climate. Rubber tired loaders operate on the surface moving coal from storage to rail car loading hoppers. There has been no regular maintenance on the pavement since construction, although one small area of subbase failure was repaired with conventional concrete.

The owners are totally satisfied with the pavement, citing the advantages of higher operating speed and significantly reduced maintenance on equipment.

Outside the limits of the RCC pavement, coal is used as the base and operating surface of the storage area. The transition between the two materials is almost invisible, showing no settlement. Frost penetration in the area is 1.8 m to 2.4 m (6 ft. to 8 ft.) The subgrade is gravel.

Other than the typical loss of fines from the top 2 mm (1/16 in.), there is no distress in the pavement. Maximum aggregate size is 31 mm (1¼ in.). Shrinkage crack spacing is variable, averaging 10 m (35 ft.). No crack sealing has been done, though most of the cracks are filled with coal fines. No faulting has occurred at the shrinkage cracks after 16 years of service. The pavement is in excellent condition.

Figure 26 Shrinkage cracks become filled with coal dust.

Storage

Figure 27 Hardstand for military vehicle parking, Fort Lewis, WA.

Owner:	United States Army
Engineer:	U.S. Army Corps of Engineers
Location:	Fort Lewis, WA. (south of Tacoma, WA.)
Type of Use:	Military equipment storage
Contractor:	Jack Cewe Ltd.
Year Built:	1985
Thickness:	213 mm (8½ in.)
Area:	20,900 m^2 (25,000 yd^2)

The USACE designed a test section of RCC pavement that was used as a tank training road in 1984 at Fort Lewis. The demonstration was successful and in 1985 authorization was received to built an RCC pavement on which mobile rocket launch vehicles would be stored.

The cementitious content of the mix was 267 kg/m^3 (450 lbs/yd^3) of portland cement, and 90 kg/m^3 (150 lbs/yd^3) of fly ash. The 28 day flexural strength specification of 4.1 MPa (600 psi) was met.

Located south of Seattle, the climate receives mild winter weather with little frost penetration. There are frequent cycles of freezing and thawing.

The usual shrinkage cracking pattern has developed, however no joint sealing has been done. The pavement is in very good condition although it does not appear to be subjected to much heavy loading.

Figure 28 Typical shrinkage cracking pattern at Fort Lewis, WA.

Storage

Figure 29 Apron pavement adjacent to an equipment maintenance shop.

Owner:	United States Army
Engineer:	United States Army Corps of Engineers
Location:	Fort Drum, New York (near Watertown, NY)
Type of Use:	Military vehicle parking
Contractor:	Morrison-Knudsen Inc., Boise, ID
	RCC Paving Subcontractor: Peltz Companies, Alliance, NE
Year Built:	1988
Thickness:	250 mm (10 in.)
Area:	360,000 m^2 (430,500 yd^2)

This is another RCC pavement that is in excellent condition after 10 years of service. RCC paving has been used in several compounds around the base where military vehicles are stored. Though much of the area is used for storage, and does not appear to receive heavy traffic, the RCC access roads to and from these areas are in frequent use. This part of New York State receives winter climate conditions typical of the northeastern United States. Very little deicing salt is used on the RCC surfaces.

The maximum aggregate size in the RCC mix was 20 mm (¾ in.). Portland cement content was 244 kg/m^3 (413 lbs./yd^3) and fly ash content was 81 kg/m^3 (137 lbs./yd^3). The specified 28 day flexural strength was 4.8 MPa, and 14 day job samples ranged from 5.2 MPa (750 psi) to 6.2 MPa (900 psi).

High density asphalt pavers placed the RCC in a single 250 mm (10 in.) lift. Steel wheel rollers, and combination steel/rubber tired rollers in the static mode, were used for compaction. A 200 mm (8 in.) granular subbase was placed prior to RCC construction.

According to personnel in charge of maintenance, there have been no performance problems with the RCC pavement. There is no regular program of joint maintenance in place. There is past evidence of a "route and seal" maintenance program on a few of the longitudinal joints. Spacing of transverse shrinkage cracks is variable, ranging from 7.5 m (25 ft.) in some areas up to 18 m (60 ft.) in others.

The surface shows the usual minor loss of fine material in the top 2 mm (1/16 in.) that was observed on nearly every pavement in this study.

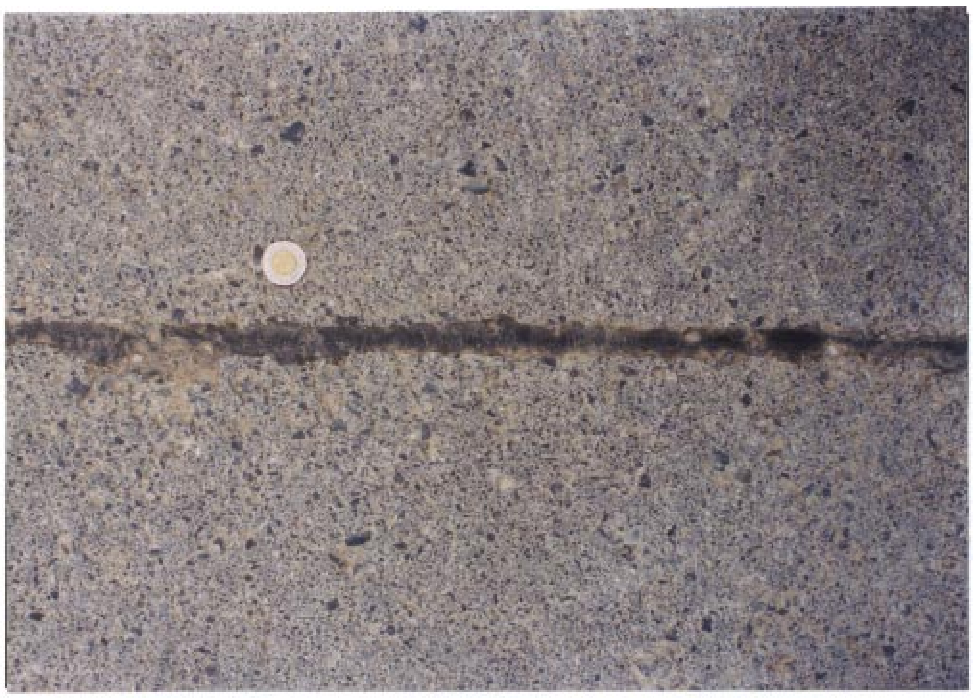


Figure 30 Bituminous joint sealant at a shrinkage crack.

Storage

Figure 31 Storage of wood chips on RCC, provides a durable surface that is easy to clean.

Owner: Fibreco Pulp Inc.
Engineer: Phase I - (unknown) Phase II - Jack Cewe Ltd.
Location: Taylor, British Columbia
Type of Use: Wood chip storage
Contractor: Phase I - DCS Construction Ltd., Ft.. St. John, B.C.
Phase II - Jack Cewe Ltd., Vancouver, B.C.
Year Built: 1988 (Phase I), 1995 (Phase II)
Thickness: 300 mm (12 in.)
Area: 17,000 m^2 (20,300 yd^2)

Both phases of this pavement are in excellent condition. There is the usual small amount of surface erosion on the older section, up to 2 mm (1/16 in.) in a few areas. The most recent phase has lost practically none of the fine surface material. The site is in a winter climate where frost penetrates to 1.8 m (6 ft.). While the ground under the chip pile does not freeze, approximately 3.6 m (12 ft.) around the outside edge of the chip pile remains exposed most of the time for equipment travel. There is no evidence of differential frost heaving on this perimeter roadway.

The granular base consisted of 50 mm (2 in.) of 20 mm (¾ in.) crushed gravel over 150 mm (6 in.) of pit run gravel. Coarse aggregate specification for the RCC mix was 100% passing 20 mm (¾ in.) sieve. Up to 8% was allowed past the 75 μm (#200 sieve). Cement content was 311 kg/m^3 (525 lbs./yd^3)

The 300 mm (12 in.) thick pavement was placed in two 150 mm (6 in.) lifts. There is no evidence of delamination between the layers.

Shrinkage cracks remain tight with only minor edge breaking at the surface to a maximum width of 6 mm (¼ in.). Spacing of the cracks averages 9 m (30 ft.). No joint sealing or other maintenance has been done. Wood debris from the chips fills all of the cracks.

Figure 32 Shrinkage cracks remain tight. Debris from the wood chips fills any space.

Storage

Figure 33 The heat generated in the composting process demands a pavement that will withstand high temperatures, such as RCC.

Owner: Gro-Bark Organics Inc., Hornby, Ontario
Engineer: John Emery Geotechnical Engineering Ltd., Toronto, Ontario
Contractor: Dufferin Construction, Toronto, Ontario
Location: Hornby, Ontario
Type of Use: Compost processing
Year Built: 1990
Thickness: 200 mm (8 in.)
Area: 24,000 m^2 (28,700 yd^2)

Since the composting process generates considerable heat, 65°C (150°F), a rigid pavement was the only option when considering surfacing for the site. RCC was chosen as a lower cost alternative to conventional concrete. This pavement was also the first use of RCC in Ontario.

Fine material from the surface has been worn off leaving the coarse aggregate exposed to a depth of approximately 2 mm (1/16 in.) in some areas.

RCC compressive strength tests in excess of 30 MPa (4350 psi) at 28 days were reported.

The owners have experienced no significant problems in the eight years of operation and are thoroughly satisfied with the performance of the pavement. The pattern of shrinkage cracking is typical of most RCC pavements. Spacing averages 12 m (40 ft.) No faulting is apparent at the cracks. There is no regular maintenance program of crack sealing. All cracks are filled with compost debris.

While no deicing salt is applied to the working area of the pavement, some amount is inevitably tracked onto the RCC surface of the access road in winter. The is no evidence of significant surface scaling from salt action in this area.

Figure 34 Typical RCC crack showing little deterioration. Joint sealer would be difficult to apply.

Storage

Figure 35 Wood chips are piled to a height of 12 m (40 ft.) on this RCC pavement in Northern Alberta, Canada.

Owner:	Alberta Pacific Forest Industries
Engineer:	EBA Engineering Consultants Ltd., Edmonton, Alberta
Location:	Athabaska, Alberta, Canada
Type of Use:	Wood chip storage for pulp manufacturing
Contractor:	Standard General Construction Inc., Edmonton, Alberta
Year Built:	1992, 1993
Thickness:	Variable: 200 mm - 350 mm (8 in.-14 in.) Predominant thickness: 250 mm (10 in.)
Area:	117,400 m^2 (128,400 yd^2)

This pavement is in excellent condition. The location is in the north central region of the Province of Alberta, where severe winter conditions are common. Frost penetration reaches 2.4 m (8 ft.) Subgrade soil is clay (unstabilized).

Maximum size aggregate in the mix was 20 mm (¾ in.), with 5-8% passing the 75 μm (#200) mesh screen. Cementitious content was 275 kg/m^3 of portland cement (465 lbs/yd^3) and 74 kg/m^3 (125 lbs/yd^3) of fly ash. The average 28 day compressive strength was 27 MPa (3915 psi).

The 250 mm (10 in.) thick pavement was placed in 2 lifts, 100 mm (top) and 150 mm (base) (4 in. and 6 in.). The slab thickness was increased to 300 mm (12 in.) along the outside 1.5 m (5 ft.) to provide a thickened edge.

The surface is covered most of the time with wood chips to a height of at least 12 m (40 ft.).

Periodically rubber tired loaders (CAT 988) clean the surface to bare pavement. A few surface scars were observed but there is no gouging. Occasionally bulldozers (CAT D-8 type) with lugged tracks will travel on the RCC. Even this equipment causes no damage other than a few scuff marks. (Fig. 37)

There is no frost penetration where wood chips are stored, though the exposed perimeter of the chip piles are subject to winter conditions. There is no evidence of freeze/thaw deterioration or differential heaving due to freezing from the edges of the piles.

Spacing of transverse shrinkage cracks averages 18 to 20 m (60 to 65 ft.). Crack width at the surface averages 6 mm (¼ in.) though the cracks are only hairline a few millimeters below the surface. Both the transverse shrinkage cracks and construction joints are tight and filled with wood debris. No crack maintenance whatsoever has been done since initial construction. Load transfer across all cracks appears to be excellent since there is no evidence of faulting anywhere.

Figure 36 Wood debris fills the shrinkage cracks. The company finds no need to carry out any maintenance on the cracks.

Figure 37 Bulldozer lugged tracks only scuff the surface of the RCC chip storage pile base.

Storage

Figure 38 RCC composting site, City of Vancouver

Owner: City of Vancouver, British Columbia
Engineer: SRK Robinson, Burnaby, B.C.
Location: Delta, British Columbia (a Vancouver suburb)
Type of Use: Processing of yard waste into compost
Year Built: 1995
Thickness: 200 mm and 250 mm (8 in. & 10 in.)
Area: 18,000 m^2 (21,500 yd^2)

RCC was selected for construction of this facility over options of conventional concrete and asphalt pavement. Though 10% higher than the asphalt option in first cost, the estimated lower maintenance cost over the projected ten year life of the project weighted the decision in favour of RCC.

The RCC mix design included 290 kg/m^3 (490 lb./yd^3) portland cement and maximum 20 mm (⅝ in.) crushed gravel aggregate. Poor subgrade conditions necessitated placement of an 200 mm (8 in.) gravel subbase. Compressive strength of cores taken at one month ranged from 28-35 MPa (4100-5100 psi).

After three years of service the pavement is performing to the full satisfaction of the City. No maintenance has been required. Shrinkage cracks are spaced at approximately 15 m (50 ft.). At this early stage there is no evidence of deterioration at construction joints. Nor is there any indication of faulting at the cracks.

Roads

Figure 39 Likely Road, near Williams Lake, B.C.

Owner: Ministry of Transportation & Highways, Province of British Columbia, Canada
Engineer: Min. of Transportation & Highways, B.C.
Location: Likely Road (near Williams Lake, British Columbia)
Type of Use: Secondary highway carrying loaded logging trucks
Contractor: Jack Cewe Ltd., Vancouver, B.C. Canada
Year Built: 1987
Thickness: 213 mm (8½ in.)
Area/Length 1.5 km (0.93 mi.) 1 lane wide

This project (also known as the "Horsefly Rd.") has been reported on in several other RCC papers. On inspection in 1998, it is in excellent condition. The pavement was built to carry loaded logging trucks down an 8% grade. Only the downhill lane was milled out and replaced with 200 mm (8 in.) of RCC. A chip seal surface was applied following completion of the RCC in 1987. Approximately 60 loaded logging trucks per day travel on the RCC pavement

The mix design included 252 kg/m^3 (425 lbs./yd^3) of portland cement and 85 kg/m^3 (143 lbs./yd^3) of fly ash. Maximum aggregate size was 20 mm (¾ in.).

Within three years, approximately 60 m (200 ft.) of the chip seal surface was abraded away as the trucks stopped at a main highway intersection, exposing the RCC surface to winter conditions of sand and deicing salt. While some of the fine surface material, ±2 mm (1/16 in.) was abraded away, the pavement performed satisfactorily.

In 1995 a 25 mm (1 in.) asphalt overlay replaced the chip seal surface. At the time of inspection, even this surface is showing traffic wear at the intersection, again exposing a small area of RCC base. Shrinkage cracks have reflected through the asphalt and crack sealing maintenance has been done. There is no evidence of faulting at the transverse shrinkage cracks. Initial concern about performance of the longitudinal centre line joint between the RCC lane and the pre-existing asphalt pavement on the uphill lane has proven to be unfounded. There is no faulting and the longitudinal centerline reflection crack is hairline in appearance. At eleven years of service, this pavement provides strong evidence to support the use of RCC for secondary highways.

Figure 40 RCC surface is exposed again, as the 25 mm (1 in.) asphalt overlay is worn away at the intersection.

Roads

Figure 41 99th Avenue, Portland, OR. A successful experiment in RCC street paving.

Owner: City of Portland, Oregon
Engineer: CH2M Hill, Portland, Oregon
Location: 99th Avenue, Portland, Oregon
Type of Use: Collector street
Contractor: Jack Cewe Ltd., Vancouver, B.C.
Year Built: 1985
Thickness: 200 mm (8 in.)
Area/Length: 305 m x 8 m (1000 ft. x 26 ft.)

A two block test section of exposed RCC pavement, one lane each way, was built as an experiment in 1985. An asphalt parking lane was built on each side. The pavement continues to carry local auto, truck and bus traffic, and is little changed from the day it was completed.

There is no evidence of any major maintenance having been done. Some utility cuts have been patched with conventional concrete.

To evaluate the performance of an RCC pavement constructed with no external compaction, one block of this project was placed with the only compaction being that from the tamping bars of the paver. The only difference between the two sections that can be observed today is an abnormal amount of surface erosion in a few areas near the gutter line of the uncompacted section. Otherwise the pavement remains smooth and fully functional. There is no difference in the ride between the section compacted with rollers and the section built without external compaction.

Figure 42 The surface of 99th Ave. shows very little wear after 12 years.

Roads

Figure 43 All of the internal plant roads are exposed RCC pavement.

Owner: Saturn Corporation
Engineer: General Motors Argonaut Division
Location: Spring Hill, Tennessee
Type of Use: Internal roads, parking and vehicle storage
Contractor: Morrison-Knudson Co. Inc., Boise, Idaho
Year Built: 1988
Thickness: Variable - parking 150 mm (6 in.), roads 200 mm (8 in.), loading docks 250 mm (10 in.)
Area/Length: Equivalent 29 km. (18 miles), 7.5 m (24 ft..) wide

Considering the relatively short period of RCC experience in road applications at the time this pavement was built in 1988, it is excellent condition. In particular, the ride is extremely good. At the time of construction, this was the largest RCC pavement project in the United States. For cosmetic reasons, a 3.2 km (2 mi.) section of the main entrance road has been capped with 50 mm (2 in.) of asphalt. Transverse reflection cracks are showing through but are of no concern, and no maintenance is planned. All remaining roads and parking/storage areas are exposed RCC. A few longitudinal cracks and cold joints have been sealed. No other crack sealing has been done.

All trucks delivering supplies to the site enter through a separate gate where the RCC is 250 mm (10 in.) thick. This pavement is also in very good condition and shows no distress.

The RCC mix contained 282 kg/m^3 (475 lbs./yd^3) of portland cement and 36 kg/m^3 (60 lbs./yd^3) of fly ash. At a water/cementitious materials ratio of 0.36, 28-day flexural strength exceeded 6.2

MPa (900 psi). The surface was water cured. Initial transverse control joints were saw cut at 30 m (100 ft.) spacing, followed at 7 days by additional cuts at 15 m (50 ft.) intervals. All saw cut joints are performing satisfactorily. As might be expected, there are a few uncontrolled intermediate shrinkage cracks, however they present no performance problems.

There are a few areas of pavement where there has been subgrade failure, less than 300 m (1000 ft.) total length. These areas have been repaired with conventional concrete. The RCC surface adjacent to of some loading docks is showing surface raveling up to a depth of 6 mm (¼ in.). This condition does not occur on the road surfaces. There is no explanation for this other than the fact that these areas are small and may not have received adequate compaction. They present no operational problem to the owners.

Figure 44 Typical RCC pavement surface at the GM Saturn plant.

Roads

Figure 45 This experimental RCC pavement was left. exposed to traffic for 3 years prior to application of the planned asphalt overlay.

Owner: City of Edmonton, Alberta, Canada
Engineer: HBT Agra Ltd., Edmonton, Alberta
Location: 112th Avenue, Edmonton, Alberta
Type of Use: Two lane collector urban pavement
Contractor: Standard General Construction Inc., Edmonton, Alberta
Year Built: 1992
Thickness: 200 mm (8 in.) on 150 mm (6 in.) cement stabilized subgrade
Area/Length: 550 m (1800 ft.)

This project was built as an experiment in RCC pavement construction. Participants in the project included the City of Edmonton, Alberta, Canada, Standard General Construction (Edmonton) and the Portland Cement Association. Extensive details of the original construction can be found in Reference 2.

The RCC pavement was left exposed to traffic and winter conditions from 1992 to 1995.

An asphalt overlay 75 mm (3 in.) thick was applied to the RCC pavement in 1995 in accordance with the original plan of the experiment. Saw cuts in the RCC were made on part of the project at intervals ranging from 15 ft. (4.5 m) to 50 ft. (15 m). Shrinkage cracks were allowed to form in a random fashion on the rest of the pavement. Most saw cuts and random shrinkage cracks have reflected through the asphalt overlay. There is no difference in the performance of either type of crack. No crack sealing was evident at the time of inspection.

There is evidence of occasional longitudinal cracking (less than 5% of the total lane length) at the mid-point of the traffic lanes. There is also a small amount of longitudinal cracking in the wheel paths. No reflection cracks were seen at the centre line joint. There is no apparent distress in the pavement due to any of the reflection cracking.

The rideability of this pavement is excellent.

Figure 46 112th Ave, Edmonton, AB

Roads

Figure 47 The smoothness of this city street built with RCC is similar to any new pavement built with traditional paving materials.

Owner: City of Alliance, Nebraska
Engineer: Peltz Companies, Alliance, Nebraska
Location: Bighorn Ave., Alliance, Nebraska
Type of Use: Two lane residential street
Contractor: Peltz Companies, Alliance, Nebraska
Year Built: 1994
Thickness: 150 mm (6 in.)
Area/Length: 4535 m^2 (5200 yd^2), 400 m x 11.3 m (1320 ft. x 37 ft.)

This project was constructed by Peltz Construction Inc., of Alliance, NE, to demonstrate the feasibility of exposed RCC pavement for urban street use. The subgrade was sandy soil. A 50 mm (2 in.) leveling course of sand was laid prior to placing the RCC between a concrete curb and gutter. Pavement width is 9 m (30 ft.), placed in two 4.5 m (15 ft.) wide passes of the high density asphalt paver. Transverse control joints were saw cut to 37 mm (1½ in.) depth at 8 m (27 ft.) spacing and sealed. There is only one longitudinal joint at the centre line, resulting in a few random longitudinal cracks near the mid-point of each 4.5 m (15 ft.) wide lane.

The RCC mix consisted of 13 mm (½ in.) coarse aggregate which produced a very tight surface. Cement content was 335 kg/m^3 (564 $lbs./yd^3$). Optimum moisture content was 7.6%

The area of Nebraska encounters typical mid-western USA winter conditions. Deicing salt is used regularly in winter. There is no evidence of any freeze/thaw deterioration whatsoever after four winters of exposure. The smoothness and quality of this pavement are outstanding. The ride is equal to the best new concrete or asphalt pavement. This project provides clear evidence that a durable, exposed RCC pavement can be built using today's road building technology.

Figure 48 Bighorn Ave. at four years. The surface is in good condition and shrinkage cracks are tight.

Roads

Figure 49 The street reconstruction program in the city uses RCC with an asphalt overlay.

Owner: City of Fort St. John. British Columbia, Canada
Engineer: Urban Systems Ltd., Fort St. John
Location: Fort St. John, British Columbia, Canada
Type of Use: Residential and collector class urban pavements
Contractors: Jack Cewe Ltd. Vancouver, British Columbia (1995, 1997)
Lafarge Const. Materials Ltd. Edmonton, Alberta (1996)
Year Built: 1995, 1996, 1997
Thickness: 225 mm (9 in.) plus 50 mm (2 in.) asphalt overlay
Area/Length: 24,700 m^2 (27,000 yd^2), 2740 m x 8.2 m (9000 ft. x 27 ft.)

This city is located in a severe winter region of British Columbia. The subgrade soil is predominantly clay which has been a factor in the poor performance of Fort St. John streets in the past.

As part of a street reconstruction program inaugurated in 1995, test sections of RCC pavement were built, including a 50 mm (2 in.) asphalt overlay. The test sections performed well and RCC was selected for the 20 year street reconstruction program.

Additional streets were paved in 1996 and 1997. Inspection during this study confirmed that all pavements are performing as expected. The only maintenance required has been a crack sealing program by city maintenance crews. The reflection cracks through the asphalt are hairline in appearance and spacing is unusually long, averaging 30 m (100 ft). Discontinuous longitudinal cracks appear near the center line in a few areas. There is no evidence of faulting at any of the cracks. Nor is there any evidence of rutting in the asphalt overlay.

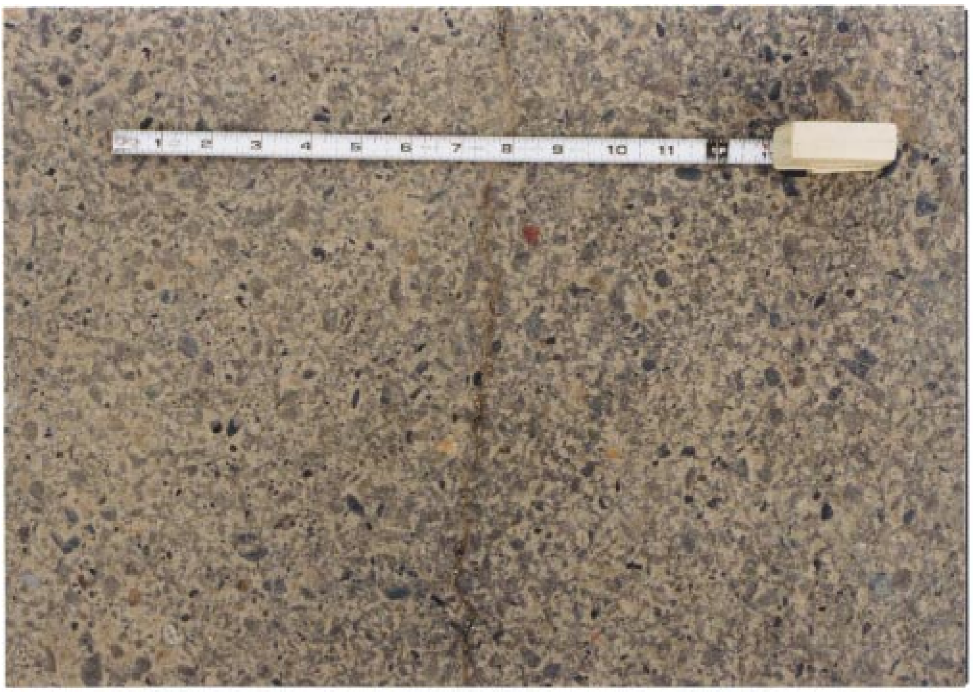
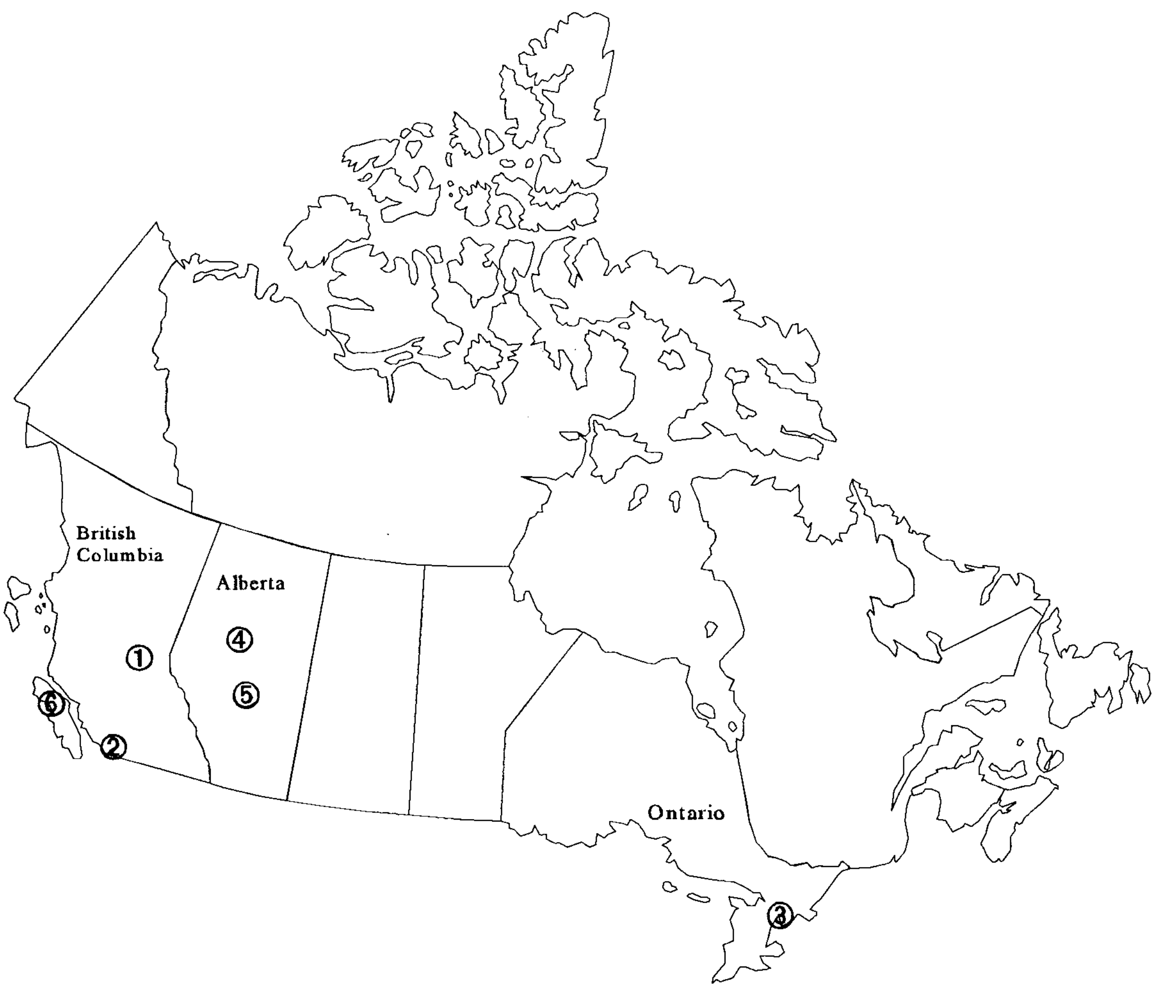


Figure 50 Shrinkage cracks in the RCC base reflect through the asphalt overlay.

Appendix B

RCC Pavement Study Sites in Canada



Key to map numbers:

1. City streets, City of Fort St. John B.C.
   Bullmoose Coal Mine, coal storage, Tumbler Ridge, B.C.
   Fibreco Pulp Inc., wood chips storage, Taylor, B.C.
   Likely Rd., secondary highway, Williams Lake, B.C. Ministry of Highways
2. Lynnterm Terminal, warehouse floor, Port of Vancouver
   City of Vancouver compost site
3. Gro-Bark Organics Inc., compost site, Hornby, Ontario
4. Alberta Pacific Forest Ind., wood chips storage, Athabaska, Alberta
5. 112^{th} Ave., collector street, Edmonton, Alberta
6. Log sorting yard, MacMillan Bloedel Ltd. Port McNeill, Vancouver Is., British Columbia

RCC Pavement Study Sites in the United States

Key to map numbers:

1. Fort Lewis, Washington
2. 99th Ave., Portland, Oregon
3. Bighorn Ave., Alliance, Nebraska
4. Fort Drum, New York
5. Burlington Northern Santa Fe Intermodal Terminal, Denver, Colorado
6. Massachusetts Port Authority Intermodal Terminal, Boston, Massachusetts
7. General Motors Saturn Plant, Spring Hill, Tennessee
8. Central Freight Terminal, Austin, Texas

Appendix C

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Appendix D

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