

Light Rail Transit Direct Fixation Track Rehabilitation: The Calgary Experience

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Shortly after the south leg of Calgary's light rail transit (LRT) system went into revenue service in May 1981, the portland cement grout plinths supporting the rail began to show signs of deterioration. By 1988 the direct fixation plinths, particularly on the approaches to tunnels, required immediate attention, but shutting down LRT service for the repairs was problematic except during narrow windows when the LRT was lightly used or was out of revenue service. After criteria were drawn up for the replacement material and materials testing was conducted—including field tests—a particular cementitious grout was selected and bids were solicited for the repair work, which involved the construction of some 3,600 new plinths during the narrow windows when LRT operation was suspended. The material selected and the method used to make the repairs both proved successful despite the time constraints.

The 12.2-km south leg of the Calgary light rail transit (LRT) system was opened to revenue service in May 1981. The double-track system was constructed on an exclusive right-of-way with entry to a transit mall at Seventh Avenue and Third Street and the southern terminus at Anderson Station. A shop and maintenance facility was also constructed at the south terminus. This leg has seven center-loading platform stations with connections to the bus system via transit terminals.

The second leg constructed was in the northeast part of the city. This 10.2-km double-track station also uses an exclusive right-of-way and was opened to revenue service in September 1984. The northern terminus is at the Whitehorn Station and connects also to the transit mall at Seventh Avenue and Third Street S.E. This leg of the LRT has seven center-loading station platforms.

The northwest leg was completed by September 1987 in time for the 1988 Winter Olympics. This double-track system is 8 km long and extends from the west end of the Seventh Avenue transit mall in downtown Calgary to the northern terminus at the University of Calgary and has two center-loading platform stations and five side-loading platforms.

The section of Seventh Avenue in downtown between Third Street S.E. and 10th Street S.W. is common to the three legs of the LRT system and has 11 side-loading platforms.

A short 2-km extension of the northwest line was completed in 1990. This extension was from the University of Calgary Station to Brentwood Station and included a parking facility at the terminus.

DETERIORATION

The south leg of the Calgary LRT system utilizes 100-lb ARA continuous welded rail. In the ballasted section this rail is fastened to concrete ties with the Landis-Pandrol fastening system. The direct fixation sections (2.5 km) used the Landis-Pandrol 5301 fasteners supported on portland cement grout plinths at 750-mm intervals. A detailed drawing of this direct fixation system is included as Figure 1.

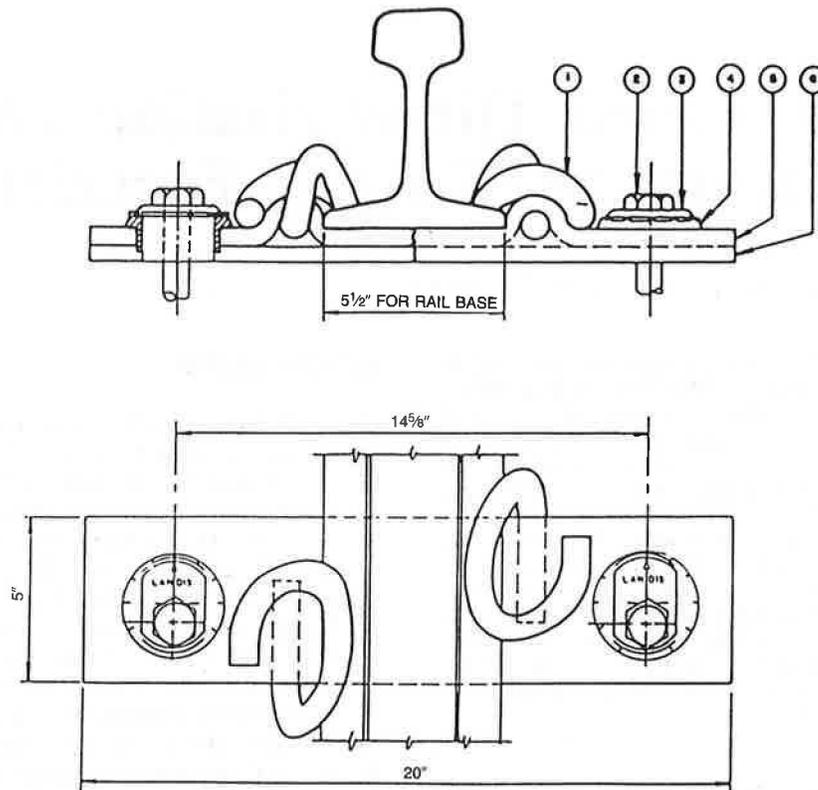
Shortly after entering revenue service in May 1981, the portland cement grout plinths supporting the rail began to show signs of distress. The deterioration appeared in the form of cracking of the cement grout, delamination from the primary concrete invert, and anchor bolts pulling out. The extent of the deterioration varied depending on the location of the plinths. The majority of the deterioration was found at the tunnel approaches and on the Elbow River Bridge. By 1984 one tunnel, namely the 42nd Avenue S.E. tunnel, had reached a point where rehabilitation work was mandatory. At this time the northwest leg was nonexistent and the northeast leg was under construction. Based on the systems requirements at that time and the emergency nature of the plinth pad failures, it was decided that a steel-reinforced concrete plinth system be used. The standard Lord fastening system was used to replace the Landis-Pandrol System. The portland cement grout plinths in this area were replaced with 40 Mpa portland cement concrete plinths and steel reinforcing. A shutdown of each revenue track was required for 3 weeks to complete this repair.

By 1988 the direct fixation plinths, particularly on the approaches to tunnels in the remainder of the south leg, required immediate attention. The northeast and the northwest legs of the Calgary LRT system were in service at this time.

A shutdown of one revenue track for an extended period was no longer feasible. Because all three legs utilized the Seventh Avenue transit mall, a change in the headways along one route would create a considerable operations problem on Seventh Avenue. The single train maintenance and storage facility is located at the south terminus of the south leg of the LRT system, and trains are dispatched to the northeast and northwest legs from there. A slowdown on the south line would have an impact on the other two legs.

The need to carry out this rehabilitation work with minimum impact on the train operation presented a significant challenge in the engineering design and construction. The longest period that a section of track could be taken out of service was set at 68 hr (from 9 a.m. Friday to 5 a.m. Monday). This period was not available at all times but only for the weekend when a concrete pour was scheduled. However, one

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ITEM	TITLE	MATERIAL	QTY
1	PANDROL CLIP	601-A	2
2	BOLT	7/8" DIA. - NOT INCLUDED	2
3	ECCENTRIC POST	SINTERED SD2-1 STEEL MAT. DENSITY 6.1-6.4	2
4	INSULATOR	URETHANE - POLYETHER BASE DM94-	2
5	TRACK PLATE	STEEL	1
6	PAD	NEOPRENE RUBBER	1

FIGURE 1 Original Landis-Pandrol 5301 fastener assembly used on the south line direct fixation areas.

track was available every weekend from 7 p.m., Friday to 5 a.m., Monday.

The material selection criteria included the following:

- Structural capability,
- Long-term durability
- Construction under various site conditions,
- Set time and strength gain, and
- Economics.

To be able to satisfy the basic engineering requirements as well as the constraints imposed by various external factors, the ideal material had to have the following characteristics:

- "Quick set" characteristics,
- "Nonshrink" type,
- Rapid strength gain—20 MPa in less than 12 hr,
- Long-term durability to freeze-thaw cycles,

- Be readily available,
- Be economically viable,
- Be capable of being placed on dry as well as wet substrates, and
- Be capable of being placed in cooler temperatures—around 5°C.

EVALUATION

In 1988 the city of Calgary, in conjunction with the Civil Engineering Department of the University of Calgary, evaluated two potential plinth construction materials, Icosit KC and a modified epoxy grout. Both materials exhibited desirable properties but required further field testing for applicability to this project.

Reid Crowther & Partners Ltd. of Calgary were retained to undertake an independent assessment of all potential plinth

repair materials and the related construction procedures (including the two evaluated at the University of Calgary) that would have minimal impact on the train operation.

The evaluation used in the assessment of the numerous repair methods included the following major criteria:

- Meet structural design requirements.
- Provide a durable long-term repair.
- Meet construction constraints imposed by the existing site conditions.
- Meet constraints imposed by revenue service operation.
- Be economically viable.

It became evident early in the evaluation that a single repair material would not rank number one in all five of the major criteria established. The four types of plinth pad materials and their construction procedures that ranked highest were the following:

- Portland cement concrete (uses the same construction procedures as for new construction),
- Modified epoxy grout,
- Cementitious grout, and
- Icosit KC—a polyurethane rail compound.

The plinths were to be designed to withstand lateral, longitudinal, and vertical forces generated by the passage of many trains as well as the internal forces generated by the torquing of the plinth anchor bolts. Each of the four products had physical properties that governed the plinth design and preset construction procedures.

The Lord fastening system had been implemented in the direct fixation sections of the northeast and northwest legs and was performing as expected. To maintain system consistency, the Lord fastening system was to be used on the south leg rehabilitation project. The Lord fastening system was approximately 20 mm thicker than the existing Landis-Pandrol system. This difference in height along with the restricted vertical clearance on approaches to tunnels established the design criterion of the vertical geometry of the rehabilitation track. There was no change in the horizontal geometry.

PORTLAND CEMENT CONCRETE PLINTH

The portland cement concrete plinth method is similar to that specified for the construction of new rail plinths. This system consists of a high-strength (40-Mpa) concrete plinth bonded to the existing concrete invert and reinforced internally with steel rebar or wire mesh. Female inserts are embedded in the concrete and are used to anchor a Lord fastener to the top of the concrete plinth surface. To withstand the pull-out force generated by the bolt torque of 260 ft-lbf, the female insert had to be embedded 145 mm into the concrete plinth. This, along with providing room for the steel reinforcement and the vertical geometry, resulted in plinth heights of between 100 and 200 mm. Concrete is relatively weak in bond strength. Therefore the plinths were recessed into the concrete invert to resist lateral and longitudinal loads and mechanically anchored in the recess to resist uplift forces. The recess was also used to minimize the amount that the rail had to be lifted.

The recess depth was limited to 50 mm so as to only expose the reinforcing and not cut through it.

The general construction procedure would be as follows:

1. Release and remove the rail.
2. Hydromill 50 mm recess.
3. Install anchors, mechanical or epoxy.
4. Install steel reinforcing.
5. Install forms.
6. Check alignment.
7. Pour concrete.
8. Strip forms.
9. Grind plinth tops to achieve desired bearing surface.
10. Check alignment.
11. Install fastener assembly.
12. Install and fasten rail.

The compressive strength gain of normal concrete is relatively slow, and therefore the time between the concrete pour and allowing loads on the plinths was set at a minimum of 3 days. On the south line rehabilitation project this procedure would require that one revenue track be shut down completely for a period of 1 week for each area of work.

But this does not satisfy the 68-hr maximum shutdown time criterion. Various train and train/bus simulations were run to determine if there was any possible way that one track could be taken out of service for the required week.

This method was subsequently dropped and a field evaluation was not performed.

MODIFIED EPOXY GROUT

The modified epoxy grout plinth system consists of a high-strength epoxy grout mixed with specially graded aggregate. Female inserts would be embedded in the parent concrete invert and be used to anchor the Lord plate to the top of the plinth.

Epoxy grouts can have higher tensile strength and relatively high compressive strength. The plinths can therefore be kept reasonably thin (± 50 mm) above the surrounding concrete invert and do not require steel reinforcing. Because of the high bond strengths a recess depth of 25 mm was considered sufficient. Where the change in profile is restricted, the female insert would be embedded into the existing concrete invert. The compressive strength gain is rapid for this type of material and therefore the new plinths could be stressed and loaded after 12 to 24 hr of curing if the ambient temperature were above 20°C.

Epoxy grouts are self-leveling until they reach initial set. This property of the material makes it more difficult to finish the top surface of the plinth on a slope as would be experienced on the inclined tunnel approaches and superelevated sections of the track system. The solution was to use a steel shim plate between the top of the plinth and the bottom of the Lord plate. The shim plate in combination with the forms could be used to completely enclose the plinth, leaving only a small opening on one side (the high side) to pour the grout in. See Figures 2 and 3 for details. The grout is poured slowly into the opening to ensure that all of the air escapes from the

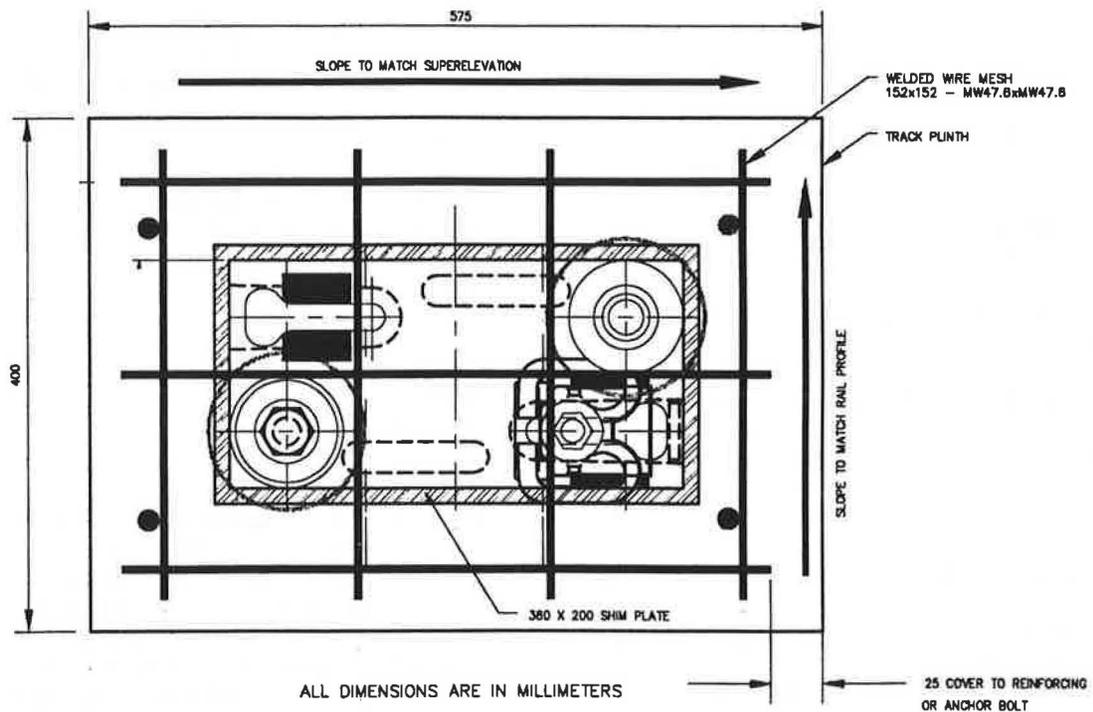


FIGURE 2 Plan view of the direct fixation assembly.

bleed holes. The general construction procedure would be as follows:

1. Hydromill a 25-mm recess.
2. Core holes for female inserts.
3. Check and adjust alignment.
4. Install forms.
5. Suspend Lord fastener assembly.
6. Pour epoxy grout.
7. Remove forms.
8. Final track fastening.

This material satisfied the five general criteria set for material selection. Therefore this material was carried through to the next phase of material testing.

CEMENTITIOUS GROUTS

The cementitious grout plinth system consisted of a Lord fastener anchored in a cementitious grout pad. The grout mix was derived from one part cement to one part of 10-mm nominal size aggregate and a water-to-cement ratio of 0.28. The cementitious grout material exhibited good physical characteristics and could be suitably placed under the field conditions experienced on the south line track. However, the rate of strength gain was not acceptable and concerns were raised as to its performance at cooler temperatures.

Of all the materials tested to this stage, not one of these had satisfied all of the requirements. Therefore it was decided that the cementitious grout not be eliminated at this time.

ICOSIT KC

The Icosit KC plinth consists of a two-part elastomeric polyurethane plinth bonded to the existing concrete invert and a Krupp fastener assembly. In addition steel studs are epoxied into the existing concrete invert to hold the Krupp fastener in place.

Icosit KC has good tensile strength, compressive strength, and bond strength; therefore the plinths do not require reinforcing. However, the Icosit KC material is not rigid and exhibits some deformation in the direction of an applied lateral load.

The plinth heights must not exceed 100 mm, and all plinths should be roughly the same height to maintain the same material stiffness properties. For adjacent plinths with varying plinth heights, the material stiffness should be modified. By bonding the Krupp fastener to the Icosit KC material, the design does not permit any future adjustments to the vertical alignment without removal of the plinth.

The strength gain of the Icosit KC material is rapid, and the new plinths could be constructed in between existing plinths using techniques that allow the rail to remain in place.

The Icosit KC material exhibits self-leveling characteristics, which make it difficult to finish the top surface of the plinth on a slope as would be experienced on the inclined tunnel approaches and superelevated sections of the track system.

The general construction of these type of plinths would be as follows:

1. Hydromill or scabble the top of the existing concrete invert.

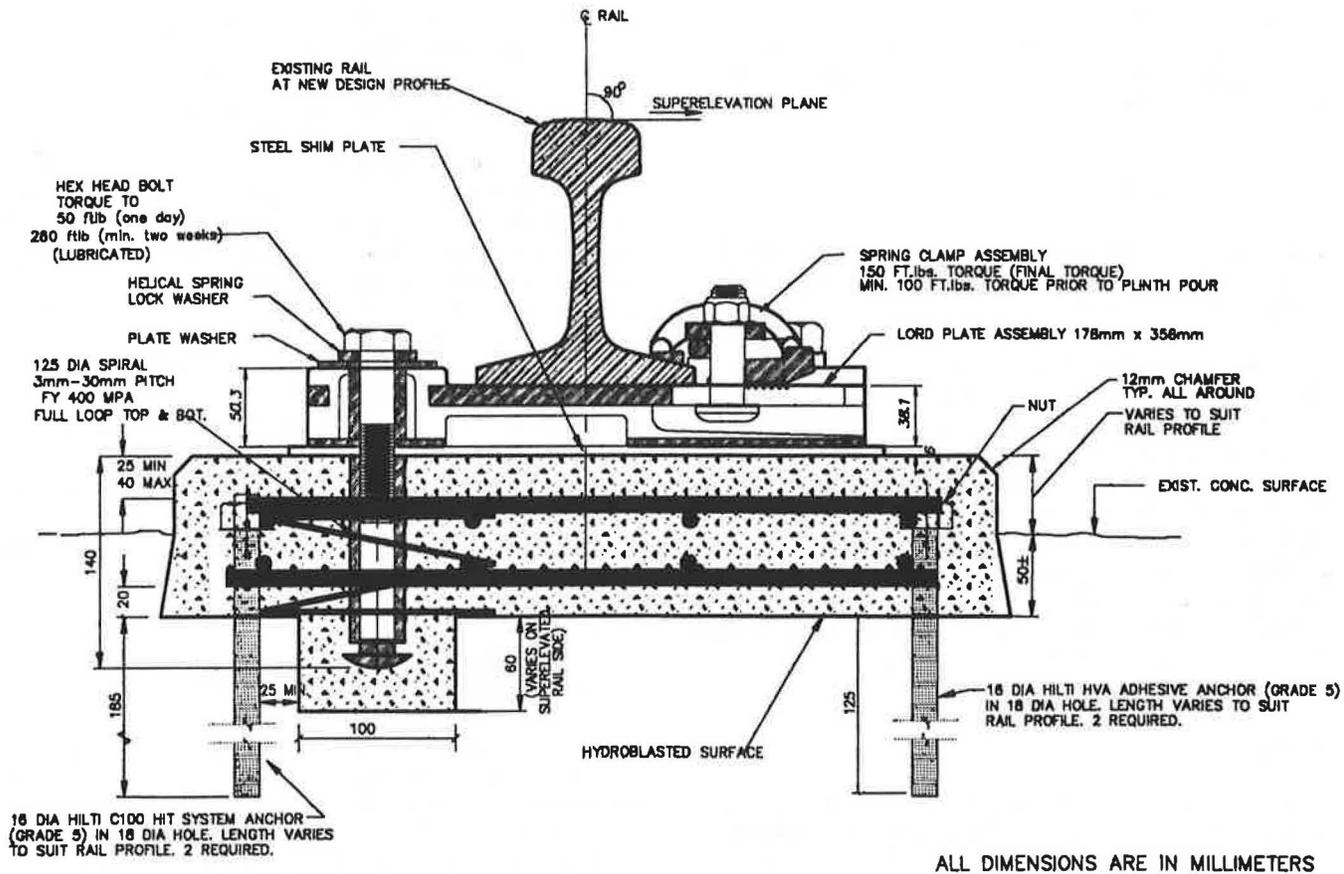


FIGURE 3 Section through the south line direct fixation assembly.

2. Check and adjust alignment.
3. Core holes for anchor studs.
4. Epoxy anchor studs.
5. Install forms.
6. Suspend Krupp fastener assembly.
7. Install forms.
8. Pour Icosit KC.
9. Remove forms.

MATERIALS TESTING

Various materials were tested and evaluated under field conditions to determine their compressive strengths and bond characteristics to wet and dry-concrete substrate. The materials' behavior when placed on sloped surfaces was also investigated.

Working with the suppliers of various materials and their product specifications, the following materials were best suited.

Portland Cement Concrete

The portland cement concrete and plinth system had to be used on the northwest and northeast legs of the LRT system as new construction. These plinths have performed as ex-

pected to date and there was no reason to perform any further tests with this material.

Modified Epoxy Grouts

Four epoxy grouts that were evaluated were Sikadur 43, Cappar HLP/VLT, Talleygrout 200 (modified), and Kammacrete 17. The grouts were tested as follows:

- Sikadur 43 is an epoxy-based resin grout that was mixed to the manufacturer's recommendations. This material used a sand as the mineral filler with an aggregate-to-resin ratio of 3:1.
- Cappar HLP/VLT is a polymer-modified grout that was mixed using prebagged 10-mm aggregate. The aggregate-to-resin ratio was approximately 7.75:1 mixed to the manufacturer's specifications.
- Talleygrout 200 (modified) is an epoxy-based resin that was modified to achieve a faster set time. The mix was batched as follows:

Part A, resin, 4.22 kg/batch;
 Part B, hardener, 0.98 kg/batch; and
 Aggregate finer than No. 8 sieve, 3.75 kg/batch.

- Kammacrete 17 is a polymer-modified grout that was mixed to the manufacturer's requirements with coarse 10-mm concrete aggregate and concrete sand. The aggregate-to-resin ratio was approximately 8.5:1.

Cementitious Grouts

Two cementitious grouts were evaluated: Elsro X-L flowable grout mixture and Pyrament PBC-XT cementitious grout. The grouts were tested as follows:

- Elsro X-L premix grout is a flowable, nonshrink cementitious grout that was mixed as follows: 1 part Elsro X-L premix grout, 1 part 10-mm concrete coarse aggregate, and a water-to-cement ratio of 0.28 calculated based on the aggregate being in saturated surface dry condition.

- Pyrament PBC-XT cementitious grout is a modified hydraulic cement with nonshrink characteristics. The mix was batched in the following proportions: 1 part Pyrament PBC-XT, 1 part clean natural sand, 1 part coarse aggregate (clean, well-graded, 20-mm top size), and 0.28 water-to-cement ratio including free and absorbed water.

Icosit KC

Icosit KC was tested extensively at the University of Calgary in 1988. The Krupp fastener and Icosit KC 330 combination performed reasonably well at above 10°C temperatures and when constructed on dry substrate. The manufacturer recommended that this material should not be used on damp or wet substrate. The university testing also concluded that a 100-mm-high plinth did not perform as well as a 50-mm-high plinth. In the case of the 100-mm-high plinth, excessive swelling of the mastic had occurred during the early stages of the curing process and there were indications that mechanical properties had been impaired. At low loads (up to 20 kN) the 100-mm-high plinth exhibited acceptable stiffness but became too flexible at higher loads. Therefore it was recommended that the plinth heights be limited to 50 mm.

Because of these limitations, it was decided that the Icosit KC 330 would be eliminated from the field testing program.

FIELD TESTING

Various blends of coarse and fine aggregates were tested to determine the optimum ratio that would result in good workability and placement of the mix.

For each material, modified epoxy grout and cementitious grout, a 325 mm × 550 mm × 13 mm-deep recess was created using an electric chipping hammer. A 13-mm recess was used to expose the concrete aggregate and provide the same texture as would be achieved with a 25-mm- or 50-mm-deep recess. A 50-mm-high plinth was then constructed in the recessed area. During the test the ambient temperature was approximately 3°C with the grout mix temperature of 6°C. Material core samples were taken after 24 hr, 7 days, and 28 days. These cores were used to determine the bond strength at the

interface between the grout and the concrete substrate. The bond strengths were a measure of the direct tensile load capacity of the core. In addition the compressive strengths of the various grout materials cured under field conditions were determined. Table 1 presents a summary of these data.

Generally the modified epoxy grouts exhibited excellent compressive strength gain characteristics. In most cases, the specified minimum compressive strength requirement of 55 Mpa was achieved in 7 days. These grouts also exhibited good bond characteristics to a dry concrete substrate with the 7-day bond strengths in excess of 1.5 MPa. In all cases the failure occurred at the bond line. In all cases the bond developed to a wet substrate by the modified epoxy grouts was poor and in some cases there was no bond. When poured onto a damp substrate the entire plinth delaminated after 24 hr making it difficult to obtain a core sample. At lower temperatures (of less than 5°C) some of the modified epoxy grouts did not set up in the first 12 hr.

As a result of the low bond strength data obtained for the modified epoxy grouts and the longer set times required in colder temperatures, attention was diverted to the cementitious grouts.

The cementitious grout plinths exhibited excellent compressive strength gains with acceptable bond strengths. The Elsro XL-Premix grout exhibited excellent strength increases under ideal conditions (ambient temperature of 20°C). However concerns regarding the freeze-thaw durability of the material and the strength gain characteristics at cooler temperatures were raised. This material was not considered further in the testing program. The Pyrament PBC-XT exhibited excellent strength gains—10 MPa in 4 hr with 32 MPa compressive strength achieved in 3 days. The excellent bond characteristics were demonstrated by the difficulty experienced in removing some overflowed material that had set up on the concrete floor.

Therefore only the Pyrament PBC-XT was tested further. Various blends of coarse aggregate and sand were investigated in terms of compressive strength and placability. It was observed that flowable mixes could be obtained while maintaining a water-to-cement ratio of 0.265. Exceeding a 1:2 ratio of cement to combined aggregate blend resulted in either a stiff mix or lower-than-specified compressive strengths or both.

DESIGN MIX

As a result of this testing program it was decided that the Pyrament PBC-XT mix would be used for the repair of the

TABLE 1 Modified Epoxy Grout Evaluation Results

Product	COMPRESSIVE STRENGTH (MPa)		TENSILE STRENGTH (MPa)			
	1 Day	7 Day	1 Day Dry	1 Day Wet	7 Day Dry	28 Day Dry
Sikadur 43	6.5	31.8	0.89	0.80	2.12	1.20
Cappar HLP/VLT	65.0	80.0	0.87	...	0.97	0.85
Talleygrout 200 (Modified)	42.1	67.5	1.92	0.21	1.76	1.08
Kammacrete 17	80.0	83.0	1.28	...	1.42	0.64

Calgary LRT system. The design mix is summarized as follows:

	Volume	Weight
Pyrament PBC-XT cement	1.0 parts	25.0 kg
Concrete sand	0.6 parts	6.3 kg
Coarse aggregate	1.4 parts	45.0 kg
Water	6.6 L	6.6 L
Water-to-cement ratio (based on total water)	0.265	0.265

The material gradation for the concrete sand and coarse aggregate used on this project is shown in Table 2.

CONSTRUCTION

To carry out the rehabilitation work, changes were required to the LRT operations and schedules. The construction was carried out on one track while the trains ran on the other. The hours of reverse running during week nights as specified in the contract were from 7 p.m. to the end of revenue service at 1 a.m. After revenue service work could be carried out on both tracks until 5 a.m. when both tracks were returned to revenue service. During the weekends the construction was carried out continuously on one track from 7 p.m., Friday to 5 a.m., Monday.

The rehabilitation project was divided in two phases:

- Phase 1—North approach to C.P. tunnel.
- Phase 2—Big 4 slab, Elbow River Bridge, north approach to the Cemetery Hill Tunnel, and south approach to the Cemetery Hill Tunnel.

Bids were requested for Phase 1 of this project in July 1989 with the construction starting in August 1989. This phase consisted of the construction of 1,200 new Pyrament PBC-XT direct fixation plinths and removal of the old plinths. Bids were requested for Phase 2 in March 1990 with construction starting in June 1990. This phase consisted of approximately 2,400 new plinths.

Hydromilling

The system of plinth construction as suggested in the contract documents included creating a 50-mm recess in between adjacent plinths. A 50-mm recess was used to reduce the amount that the rail had to be lifted to accommodate the new plinth system. A hydromilling system was specified exclusively to eliminate the problems that may arise from the microcracks caused by pneumatic hammers. In this system water at 36,000 psi pressure is used to wash away the cement binder in the concrete, thus creating the desired recess. The recess has a rough texture with some aggregates exposed. A rail-mounted hoarding system was used to contain the cement and aggregate that was removed from the concrete substrate as well as to keep the water from contacting the catenary that was live with a 600-V direct current.

The hydromilling work was completed during the week-nights and on weekends. The time required to hydromill a 525 mm × 350 mm × 50 mm-deep recess was approximately 25 min, excluding downtimes because of equipment failures.

TABLE 2 Cementitious Grout Evaluation Results: Pyrament PBC-XT

			COMPRESSIVE STRENGTH (MPa)				
W/C RATIO	10 MM COARSE AGGREGATE BY VOLUME	SAND BY VOLUME	1/2 DAY	1 DAY	3 DAY	7 DAY	REMARKS
0.28	1.4 C.	0.7 C.	19.1	28.6	42.5	47.7	Stiff
0.28	1.4 C.	0.6 C.	35.7		60.7		Stiff
0.28	1.3 C.	0.7 C.	22.6		40.4		Flowable
0.265	1.4 C.	0.6 R.M.	25.7	35.4	52.4	59.9	Flowable
0.265	1.4 C.	0.65 R.M.	19.9	28.8	46.0	51.5	Flowable
0.265	1.4 C.	0.625 R.M.			37.1	44.6	Flowable

			COMPRESSIVE STRENGTH (MPa)				
W/C RATIO	10 MM COARSE AGGREGATE BY VOLUME	SAND BY VOLUME	1 DAY	1 1/2 DAY	7 DAY	28 DAY	REMARKS
0.265	1.2 R.M.	0.8 R.M.	41.2	48.1	55.9	67.2	Flowable
0.265	1.4 R.M.	0.7 R.M.	30.5	36.2	39.55	50.3	Flowable
0.265	1.6 R.M.	0.7 R.M.	47.9	59.3	70.0	77.5	Stiff

Note: R.M. = Aggregate Supplied by Rolling-Mix of Calgary
C. = Aggregate Supplied by Consolidated Concrete of Calgary

Coring of 75-mm Holes

The 75-mm holes were cored to allow for the embedment of the female insert. The holes were cored with diamond-tipped coring bits capable of cutting through steel reinforcing when encountered. The contractor converted an old tamping machine to core these holes. This equipment was rail-mounted and produced very even, accurately placed cored holes at constant depths. The concrete core was then removed with the aid of a cold chisel and a hammer.

Install Anchor Studs

The 18-mm diameter core holes were cored using a specially designed rail-mounted, self-propelled drill capable of coring two holes at the same time. Diamond-tipped bits were used that were capable of cutting through steel reinforcing when encountered. The Hilti HVA cartridge and Hilti HIT system were used to epoxy the 16-mm-diameter threaded rods into the substrate concrete.

The hydromilling, coring, and anchor stud installation were completed prior to the weekend when the remainder of the plinth construction, including the concrete pour, was to take place.

Plinth Construction

The longest period that one track could be taken out of revenue service had been set at 68 hours. Therefore the work was scheduled on long weekends whenever possible.

During this period the spring clips on the existing Landis-Pandrol fasteners were removed and the rail was raised to the designed elevation. Mechanical jacks and wood bracing were used to ensure that the rail remained at its designed alignment, both vertically and horizontally. Two layers of steel reinforcing were installed along with wax-treated metal forms. The steel reinforcing was tied to the Hilti anchor studs with a minimum of 25-mm cover provided on the top surface and on the sides. Construction details are shown in Figures 2 and 3. The Pyrament PBC-XT was preblended with the required amount of aggregates and was delivered to the site in 35-kg bags. To produce the Pyrament PBC-XT in 70-kg batches, 0.25 cu.m. grout mixers were used. The Pyrament mix was very sensitive to water; therefore great care was taken to ensure that the mix was the desired consistency. The Pyrament PBC-XT mix was placed into the formed plinths using a tapered chute. Pencil vibrators were used to consolidate the mix. Finishing was completed using conventional concrete finishing tools. The quality assurance program for this project included full-time supervision at the mixers and concrete test cubes were cast every 3 hr or at the engineer's discretion. The concrete compressive tests were carried out at 8 hr, 12 hr, 24 hr, and 28 days. Table 3 shows the results of these tests.

The mechanical jacks and wood bracing were removed after the concrete had cured for at least 4 hr. The rail was fastened to the new Lord fasteners anchored to the Pyrament PBC-XT plinths. The horizontal and vertical alignments were checked and adjusted to comply with the design requirements. After the Pyrament PBC-XT plinths had cured for minimum of 8

TABLE 3 Test Results

Material: Pyrament PBC-XT
Area: C.P. Tunnel, North Approach - Inbound Track
Date: 16th September 1989 - 17th September 1989

COMPRESSIVE STRENGTHS IN MPA					
Test #	Time				
	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	26.0	29.5	36.3	65.7	78.2
C2	30.8	31.1	40.0	66.9	91.7
C3	26.1	28.3	35.8	67.6	86.4
C4	31.6	34.9	43.5	74.3	86.8
C5	31.9	36.0	43.7	71.4	101.4
Avg.	29.3	32.0	39.9	69.2	88.9

Material: Pyrament PBC-XT
Area: C.P. Tunnel, North Approach - Outbound Track
Date: 19th May 1990 to 20th May 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	25.6	31.4	39.2	73.8	94.3
M1	25.8	-	-	-	-	72.5
C2	-	18.4	22.0	26.7	57.1	66.2
M2	20.4	-	-	-	-	59.7
C3	-	20.2	21.5	32.8	47.9	59.7
M3	18.9	-	-	-	-	61.7
C4	-	34.4	40.1	43.5	73.7	84.6
M4	28.3	-	-	-	-	70.9
C5	-	17.9	18.3	22.0	46.0	55.6
M5	25.5	-	-	-	73.5	77.0
C6	16.6	-	18.2	-	49.3	56.6
C7	20.0	-	23.0	-	55.0	65.8
Avg.	22.2	23.3	24.9	32.8	59.5	68.7

Material: Pyrament PBC-XT
Area: Cemetery Hill Tunnel, South Portal - Inbound Track
Date: August 4th, 1990 to August 8th 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	14.4	18.8	25.0	46.2	55.3
M1	20.4	-	-	-	-	60.0
C2	-	24.8	26.8	37.8	57.7	69.4
M2	19.1	-	-	-	-	58.1
C3	-	24.9	32.9	45.7	61.0	73.5
M3	10.7	-	-	21.7	-	41.9
C4	-	23.9	26.8	32.8	50.7	57.4
M4	9.0	-	-	20.4	-	30.2
C5	-	18.8	27.1	40.3	54.7	68.6
M9	17.0	-	22.9	30.2	50.9	60.0
C10	13.2	14.3	-	25.0	32.3	46.3
C11	-	23.8	27.1	32.9	50.5	-
Avg.	14.9	20.7	26.1	50.5	56.4	51.7

Material: Pyrament PBC-XT
Area: Cemetery Hill Tunnel, South Portal - Outbound Track
Date: September 15th 1990 to September 16th 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	25.9	36.3	44.4	77.6	91.0
M1	-	16.4	-	-	-	62.0
C2	-	22.8	30.5	34.4	69.1	74.1
M2	-	25.8	-	-	-	78.9
C3	-	13.3	16.7	22.8	43.4	45.6
M3	-	25.4	-	-	-	83.9
C4	-	27.4	32.7	36.1	69.8	80.6
Avg.	-	22.4	29.0	34.4	65.0	73.7

(continued next page)

TABLE 3 Test Results (continued)

Material: Pyrament PBC-XT
Area: Elbow River Bridge - Inbound Track
Date: August 7th 1990 to August 8th 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
M5	21.6	-	-	-	-	66.8
C6	-	14.7	21.7	32.8	48.7	57.6
M6	19.6	-	-	-	-	68.9
C7	-	17.9	21.7	25.6	41.2	50.6
M7	25.6	-	-	-	-	71.2
C8	29.2	33.7	35.4	40.6	-	71.5
M8	20.8	-	28.9	42.7	54.6	70.0
Avg.	23.4	22.1	26.9	35.4	48.2	65.2

Material: Pyrament PBC-XT
Area: Elbow River Bridge - Outbound Track
Date: September 17 1990 to September 18 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
M4	22.7	-	-	-	-	80.1
C5	-	19.9	28.9	29.6	63.1	76.6
M5	24.5	-	-	-	-	85.7
C6	-	31.7	35.7	46.6	74.2	82.8
M6	27.3	-	-	-	-	101.3
C7	-	25.6	29.6	40.4	73.9	87.5
C8	26.0	28.9	33.3	37.9	59.7	72.3
M8	25.7	-	-	-	-	77.5
Avg.	25.2	26.5	31.9	38.6	67.7	83.0

Material: Pyrament PBC-XT
Area: Cemetery Hill, North Portal - Outbound Track
Date: October 14th, 1990

COMPRESSIVE STRENGTHS IN MPA						
Test #	Time					
	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	27.2	31.9	-	-	83.2
M1	30.9	-	35.3	-	-	90.7
C2	-	24.8	28.1	32.2	76.5	94.1
M2	17.9	-	23.2	-	-	84.5
Avg.	24.4	26.0	29.6	32.2	76.5	88.1

hr and attained a minimum compressive strength of 20 MPa, a final rail gauge check was performed. The Lord fastener anchor bolts were torqued to 50 ft-lbf and the track was returned to revenue service. The main anchor bolts were torqued the designed 260 ft-lbf after 14 days.

CONCLUSIONS

The material selection program was carried out independent of the design during the initial stages. After having selected the most suitable material, the Pyrament PBC-XT in this case,

TABLE 4 Pyrament Plinth Test Results After Curing

Location	Strength MPa	Density Kg/m ³	Air %	Spacing Factor	Permeability
Elbow River	56.3	2219.3	11.4	0.148	2.15
	27.7	2000.0	9.98	0.189	32.5
	71.3	2180.6	6.78	0.194	3.90
	59.0	2226.9	6.25	0.248	0.97
	69.5	2246.2	5.87	0.189	1.60
	63.8	2241.6	9.43	0.138	1.79
Cemetery Hill - South	73.1	2282.6	5.17	0.279	0.75
	75.1	2339.0	6.76	0.200	0.73
	53.4	226.1	8.55	0.134	2.81
	45.4	2130.3	7.69	0.167	3.54
	44.5	2117.9	9.17	0.157	3.05
C.P. Portal	55.8	2287.0	6.19	0.229	0.53
	58.8	2234.6	6.45	0.202	1.61
	87.8	2503.7	3.31	0.316	0.53

a complete testing program to simulate plinth construction under field conditions was carried out. As a result, the plinth dimensions were modified slightly to make the plinth construction procedure simple with good quality control.

The testing and evaluation of the materials to simulate the construction of the new plinths under field conditions were also key to the success of this project. The Pyrament PBC-XT material worked as expected. The material is very sensitive to water content and therefore close attention is required to ensure that the quality of the mix is maintained. The approximate working time available is 90 min but varies with temperature. The material worked well in colder temperatures but the resulting compressive strengths were considerably lower than those of the mix that was placed at higher temperature (around 20°C).

The constraints imposed by the train operations and schedule, the fixed horizontal alignment, and a vertical alignment that could not be changed appreciably presented challenges that were successfully conquered by the design team. The proof is exhibited in the successful completion of the south line rehabilitation project within the scheduled time and allocated budget. There were also no disruptions to revenue service recorded on the project.

Further testing of the new Pyrament concrete plinths was carried out after the curing period. Table 4 displays the results.

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