to spike solutions of concrete samples having low Cl^- contents with a known amount of Cl^- before titration to facilitate endpoint determination.

3. The use of the Gran method improved the precision of the potentiometric titration procedure.

4. The average absolute difference of 0.0005 percent Cl^- between measured Cl^- and known added Cl^- contents, as determined by analyzing several test specimens, is probably a good indication of the accuracy of this improved potentiometric titration procedure.

5. Among the procedures tested, the improved potentiometric titration procedure showed the best agreement among the test specimens. In addition, this procedure showed no discernible effects of the particular siliceous and carbonaceous aggregates used to prepare the specimens.

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Comparison of Performance of Concrete Bridge Decks in British Columbia

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The bridges of the freeways south and east of Vancouver, British Columbia, were chosen as a sample of concrete bridge decks in the area. They are of similar ages and quality of supply of ready-mixed concrete and subject to the same weather, salting, and traffic conditions. They have the following types of decks: monolithic, monolithic recapped, two layer on precast box beams, and two layer on cast-in-place concrete; the two-layer decks used either cement grout or two-part epoxy as bonding agents. The use of site-mixed versus plant-mixed concrete is related to the performance of the bridge decks. Six observations are made why two-layer decks are more satisfactory than monolithic decks, and 16 recommendations for construction of two-layer decks are given. It is concluded that (a) two-layer decks are more durable than monolithic concrete decks and guarantee a minimum coverage of the steel, (b) the placement of the overlay requires rigid quality control of the site-mixed concrete, and (c) application of the two-part epoxy bonding agent requires constant technical attention.

There are more than 2600 bridge and overpass decks in British Columbia, of which 650 are exposed concrete. Of the latter, 570 are monolithic and 80 are of two-layer deck construction. Of the monolithic concrete decks, 140 have concrete resurfacing, 30 are in immediate need of resurfacing, and a further 100 will need resurfacing in the next 3 or 4 years. Some of the older bridges that are still in use were built before 1920, and some of the newer bridges have been resurfaced with concrete just a few years after being opened to traffic.

The weather conditions cover a freezing-index range of from 100 to 500 degree days (1), and the traffic volumes vary from very light to 20 000 vehicles/lane/d. The concrete aggregate used in British Columbia varies from a granular material taken from a river bank to a high-quality aggregate produced to size and standard in modern plants. The concrete quality is variable and depends on the location of the bridge site and the plant and expertise available. The types of concrete deck used are (a) 20 700-kPa (3000-lbf/in^2) monolithic, (b) resurfaced monolithic, (c) two layer with precast box beams as the structural deck, and (d) two layer with 20 700-kPa concrete as the structural deck, both with a concrete running surface. Either cement grout or two-part epoxy is used to bond the overlays to the structural decks.

This report presents a comparison between the behavior of monolithic decks and two-layer decks in respect to site conditions, concrete used, method of placement, types of structure, chloride content of the concrete (2), bonding method, and deck performance.

SAMPLING OF BRIDGE DECKS

Of the total bridge population of British Columbia, all those with concrete riding surfaces from two freeway systems south and east from Vancouver were chosen for study. These bridges were chosen because (a) they are approximately the same age (constructed between 1959 and 1964), (b) they are subject to similar weather and traffic conditions, (c) they were made from good-quality ready-mixed concrete, and (d) they contain a variety of types of bridge decks. A total of 73 bridges were studied.

The average annual rainfall in the Vancouver area varies from less than 900 mm (35 in) in the south to more than 1800 mm (70 in) along the mountains (3). The annual number of days of measurable precipitation varies from 160 in the south to 180 along the mountains (4).

The maintenance practice for freeway salting is to do the bridges first because they tend to ice up and become unsafe. When overnight freezing is anticipated, salt is applied once before the heavy evening traffic, once during the night, and once early in the morning. During snowfalls, salting is relatively continuous. Generally, there are about 12 snow d/year (a range of 10 to 18) and 50 to 100 freeze-thaw cycles/year.

One of the bridges in the sample, the Port Mann Bridge, crosses the Fraser River and is subject to wind chill. Its salting period begins at least a month before and ends a month after salting of the other bridges. Its traffic density is approximately 15 000 vehicles/lane/d. More than 10 percent of the automobiles use studded tires between October 31 and March 31.

The following procedures were used during the construction period for the bridges in this study:

1. Aggregates for concrete were produced in modern plants in the area;
2. Material from glacial outwash was crushed, washed, screened, and stockpiled in various sizes;
3. The resulting aggregates were of sound, durable particles and free from deleterious substances;
4. The sand varied somewhat in gradation, but was within the ASTM specifications for variation in fineness modulus;
5. The ready-mix plants in the area were modern and all had quality-control service available to any customer;
6. The concrete was centrally batched, mixed, and truck agitated or centrally batched and mixed in trucks en route to the site;
7. Trucks and plants were maintained to produce consistently mixed concrete; and
8. Admixtures for air entrainment were available at most plants.

DETAILS OF BRIDGE-DECK CONSTRUCTION

The bridges in the study have monolithic decks, concrete-resurfaced monolithic decks, or two-layer decks with a 34 500-kPa (5000-lbf/in^2) concrete wearing surface. The two-layer decks can be further subdivided into structural or precast substructures with either two-part epoxy or cement-grout bonding agents.

Monolithic Decks

The monolithic decks were cast in place from ready-mixed concrete supplied in truck mixers. The concrete was produced to the following specifications and was transported to the deposit position by either buggies or crane and bucket (1 kPa = 0.145 lbf/in^2 and 1 mm = 0.039 in).

Specification	Value
Strength, kPa	20 700
Slump, mm	100
Entrained air, %	5

Vibrators were used to consolidate the concrete. The minimum steel cover was specified to be 40 mm (1.5 in), but some of the decks were later found to have less than 20 mm (0.75 in) cover. The concrete surface was screeded to elevation. Generally, the concrete was finished by using a burlap drag and cured by using a curing compound or saturated burlap.

The records show that

1. The concrete was produced to a low coefficient of variation with strengths greater than 20 700 kPa and air entrainment of 3 to 6 percent by volume,
2. Excessive vibration of the concrete for the deck surfaces usually overworked the concrete,
3. Quality control of the construction was rather loose, which resulted in sacrifice of surface concrete quality (for example, calcimine brushes were used extensively to apply water during the finishing process).

By 1971, some of the decks were showing signs of distress, and it was necessary to decide whether to repair or resurface. The main reasons for deterioration were spalling and pop-outs over the reinforcing steel. If the pop-outs were minor, the bridge deck could be patched. However, usually the patches came out, or the concrete deteriorated around them and the deck became rougher. When considerable reinforcing steel was exposed, the deck was resurfaced (Figure 1). Thus, the criteria used for determining whether decks should be resurfaced were ride and safety.

Some of the resurfacing has shown distress for which inspection and a review of diaries indicates the following causes:

1. A poor bond resulted when the grout dried out before the paving was placed;
2. The overlay hardened before the curing was applied;
3. The concrete was retempered in the ready-mix trucks waiting for the paver; and
4. Large calcimine brushes were used to supply finishing water, which increased the water-to-cement ratio of the overlay surface. Thus far, no resurfaced sections have been replaced, but some have been patched and show signs of failing in bond and around the patches.

The chloride contents and bond strengths of the bridges cored are shown below (1 kg/m^3 = 0.062 lb/ft^3 and 1 kPa = 0.145 lbf/in^2).

	Chloride Content		
Type of Structure	At Surface (kg/m^3)	At Rebar (kg/m^3)	Bond Strength (kPa)
Monolithic	1.69 to 14.0	0.69 to 14.40	–
Monolithic overlay (cement)	0.69 to 14.17	3.22 to 14.00	0 to 1199.68

Figure 1. Deck in need of resurfacing.

Type of Structure	Chloride Content At Surface (kg/m³)	Chloride Content At Rebar (kg/m³)	Bond Strength (kPa)
Precast beam (epoxy)	3.59 to 11.68	0.29 to 0.46	1909.83 to 1937.41
Precast beam (cement)	0 to 2.25	0.19 to 9.91	241.31 to 1999.41
Structural concrete (cement)	0.10 to 14.32	1.20 to 4.86	620.5 to 2757.9
Structural concrete (epoxy)	0.23 to 11.05	0.07 to 0.52	827.4 to 2089.1

Five-cm (2-in) diameter cores were pulled perpendicular to the bond surface to determine the bond strength. The high concentration of chloride in the lower concrete is probably residual salt from the application of deicing salts before the deck was resurfaced.

Two-Layer Decks Over Box Beams

These bridges were built with precast beams erected at the site and later covered with a concrete riding surface. After the beams were placed, they were posttensioned laterally, and then the ducts were grouted. The upper surface of the box beams became the subdeck surface. This surface was sand blasted, washed, and blown dry with oil-free compressed air to give a good surface for the bonding agent.

Some of the longer box beams had excessive camber. To establish the required deck alignment, the depth of the overlay was varied from more than 5 cm at the beam ends to less than 2.5 cm at their centers. Consequently, two mix designs were used for the concrete overlay. Both used 34 500-kPa concrete having 6 to 8 percent air and 2.5 to 5-cm slump; the shallow sections were constructed with 9.5-mm (3/8-in) coarse aggregate and 298 kg (656 lb) of cement, but the deeper end sections were constructed with 19-mm (3/4-in) aggregate and 278 kg (612 lb) of cement were used.

The bonding agent for the deep-section concrete was cement grout, and that for the shallow-section concrete was a two-part epoxy mixture that gave higher bond strength for the thinner overlay. The concrete was supplied by a ready-mix plant. The surface was struck and finished by using two channels mounted back to back with a vibrator mounted on the top of the channels. This apparatus rested on rails or curbs that had already been cast to the final deck elevation and was dragged over the decking concrete by a man at each end. The compressive strengths of cylinders cast of the surfacing concrete were all greater than 34 500 kPa. The concrete surfacing was cured by using burlap covered with 76 mm (3 in) of sand, kept saturated 24 h/d for 3 d, and then covered with polyethylene for a further 4 d.

Today, about 14 years later, the areas of apparent distress over the box beams are bond failures near the ends that are up to 1 m (3 ft) across on one structure and longitudinal cracks along the seams between the box beams on all the structures. The longitudinal cracks are evident in the winter by long icicles hanging over the freeway. Resurfacing is not yet required, but the bond-failure area has been patched and shows signs of breaking away around the patches.

Two-Layer Decks Over Structural Concrete

In this category, there are minor subdivisions. All the cast-in-place structural concrete was supplied from a ready-mix plant. The design mix and the placement procedure were the same as for the monolithic decks. The surface of the structural deck was rough finished. The surfacing of the decks was either ready-mixed concrete with cement grout or two-part epoxy bonding agent or site-mixed concrete with two-part epoxy bonding agent. The placing, finishing, and curing of the ready-mixed concrete and both bonding agents were similar to the procedures used for the overlay of box beams described above.

Thus far, there is only minor bond failure on one deck of this two-layer type.

The chloride contents and bond strengths for two-layer decks using ready-mixed concrete for the overlay and cement grout for the bonding agent are shown in the table above.

The Port Mann Bridge was constructed over the Fraser River as part of the freeway east of Vancouver in 1963. The total length of the approach spans is more than 1200 m (4000 ft). Special provisions were followed for the construction of the viaduct deck (5). Before beginning the overlay, special aggregates were produced locally for the project and stockpiled at the site. They were kept covered to maintain a more constant moisture content. The coarse aggregate was supplied in two sizes: 16 to 10 mm (5/8 to 3/8 in) and 10 to 5 mm (3/8 in to no. 4). The sand was supplied with a fineness modulus range of 2.4 to 2.9. Cement was supplied in bags and stored dry at the site.

The surface of the structural deck concrete was acid etched, stiff-bristle-broom brushed, neutralized with industrial ammonia, and washed with water. The wash water was ponded on the structure away from the expansion joints and gutters and tested with pH paper before being pumped over the side.

The bonding agent used was a two-component, polysulphide-epoxy adhesive. The specifications required that the epoxy supplier be responsible for the bond between the structural deck and the overlay, and the penalty for any bond failure was the replacement of the overlay in the area that failed. It was the responsibility of the contractor to hire an epoxy-bond inspector to oversee the mixing and placing of the bonding agent. This requirement prompted the bonding-agent supplier to put one of its best technicians in charge of placing the epoxy layer. If, due to delay or weather, the epoxy layer set up, another layer of epoxy was applied before the concreting continued.

The concrete for the overlay was made of 16-mm aggregate and 260 kg (570 lb) of cement and had 19-mm slump, 6 to 8 percent air, and a water-to-cement ratio of 0.39. There was a technician at the batch plant and a technician at the mixer paver. A 9100-kg (20-ton) batch plant was used off the structure, and the aggregates were trucked to the mixer paver in 1800-kg (4-ton)

Figure 2. Paving the Port Mann Bridge.

dump trucks, with bins to hold four separate batches. The mixer paver had a capacity of 0.38 m^3 (0.5 yd^3). The concrete was placed one lane at a time. The technician at the paver monitored each batch for aggregate blend, slump, and entrained air.

The epoxy bonding agent was machine mixed on the back of a truck at the site and never spread more than 3 m (10 ft) ahead of the overlay concrete (Figure 2).

After the overlay concrete was placed, it was screeded and vibrated by using a screeder with vibrators mounted 0.6 m (2 ft) in from each end. The concrete was finished by using a 3-m (10-ft), longitudinal, scraping straightedge. A burlap drag finish was applied to the surface, and the overlay concrete was cured by using burlap, kept saturated for 3 d, and then covered with black polyethylene for a further 4 d.

Thus far, there are no areas of distress on the surface of the approaches to the Port Mann Bridge except some stud wear in the wheel paths of the slow lanes. The chloride contents and bond strengths of the Port Mann Bridge approaches are shown in the table above.

Recently, the British Columbia Ministry of Highways and Public Works commissioned an analysis of the durability of the Port Mann Bridge deck (6). On thin sections prepared from the bridge deck cores and magnified 150 times, both the overlay and the structural concrete showed micro cracks, but the entire section through the bonding agent had no cracks. The epoxy bonding agent is apparently acting as a seal, keeping the salt away from the reinforcing steel in the structural deck. The amount of chloride in the structural concrete also indicates that, when the epoxy is well placed, it acts as a deterrent to chloride migration.

DECK PERFORMANCE

The performances of the different types of concrete deck areas studied are summarized below (1 m^2 = 10.8 ft^2).

Performance	No. of Decks	Area (m^2)	Percentage of Total Area
Monolithic decks			
Resurfaced or needs to be	26	29 610	66.6
Fair	13	8 574	19.3
Good	9	6 232	14.1
Total	48	44 416	100.0
Two-layer decks			
Resurfaced or needs to be	2	1 916	4.1
Fair	3	4 656	9.9
Good	20	40 601	86.0
Total	25	47 173	100.0

SITE MIXING VERSUS PLANT MIXING

Site-mixed concrete for bridge-deck overlays is preferable to ready mixed for the following reasons:

1. Concrete mixed 5 min before placement is more easily handled than is concrete mixed 30 min before placement because of temperature increases, loss of air, aggregate absorption, and cement hydration in the longer mixed concrete.
2. Concrete produced in mixers at the site allows more rigid quality control and the necessary adjustments than is possible in the production of large loads of ready-mixed concrete.
3. It is more economical to reject a small quantity of concrete than a truckload because less concrete is rejected, replacement time is less, and there is less chance of cold joints.
4. Communication among work persons batching and placing the concrete at the site is quicker and more direct than is communication among those on the site and at the ready-mix plant.
5. Aggregates produced in separate sizes, delivered to the site, and covered have more constant moisture contents and less variability. Errors in batching will be fewer, because only one mix is being used, for only one project, and in small quantities. For special projects, aggregates can be produced to exacting specifications.
6. Site-mixed concrete allows better construction control because (a) the same personnel can spread the concrete and place the saturated burlap and (b) production of the concrete can be controlled more easily (e.g., if the epoxy layer is not far enough ahead of the concrete, the work persons can stop spreading concrete and help spread epoxy, and the mixing will stop with no old concrete in the mixer; if the overlay is starting to set up, the work persons can stop spreading concrete and help apply saturated burlap, and the mixing will stop with no old concrete in the mixer; or if rain or breakdowns cause delays, the mixing will stop with no concrete in the mixer, until the operation can proceed).

OBSERVATIONS—MONOLITHIC VERSUS TWO-LAYER DECKS

Two-layer construction for concrete bridge decks is superior to monolithic construction for the following reasons:

1. The 20 700-kPa (3000-lbf/in^2) concrete used for the monolithic decks is less durable than the 34 500-kPa (5000 lbf/in^2) concrete used for the two-layer decks.
2. If the structural part of the deck is to be covered with a high-quality, carefully controlled, durable overlay, then the concrete for the structure can be placed by using normal quality control.
3. Because the structural deck settles during placement to almost its full deadload deflection, the final profile is more nearly correct when the overlay is placed, and better vertical alignment and better drainage will result.
4. The structural deck allows access to the topping placement for heavier equipment, guarantees no displacement of the reinforcing steel during placement, makes pumps unnecessary, deposits the topping almost in place, and allows drier mixes that consolidate with less vibration because there is no steel in the overlay.
5. The overlay will have few shrinkage cracks and none of the segregation of the structural deck.
6. Placing an overlay on a hardened structural deck guarantees that the thickness of cover of the reinforcing

steel in the finished deck is at least the thickness of the overlay.

SUMMARY AND CONCLUSIONS

Of the concrete bridge decks in two freeway systems in the Vancouver area, which were all built about the same time, with aggregates and concrete from the same sources, and subject to about the same weather conditions and to some of the heaviest traffic in British Columbia, the monolithic structures have the most surface failures. For the overlays on the two-layer bridge decks, site mixing with site-stored aggregates produced more durable concrete decks than did ready-mixed concrete. A two-part epoxy bonding agent used under the supervision of a competent technician produces a more consistent bond than does a randomly placed, unsupervised mix of cement grout. The two-part epoxy bonding agent inhibits the migration of chloride ions to the reinforcing steel. Tire studs and the application of extra water for deck finishing at the time of placement contribute to deck deterioration. Rigid adherence to the principles of batching, mixing, placing, finishing, and curing concrete is mandatory for concrete-deck durability.

1. Well-bonded, two-layer decks are more durable than monolithic decks and guarantee adequate cover of the steel.
2. Rigid quality control of the concrete and bonding agent used for the overlay of two-layer bridge decks is mandatory for satisfactory bond and deck durability.
3. Rigid control of the application of the bonding agent appears to produce a positive bond and inhibit chlorides from reaching the reinforcing steel.
4. Site mixing of deck overlay concrete allows excellent quality control and more expedient placement of the concrete.

RECOMMENDATIONS

1. Bridge decks should be two-layer systems.
2. Concrete for deck overlays should be site mixed, preferably in small batches.
3. Aggregates for bridge-deck overlays should be screened to 16 to 10-mm (5/8 to 3/8-in) and 10 to 4.75-mm (3/8-in to no. 4) sizes, stockpiled separately at the site, and covered until used.
4. Cement sufficient for the deck overlays should be stored dry at the site.
5. The overlay should be 34 500-kPa (5000-lbf/in^2) concrete with a maximum slump of 19 mm (3/4 in), a water-to-cement ratio of not more than 0.35, 6 to 8 percent entrained air, and the minimum sand content that allows placing and finishing.
6. The bonding agent should be two-part epoxy.
7. Placing the epoxy during the overlay of the structural deck requires scrupulous supervision by qualified personnel.
8. The structural deck surface should be thoroughly cleaned down into the matrix and kept clean.
9. The overlay concrete should be spread in even rows in front of the paver and struck perpendicular to the centerline of the bridge.
10. The overlay concrete should be placed longitudinally in single-lane widths.
11. The finishing machine should have some form of surface vibration for consolidation.
12. Any cold joints should be vertical, not sloped (including the longitudinal joint between mats), and the vertical surface should be covered by bonding agent when pouring the concrete begins again.
13. Large [170-L (45-gal)] drums of water should be placed along the paving route at suitable intervals for saturating burlap sheets for curing. The saturated burlap should be applied as soon as the surface is finished.
14. The burlap curing should be kept saturated for 3 d and then covered with polyethylene for 4 d.
15. After curing, the surface should be air dried for 1 d and then sealed.
16. Stringent care should be exercised to ensure good concrete practice in batching, mixing, spreading, consolidating, finishing, and curing of the overlay.

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