Figure 15. Wax beads being added by concrete bucket to already mixed concrete at jobsite.

lay on a fresh concrete lower course within 1 h of lower course placement was successful. In addition, tests on other cores indicated that the top 13 to 25 mm (0.5 to 1 in) of the deck was completely sealed by the wax-bead process.

CONCLUSIONS

The results of this project indicate that a good bond can be developed between two concrete courses (internally sealed and conventional concretes) when both courses are placed in the same operation. The integrity of this bond was not reduced by the temperatures it experienced during the heat treating of the wax-bead concrete, temperatures ranging from 85° to 93°C (185° to 200°F).

When the second concrete course was placed on the test slabs 1 d after the first course was placed, both surface preparation procedures—8.3-MPa (1200-lbf/in^2) water blast and grout and 8.3-MPa water-and-sand blast and grout—proved to be effective. However, the water-and-sand blast and grout procedure yielded higher direct tensile strength of the bond.

Recommended areas of future research on two-course construction are as follows:

1. Further study should be done on the effectiveness of various methods of consolidating the second course of concrete.
2. More research should be performed on the water-blast procedure (minus sand) because it was a simpler and thus less costly procedure than the water-and-sand blast cleaning.

ACKNOWLEDGMENTS

The test-slab and bridge-deck construction described here was accomplished as a joint effort between the Washington State Department of Highways and the Federal Highway Administration. State highway department personnel who contributed significantly to the effort were Jack Launceford, project engineer; Mike Myette, assitant project engineer; and Tom Marshall, assistant materials engineer. The bridge contractor was Lockyear and Sons, and the heating subcontractor was Frank Murry of Lahr Corporation. The electric blankets used to heat the deck were manufactured by Johanson Electrotherm.

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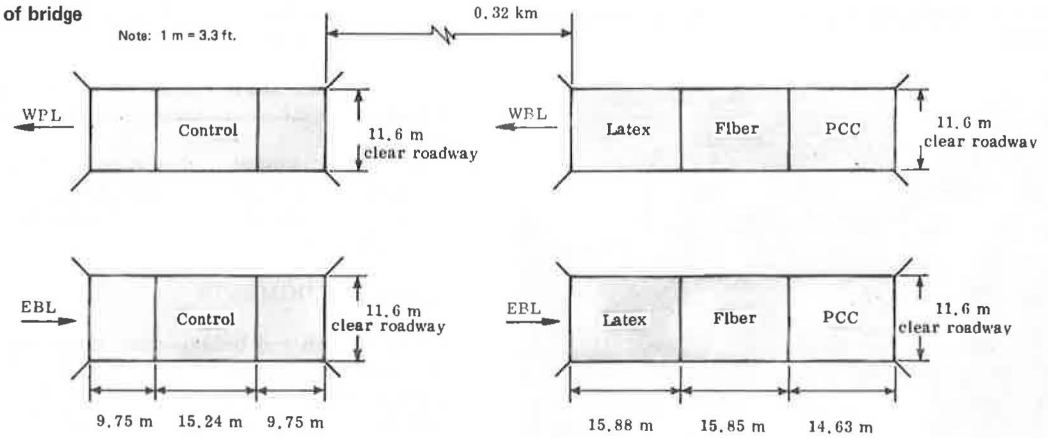
Two-Course Bonded Concrete Bridge-Deck Construction in Virginia

Samuel S. Tyson, Virginia Highway and Transportation Research Council

Six bridge decks were constructed in Virginia by using the two-course bonded technique. The wearing course layers consisted of a high-quality portland cement concrete, a wire-fiber-reinforced concrete, and a latex-polymer-modified concrete. Analyses of construction activities, labor requirements, and cost are used to demonstrate the viability of two-course construction when additional protection of the upper reinforcing steel is warranted. It is shown that normal cover depths and an adequate degree of consolidation were attained in the two-course decks. The significantly better strength of the overlay concretes, as compared to that of concrete placed on two conventional decks used as controls in the study, underscores the primary purpose of the two-course technique, which is to promote the placement of high-quality protective concretes in the upper cover zone of bridge decks. A basis for assessing the future performance of the decks was provided by evaluating them at the age of 1 year, before they were opened to traffic and before application of deicing salts.

In June 1974, the two-course bonded technique for concrete bridge-deck construction was used in the construction of six bridge decks on the Va-7 bypass over the Norfolk and Western Railway at Berryville, Virginia. A research study was initiated to investigate the construction, the condition, and the 5-year performance of these decks and two control decks constructed nearby on bridges over Va-615. The project plan for the six

Figure 1. Plan view of bridge structures.



two-course decks as well as that for the two control decks is shown in Figure 1. The control decks were constructed under the same contract by using a conventional, single-lift technique.

Three concretes were selected for use in the wearing-course layers: a high-quality portland cement concrete (PCC) with a low water-cement ratio, a concrete reinforced with wire fiber, and a latex-polymer-modified concrete. Each concrete was selected to improve the resistance of the concrete above the reinforcement to the intrusion of corrosive substances, particularly chlorides. Low water-cement ratios reduce the permeability of the cement paste; the most significant improvement is realized by not exceeding a ratio of 0.4 (1). Fiber reinforcement resists the formation of microcracks that permit the accelerated intrusion of deleterious substances. The polymer modifiers resist such cracking and also occupy a portion of the internal pore structure of the concrete.

CONSTRUCTION

The eight study decks had a minimum design thickness of 216 mm (8.5 in) and rested on simply supported steel girders with a center-to-center spacing of 2.5 m (8.5 ft). The decks were approximately 15.2 m (50 ft) in length with a clear roadway width of 11.6 m (38 ft).

The two control spans were constructed by the single-lift technique by using a longitudinal oscillating screed that is commonly used in Virginia for bridge-deck construction. This screed rested on supports beyond the ends of the deck and did not impart loads to it. Internal vibrators were used for consolidation.

A transverse screed was used for the two-course installations. The essential elements of this screed included a surface vibrating unit for consolidation of the concrete, an auger that moved excess concrete forward, and a rotating drum that oscillated transversely over the bridge and finished the deck surface.

The sequence of construction for the two-course decks was planned so that 2 d would elapse between placement of the base layer and that of the overlay concretes on each deck. This delay period was selected because earlier placement of the overlays would risk (a) creating voids around the upper reinforcing steel and (b) causing delaminations from the outset of construction because of the tendency for the bleeding rate of the base-layer concrete to exceed the bleeding rates of the denser concrete overlays. Delays exceeding 2 d would have been acceptable structurally, but the 2-d delay was used because at that time light sandblasting was enough to remove from the surfaces of the base layers any laitance resulting from bleeding.

The high-quality PCC and fiber-reinforced concretes were delivered to the jobsite in conventional, ready-mix trucks. The latex-modified concrete was produced at the jobsite by two mobile mixer trucks. Each concrete overlay was deposited on a hardened base layer from a 0.6-m^3 (0.75-yd^3) capacity crane bucket.

Within 1 h before the placement of the concrete overlays, water was broomed onto the base layers. The intent was to maintain a moist concrete surface without free water. Before the first bucket of PCC or fiber concrete was deposited, a cement slurry with a water-cement ratio of 0.40 was broomed over the deck. No slurry was used with the latex-modified concrete; however, a portion of this concrete was broomed onto the deck surface before overlay placement.

Activities

The activities associated with the construction of the two control spans and the six experimental spans were observed and documented for the purpose of making a comparison of single-lift and two-course construction techniques. Descriptions of the placement procedures were obtained by compiling location charts for each truckload of concrete as the decks were constructed. Typical location charts for concrete placed in the single-lift control decks and in the base layers and the overlays of the two-course decks are shown in Figures 2 and 3 respectively. Figure 2 shows a chart for one of the control decks, and Figure 3 shows charts for the base course and the overlay of a two-course, fiber-reinforced deck. Records were also made of the time sequences for batching, delivering, depositing, screeding, texturing, and curing each truckload of concrete in the study decks. A complete description of the construction activities for each deck has been reported (2).

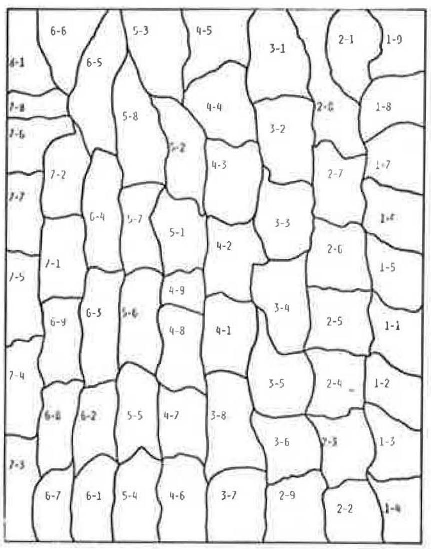
The time records for installation of all truckloads of concrete were grouped and averaged for the single-lift decks and for each layer of the two-course decks. Figure 4 shows these time periods in sequence and shows that the installation activities in the three groups progressed in a similar, orderly way.

The latex-modified concrete, which was continuously batched at the site, required zero delivery time. The wire-fiber-reinforced concrete required that considerable attention be paid to the addition of the fiber during batching. Figure 5 shows the influence of such variables by contrasting the times required to complete all activities from batching through screeding. The mean times for completion were significantly different, primarily because of the differences cited in the batching operations. The figure also shows the "datum time" for computing the time interval required for completion of the screeding activity—shown as the time of the initial deposit from each truckload of concrete. A comparison among the several installations indicated that, on the average, the duration of these critical placement operations, which required exposure and manipulation of the concrete on the decks, was approximately the same for both construction techniques and for all types of concrete in the project.

Labor

A comparison of the relative labor requirements for the two construction techniques was made by using the activities records to compute the average total times for single-lift, base-layer, and overlay installations: 5.5, 4.25, and 3 h respectively. The average total time required to install concrete in the three types of two-course decks was therefore 7.25 h, 33 percent greater than the time required to install conventional, single-lift decks. The total number of worker hours was also 33 percent greater for the two-course decks because the same crew was used to construct all of the decks.

Figure 2. Typical location chart for concrete placed in single-lift decks.



Cost

The costs of the overlay concretes in place were approximately \$18, \$29, and \$38/m^2 (\$15, \$24, and \$32/yd^2) for the high-quality PCC, the latex-modified concrete, and the wire-fiber-reinforced concrete respectively. This range of values is probably representative of the costs that can reasonably be anticipated for these and other overlay concretes in the immediate future. An increase of about 5 percent in the total cost of the bridge superstructure is therefore indicated when the two-course technique is specified instead of the conventional single-lift construction technique.

STRUCTURAL CONDITION

Depth of cover and degree of consolidation were measured in the control decks and in the two-course decks to provide on-site indications of the condition of the structures. In addition, tests to determine the strength and durability characteristics of the base-layer, overlay, and control concretes were conducted by using hardened concrete specimens from the project.

Depth of Cover

The depth of concrete cover over the topmost reinforcing steel of the study decks was determined by making direct probes in the fresh concrete during construction. The results are shown in Figure 6. The total depth of cover provided by the two-course technique was found to be equivalent to that provided by conventional, single-lift construction for identical deck designs. The average depth dimensions of the six two-course decks in the study are shown in the typical transverse section in Figure 7.

Consolidation

A nuclear gauge was used to determine the degree of consolidation for each concrete. The gauge was used in the backscatter configuration rather than the direct-transmission configuration because of the shallow depths of the overlays.

In the field, the rodded unit weight of each type of

Figure 3. Typical location chart for concrete placed in two-course decks.

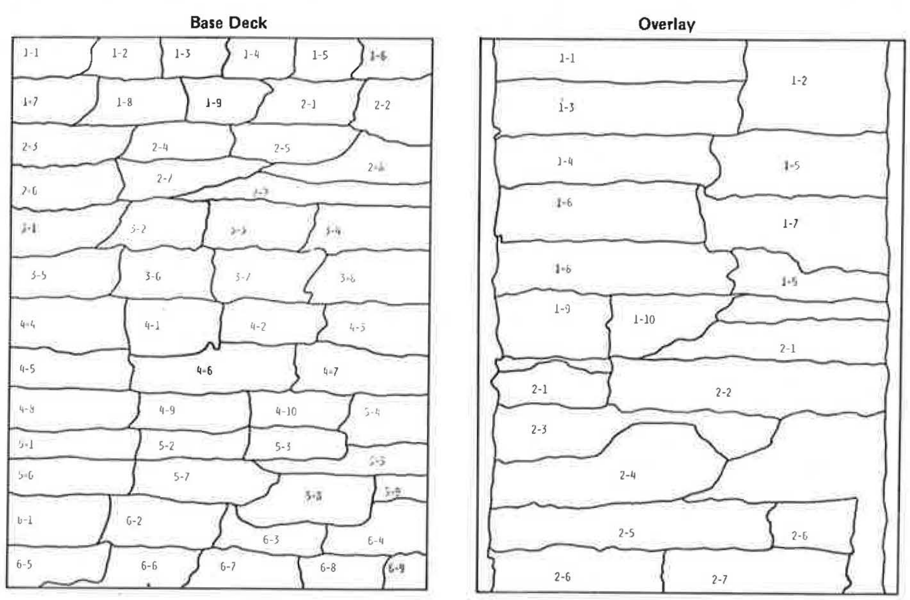


Figure 4. Sequences and average durations for concrete-installation activities from delivery through screeding.

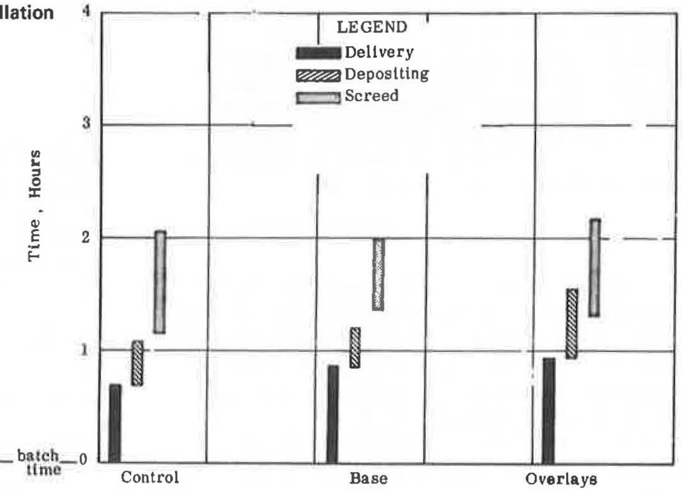
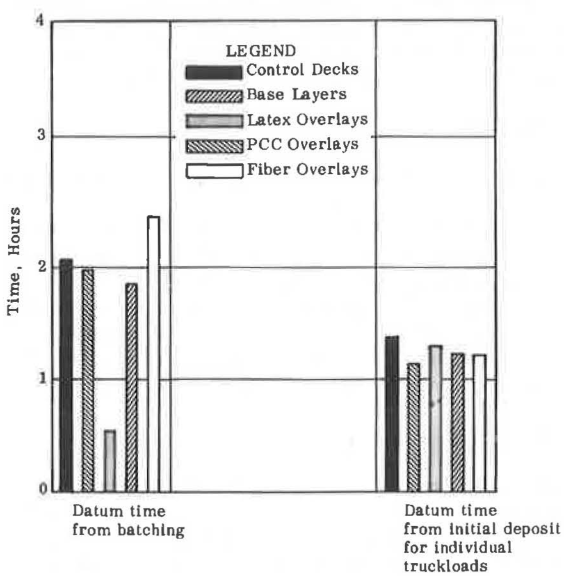


Figure 5. Average times to completion of screeding activity.



fresh concrete was determined, and nuclear density readings were obtained on the surface of the decks immediately after the screeding operation. A summary of these data is given below (1 kg/m^3 = 0.062 lb/ft^3):

Concrete	Nuclear Density (kg/m^3)	Nuclear Density as Percentage of Rodded Unit Weight
Control	2227	97.8
Base layer	2341	99.2
Latex-modified	2344	100.4
PCC	2417	103.0
Wire fiber	2429	104.9

The data seem to indicate good control of consolidation in the study decks.

A core was extracted from each of the two-course decks, and microscopic examinations of vertical sections verified good consolidation in the overlays and revealed the excellent condition of the bond interface between the overlays and the base layers.

Strength and Durability

Air contents, slumps, and temperatures were within normal ranges for each concrete, but the average strength of the normal superstructure concrete used in the single-lift control decks was lower than the average strength for the base-layer concrete of the two-course decks, which satisfied the design minimum of 2.76 MPa (4000 lbf/in^2) at 28 d. The only difference in the proportions of the base-layer concrete was the substitution of a locally available, polishing fine aggregate, which had a lower void content than the nonpolishing fine aggregate used for skid resistance in the control decks. The lower average strength of concrete in the control decks was attributed to the higher water demand of the fine aggregate. A nonpolishing fine aggregate with a lower void content than normally required was specified for the overlay concretes, and the resulting average compressive strengths exceeded the design minimum because of lower water-cement ratios. Attaining specified strengths is not always a problem in Virginia. However, a very definite advantage of two-course construction is apparent in the situation just described: The imported, nonpolishing fine aggregate needed to be specified only for the overlay portion of the decks, where skid resistance had to be provided, and the more economical, locally available fine aggregate with poor wearing characteristics could be used in the larger base layers of the decks.

The freeze-thaw resistance of field samples from each concrete was determined with guidance from ASTM C 666 (procedure A), which was modified by adding 2 percent sodium chloride by weight to the water surrounding the specimens. Percentage of weight loss and durability factor are given below for each type of concrete after 300 cycles of freezing and thawing. The surface rating system used is as follows: 0 = no scaling, 1 = very slight scaling [3-mm (0.12-in) maximum depth and no coarse aggregate visible], 2 = slight to moderate scaling, 3 = moderate scaling (coarse aggregate visible), and 4 = severe scaling. The allowable weight loss is 7 percent, and the minimum durability factor is 60.

Concrete	Number of Specimens	Surface Rating	Weight Loss (%)	Durability Factor
Control	8	1.9	2.0	96
Base layer	24	2.2	1.8	96
Latex-modified	8	2.3	2.8	88
PCC	8	3.0	1.5	100
Wire fiber	8	1.9	0.6	99

Each of the concretes performed well in this test; this finding ensures desirable freezing and thawing characteristics of the concretes delivered for placement in the decks.

Figure 6. Depth of cover over topmost reinforcing steel for eight study decks.

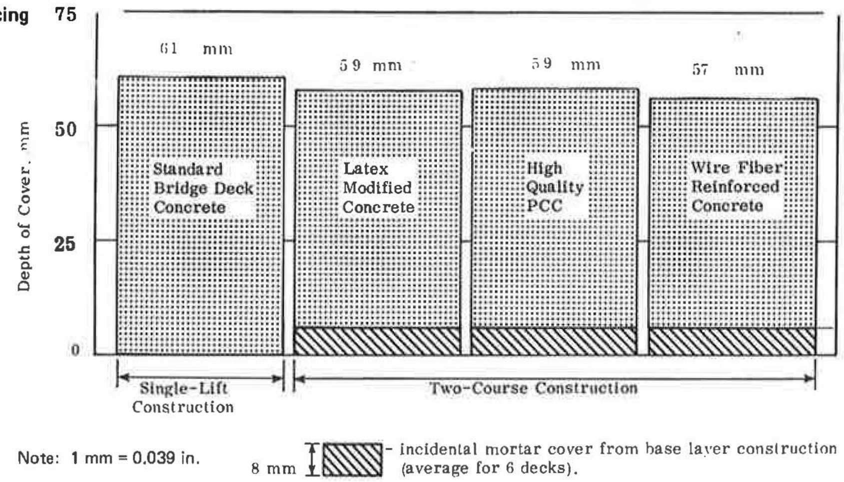
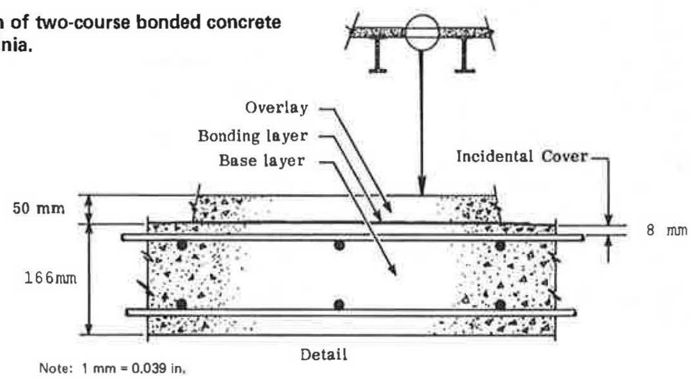


Figure 7. Typical transverse section of two-course bonded concrete bridge decks as constructed in Virginia.



PERFORMANCE EVALUATION

The study decks were constructed 12 months before they were opened to traffic, and they were 18 months old before deicing operations were required. An analysis of the condition of the concrete decks at the age of 12 months was made both to assess their quality at that time and to establish a data base for future performance evaluations (3).

Chloride Contents

An important aspect of future determinations of bridge-deck performance will be the degree to which chlorides from deicing chemicals are able to infiltrate the wearing-course concretes. The corrosion of reinforcing steel embedded in concrete depends on several factors including the presence of moisture and oxygen and the pH of the concrete; however, suspected active corrosion has been reported when the chloride ion (Cl^-) content of a concrete reaches a threshold value of approximately 0.77 kg/m^3 (1.3 lb/yd^3) (4). Investigations in Virginia and elsewhere of the specific ion electrode titration method of determining chloride content have shown it to be reproducible and satisfactory (5), and it was used to analyze the concretes included in this study.

Chloride analyses were made of hardened concrete from cylinders cast at the project and from samples drilled from the decks. The results of the analysis of samples for each type of concrete are given below (1 kg/m^3 = 1.68 lb/yd^3):

	Chloride Content (kg/m^3)	
Concrete	Cylinder Samples	Deck Samples
Control	0.48	0.46
Base layer	0.59	—
Latex-modified	0.35	0.42
PCC	0.37	0.44
Wire fiber	0.42	0.53

Clearly, the two sampling techniques caused no significant difference in the test results.

The chloride contents of the uncontaminated concretes were nearly equal in magnitude to what was considered to be the chloride-content corrosion threshold. An investigation was therefore conducted to determine the source of these chlorides (6). Samples of aggregates from several quarries in Virginia were tested and were found to contain different amounts of Cl^-. The results are given below.

Aggregate	Chloride Ion Content as Percentage of Aggregate Weight
Limestone A	0.028
Granite	0.019
Gravel A	0.014
Gravel B	0.012
Limestone B	0.012
Diabase	0.001

The chloride contents of the aggregates used on the project were thus found to be the source of approximately 85 percent of the. chlorides identified in the concretes. These chloride ions are bound within the aggregates, and only minor amounts of the ions (3.75 percent) were found to be leached from the project aggregates when they were soaked in distilled water and the pH was ajusted to 12 to simulate the alkaline environment of concrete. It is therefore assumed that the chlorides in the project concretes will not contribute to the corrosion process. However, because these chloride ions are measured by the titration method used in the analysis, they should be accounted for as baseline chloride contents in the test results. The theoretical corrosion threshold for the study decks will accordingly be 1.19 kg/m^3 (2 lb/yd^3) for the chloride content measured at the level of the upper reinforcement.

Sonic Pulse Velocities

The travel times for sonic pulses transmitted vertically from the bottom to the top of the study decks were measured and recorded at 44 locations on each deck. Before the testing of the field structures, pulse velocities were measured vertically through single-lift and two-course deck models that had the same thickness and reinforcement as the structures. Tests of the deck models revealed no significant difference in pulse velocities among the three types of two-course slabs nor between the two-course and single-lift slabs. In addition, the location of the reinforcing steel relative to the path of the wave had no noticeable influence on pulse transmission time.

In the results given below of the sonic testing on the bridge decks, the 88 measurements from each pair of decks are presented as average pulse velocities (1 m/s = 3.28 ft/s):

Concrete	Average Pulse Velocity (m/s)
Control	3090
Latex-modified	3860
PCC	3970
Wire fiber	3790

On the basis of published ratings for normal ranges of sonic pulse velocities (7), the relative quality of concrete in the two-course decks appears to be better than that of concrete in the single-lift control decks. The following table gives the rating scale used:

Pulse Velocity (m/s)	Rating
	Excellent
4500	
	Good
3700	
	Questionable
3000	
	Poor
2100	
	Very poor

Future evaluations of the study decks will consider any significant decreases in pulse velocities for individual locations or in the average pulse velocity for each deck because such changes could indicate deterioration of the concrete caused by corrosion-induced spalling or other mechanisms.

Skid Resistance

In Virginia, the safety of highway traffic has for many years been safeguarded by constructing and maintaining pavement and bridge-deck surfaces that provide adequate skid resistance. The minimum value for stopping distance numbers has been determined to be 40 on the basis of a skid-test method that uses an automobile on wet pavement. In recent years the skid trailer has come into use as a safer and more convenient method of evaluating skid resistance. Skid numbers resulting from this test have been correlated with those from the method that used the automobile, and the equivalent numbers are reported as predicted stopping distance numbers (PSDNs).

PSDNs for the travel and passing lanes of the study decks were derived from an average of five measurements in each lane by using the skid trailer in accordance with the procedures of ASTM E274. In the following table, the average PSDN for all lanes of each study deck is seen to be greater than 60, which is excellent:

Concrete	Average PSDNs
Control	62
Latex-modified	66
PCC	66
Wire fiber	65

The skid resistance of the decks will be evaluated again at appropriate times.

Other Procedures

In addition to the evaluation procedures already discussed, visual surveys and soundings and measurements of electrical potentials were made, and these data indicated no problems in the study decks. All of these procedures will be used to evaluate the decks in the third and fifth years after construction.

CONCLUSIONS

This investigation of two-course bridge-deck construction in Virginia led to the following conclusions:

1. An analysis of construction activities and related labor and cost requirements has shown the two-course construction technique to be a viable alternative to conventional construction when additional protection of the upper reinforcing steel is warranted.
2. Attainment of normal cover depths and an adequate degree of consolidation were verified for the two-course decks.
3. The superior strength of the overlay concretes as compared to that of the conventional concrete on this project underscores the primary purpose of the two-course technique, which is to promote the placement of high-quality protective concretes in the upper cover zone of bridge decks.
4. The true benefits of two-course construction must be determined by future deck-performance evaluation procedures such as visual surveys, soundings, determinations of chloride content, measurements of electrical potentials, sonic evaluations, and skid tests.

ACKNOWLEDGMENTS

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Bonded Concrete Bridge Pavements in Switzerland

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Bonded cement concrete pavements have been successfully constructed on more than 150 long, medium, and short bridges in Switzerland during the past 15 years. Traffic in Switzerland never rolls directly over the bridge structure (the deck) but always over a bridge pavement (overlay) instead. The concrete used in bridge construction is generally not proof against combined frost-thaw-salt action. The abundant use of deicing chemicals in winter increases the risks of damage to structural concrete and steel reinforcement. In addition, today's road traffic (a) subjects carriageways to horizontal shearing forces, (b) demands high standard riding quality of pavements, and (c) results in pavement wear caused by abrasion (pronounced wear in the case of studded tires). The criteria required of bonded concrete bridge pavements in Switzerland are presented. The results of on-site measurements taken on 13 test bridges prove that (a) crack-free bonded pavements perceptibly increase the bending stiffness of bridges and (b) use of bonded concrete pavement allows economies in longitudinal steel reinforcement of 7 percent or more depending on the bending stiffness of the bridge and up to 40 percent in transverse reinforcement if the pavement is fully bonded to the bridge deck. Rules to be followed in construction of such bridge-deck pavements are also given.

The subject of bridge pavement construction in Switzerland is conditioned by three factors: (a) the extraordinary relief of the earth's crust in Switzerland, (b) developments in bridge construction, and (c) significant changes that have occurred in the past 15 years in the realm of keeping roads serviceable (i.e., snow- and ice-free) in winter.

TOPOGRAPHY

The Swiss road construction engineer has to face an exceptionally dynamic relief of the earth's crust. This results in the large number of bridges found in very small geographic areas of the country. Bridge requirements per route kilometer in Switzerland are as follows:

1. In mountainous regions, 0.55 to 1.55 bridges/route·km (2 to 10 percent of route length);
2. In hilly regions, 0.30 to 0.60 bridge/route·km (5 to 28 percent of route length); and
3. In the plains, which are crossed by streams, canals, and lakes, 0.5 to 0.75 bridge/route·km (0.5 to 13 percent of route length).

These characteristics make Switzerland a classic bridge-building country.

DEVELOPMENTS IN BRIDGE CONSTRUCTION

Prestressed concrete, which came into use in Swiss bridge construction around 1960, made it possible to achieve practically crack-free structures. The prestressed concrete system, however, requires high-grade steel reinforcement, which is more vulnerable to the action of corrosive agents.

ROAD SERVICEABILITY IN WINTER

Since about 1965, deicing salts (mainly of the sodium chloride group) have been used to keep Swiss roads snow- and ice-free in winter. No sufficient frost-resistant concrete has yet been achieved in Swiss road construction. Inspections of concrete roads in Switzerland have shown that

1. No frost damage was found on such roads before deicing salts were frequently used (1960) and
2. Random scaling damages started to appear on these pavements around 1965 as a result of the extensive use of deicing salts.

In relation to concrete durability, therefore, frost-thaw-salt impact is stronger than frost impact. As a result, empirically proved air entrainers have to be added to all cement concretes used in Swiss pavement construction, and compliance is checked by means of stringent quality controls (11).

BRIDGE-DECK-OVERLAY CONSTRUCTION CONCEPTS IN SWITZERLAND

Bridges are not operated unpaved in Switzerland. This seems to be a significant difference between Swiss con-