Construction and Performance of an Experimental Thin-Bonded Concrete Overlay Pavement in Houston

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ABSTRACT

The use of thin-bonded concrete overlay (TBCO) pavements is rapidly emerging as a viable means of rehabilitating concrete pavements. In recent years, several projects have been constructed, and valuable information has been gathered with the Iowa Department of Transportation leading the way. A survey of the available literature, however, reveals that the information is scattered and, in most cases, it is difficult to make statistical inferences because either the information was not collected for any particular purpose (i.e., not task-oriented) or there is no prior well-defined experiment design. During the summer of 1983, an experimental 1,000 ft of thin-bonded concrete overlay pavement was placed on Interstate 610 (Loop 610), a 4-lane divided freeway in Houston, Texas. The original pavement structure is a continuously reinforced concrete pavement. Five design sections were constructed. Concrete reinforcement and overlay thickness were used at three and two levels, respectively. Presented in this paper are several aspects of the experimental project. First, the experiment design is discussed, along with project specifications, and a measurement program. Second, actual construction is presented, and salient features outlined. Third, initial results (including field and laboratory tests, Dynaflect deflections, and road profile data) are analyzed. Fourth, a 6-month performance report is made. In closing, conclusions and recommendations derived from the study are presented for those individuals and agencies contemplating the use of TBCOs for the rehabilitation of portland cement concrete pavements.

During the summer of 1983, an experimental 1,100 ft of thin-bonded concrete overlay (TBCO) was placed on Interstate 610 (Loop 610), which encircles downtown Houston and was built 14 years ago. The original pavement structure is a continuously reinforced concrete pavement (CRCP), 8-in. thick with a percent longitudinal steel reinforcement, P_s, of 0.5 percent. The CRCP rests on a 6-in. thick cement-treated subbase. The natural material comprising the subgrade is a silty clay (Figure 1). At the project location, Loop 610 carries an estimated average annual daily traffic (ADT) of 113,000, 8 percent of which is trucks. It is a heavily trafficked freeway experiencing near continuous traffic flow during morning and afternoon rush hours when most downtown workers commute. The site selected for the experiment is located in the southeastern part of Loop 610 between Cullen Boulevard and Calais Street, approximately 3.5 mi after the amusement park complex of Astroworld/Waterworld, eastbound. At this location, Loop 610 is an 8-lane divided highway. Only the 4 eastbound lanes were overlayed in this experiment. To date, the original CRCP has generally performed well. However, in certain areas, increasingly heavy maintenance is required. Innovative repair techniques have been tried with mixed results. These include polymer concrete patching and epoxy injection. It was felt that some form of rehabilitation would be necessary in the near future. At the site of the experimental project, the types of surface defects were primarily spalled transverse cracks, longitudinal cracks, and patches. While these were not seen as an immediate threat to the load-carrying capacity of the structure, they required increasing amounts of maintenance dollars at increasing inconvenience to the freeway users in order to protect the original investment.

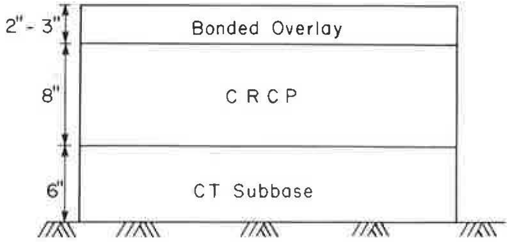


FIGURE 1 Typical cross section of pavement structure.

OBJECTIVES

The Loop 610 experiment was designed as part of a cooperative research effort between the Center for Transportation Research of The University of Texas at Austin, the Texas State Department of Highways and Public Transportation (SDHPT), and the Federal Highway Administration (FHWA). The primary objective of this study was to develop a methodology for evaluating the performance of a TBCO over an existing portland cement concrete (PCC) pavement with special attention paid to: (a) experimental projects construction and monitoring, (b) laboratory experiments, and (c) theoretical analyses.

The Loop 610 experiment met the first of these objectives. It was designed as an experiment to gain some understanding in the interactions of the many variables (i.e., materials, construction, design) that affect the performance of a TBCO. The following table gives the experiment design.

Concrete Reinforcement/ Overlay Thickness (in.)	Non-reinforced	Steel Mat Reinforced	Steel Fiber-Reinforced
2	X	X	X
3		X	X

It was thought that only a properly designed experiment with the subsequent appropriate statistical analyses would yield the proper answers.

SCOPE

Presented in this paper are several aspects of the Loop 610 experiment. First, design considerations are discussed along with specifics of the experiment design. Next, the actual construction is presented and salient features outlined. Subsequently, analysis and evaluation of initial results are presented. These include profile and Dynaflect deflection data. Statistical analysis and data interpretation of deflections data emphasize the advantages of using TBCOs.

Finally, a performance report is made of the test sections after 6 months of intense traffic and the harshest winter Houston has experienced in years. Conclusions derived from this experiment are presented and recommendations are made to those contemplating the use of TBCOs for the rehabilitation of PCC pavements.

THE LOOP 610 EXPERIMENT DESIGN

Design Considerations

Rigid (concrete) pavements are particularly appropriate when fuel spillage, high traffic volumes, and low maintenance are of concern; major distress manifestations occur less often on rigid pavements as compared with flexible (asphalt) pavements. In most cases, these distress manifestations can be related to poor construction practices, poor workmanship, or inferior materials (1). In recent years, most of the rigid pavements on interstate highways and at major hub airports have reached the end of their service lives and, consequently, need some type of rehabilitation.

To this end, an overlay pavement will normally be used. Typically, overlays for rigid pavements vary in thickness from 1 to 6 in. (2) and they are either flexible or rigid. The thinner overlays are used in a number of instances to include:

1. Restoring ride quality.
2. Improving skid resistance of original pavements.
3. Fulfilling a need for a temporary remedial measure when funds are lacking for more definitive structural overlays.
4. Curtailing maintenance requirements that may have become excessive; also, the amount of patching may have led to a rough ride.
5. Correcting minor grade problems.

The thicker overlay pavements are used primarily to restore structural capacity and minimize reflection cracking.

Many agencies having responsibility for pavements have traditionally used asphalt concrete overlays over rigid pavements. However, life-cycle costing, advances in the state of the art in pavement construction (e.g., paver types and production rates, surface preparation techniques and equipment, and concrete additives and reinforcements), and better understanding and modeling of overlay pavement behavior have brought about increased use of concrete as a viable rehabilitation alternative. Because of thermal and structural compatibility, it seems reasonable to rehabilitate a PCC pavement with a concrete overlay. The concept of a TBCO is appealing because it has the potential to increase the structural capacity of the original pavement in addition to the many uses discussed above. As a result, many TBCO projects have been built in the recent past (3-5). A compendium of many of these projects was prepared by the FHWA (6). A critical review of the literature reveals good performance in the projects constructed to date (Iowa, Louisiana, and New York) with only a few exceptions (California and Georgia).

To be effective, a TBCO must be properly bonded to the original pavement surface. In doing so, the original pavement overlay system will function as a monolithic block, thus using to the fullest extent the load carrying capacity of the original pavement. This may result in a thinner overlay pavement, thus saving a considerable amount of money in material costs. A design methodology for a TBCO must encompass wheel load and environmental (temperature and moisture) stresses. A reflection cracking analysis must be considered as it is bound to occur.

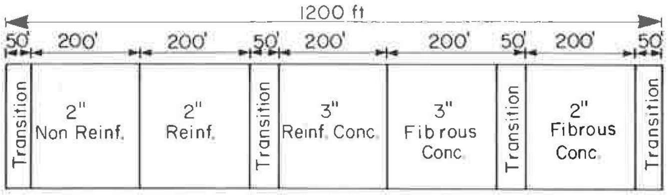
In the Loop 610 experiment design, several factors were considered that were thought to have an impact on performance. At the same time, an effort was made to factor out unnecessary error opportunities. Two effects that were factored out this way are traffic and temperature differentials due to coarse aggregate type. For the traffic, the project location was selected such that no entry or exit ramp existed for the entire length of the project. Therefore, assuming but a few lane changes and weaving, a given lane and section (one cell of or factorial design) receives the same number of load applications as the cell adjacent to it in the same lane; this design eases out the interpretation of performance results. For the temperature differential on the other hand, the same type and source of coarse aggregate is specified, in this case Colorado river gravel (i.e., a quartzite). Coarse aggregate type is known to have a significant impact on concrete strength but also on concrete coefficient of thermal expansion, and thus on concrete movement and CRCP performance. It is important to note that by using the same coarse aggregate source, the chances of differential movement between original pavement and overlay are decreased and, therefore, possible debonding due to interface shear failure is decreased.

The main factors considered in this experiment were material type and concrete thickness. The following design sections were constructed (see Figure 2):

1. Two-in. thick plain concrete overlay (section 2-in. NR).
2. Two-in. thick steel-reinforced (welded wire fabric) concrete overlay (section 2-in. R).
3. Three-in. thick steel-reinforced (welded wire fabric) concrete overlay (section 3 in. R).
4. Three-in. thick steel fiber-reinforced (Bekaert Dramix ZP 50/50) concrete overlay (section 3 in. F).
5. Two-in. thick steel fiber-reinforced (Bekaert Dramix ZP 50/50) concrete overlay (section 2 in. F).

(Note that the factorial experiment design did not include a 3-in. plain concrete section.)

Simplicity of the design was sought as a desirable feature for this experimental project. This would expedite and ease construction. It was thought



(a) As designed

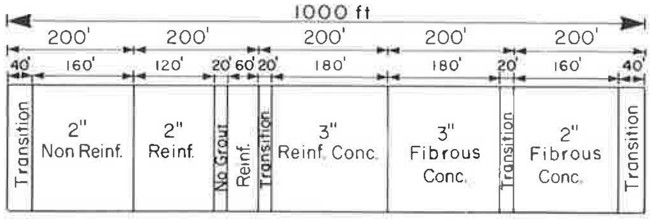


FIGURE 2 PLAN VIEWS of the Loop 610 and Houston test sections.

that any concrete paving contractor with reasonable experience could handle this project without specialized equipment. Also, the material selected would be readily available.

Project Specifications

Project specifications were written for the following areas:

- Description
- Materials
- Equipment
- Construction method
- Measurement
- Payment

The concrete mix designs under the Materials category were different for fiber versus no fiber (i.e., steel-reinforced and nonreinforced concrete) sections. The following table gives the gradation requirement for the steel-reinforced and nonreinforced sections

Sieve Size	Percent Retained
.750-in.	0-less than 1
.500-in.	1-less than 15
.375-in.	15-less than 40
No. 4	40-less than 98
No. 8	98-100

and Table 1 gives the concrete mix design specifications.

Selected information that may be of interest is as follows:

1. Overlay placement temperature should not exceed 85°F.
2. Concrete overlay should be cured above 40°F for a period of 4 days.
3. Minimum flexural strength of concrete at 7 days should be 700 psi.
4. Wire fabric size should be as follows:
   3-in. overlay--6 x 12 - D12 x D4.2
   2-in. overlay--6 x 12 - D8 x D4
   permitted end lap--12-in. minimum
   permitted edge lap--6-in. minimum
5. Scarification depth should be .125 in. Additional depth of scarification up to a 1-in. minimum shall be required at each end of concrete overlay sections to be effected over 40-ft-long transitions.

TABLE 1 Concrete Mix Design Specifications for the Loop 610-Houston Experiment

Characteristic	Fiber Sections	No-Fiber Sections
Cement type	I or II	I
Cement factor (sacks/yd^3)	8	7
Coarse aggregate factor (S.S.D.)	0.375-in. maximum at 1,335 lb/yd^3	0.60 (see table of gradation requirements)
Fine aggregate (S.S.D.)	1,320 lb/yd^3	(see table of gradation requirements)
Water factor (gal/sack of cement)	5.0	4.5
Water reducer	As directed by manufacturer	–
Entrained air (%)	4-6	4-6
Slump (in.)	3-4-1	–
Bekaert Dramix Fiber ZP 50/50 or equal (lb/yd^3)	85	–

Note: S.S.D. = saturated surface dry.

6. After scarification, the concrete surface should be sandblasted and then airblasted just before the grouting-paving operation.
7. Cement grout should consist of 1 bag of portland cement and 7 gal of water and may contain a water-reducing plasticizer at the option of the engineer.
8. Fibers that are added to the mix at the job site should be added in 66-lb bags at the rate of 2 bags per min. After all fibers are added (85 lb per yd^3), the batch should be mixed for another 2 min at 16 rpm before placement.
9. Concrete overlay should receive a metal tine finish.
10. Membrane curing should be conducted at the rate of 120 ft^2 per gal.
11. Longitudinal joint should be between .250-in. minimum and .375-in. maximum in width by 1-in. minimum in depth.
12. Longitudinal joint should be saw-cut and filled with sealing material (class 1A or 1B) or silicone sealant with backer rod.
13. Transverse joint should be cut and sealed in the overlay to match any transverse construction joint in the existing pavement.

Measurements Program

Measurement of several variables was considered in this experimental project. They can be thought of as response variables, CRCP-TBCO system output variables, or performance variables. Photologging was conducted to visually record the pavement surface condition before and after overlay construction. This was accomplished by mounting a modified Nikon camera on a horizontal pole attached to a truck.

The Dynaflect is a device that is widely used for measuring pavement surface deflections. In pavement engineering practice, surface deflections are used for many purposes (e.g., material characterization, void detection underneath slabs, and evaluation of load-carrying capacity of pavement structures). In this case, the latter application was sought. Specifically, it was desired to know how surface deflections were affected by the various TBCO designs.

The GMR digital profilometer was used to measure the road profile before and after overlay construction. By using roughness data, the profilometer permits the engineer to estimate serviceability index--a user-oriented performance measure of the roadway.

Visual condition surveys were conducted before and after overlay construction. The detailed method used in this case is called the "small sections" method whereby a crew walked along the pavement and recorded any visible distress manifestations. Cracks were mapped and spalls were counted and classified as minor or severe. Condition survey is the single most important factor of the pavement monitoring activities and will usually dictate the course of action (routine maintenance or major repair) to be taken.

Concrete movement across cracks and, therefore, crack width is a major contributing factor to the performance of CRCP. A mechanical strain gauge was used in this project to monitor concrete movement after overlay placement. To this end, metallic boxes were inserted at quarter points within each of the five design sections. The boxes had removable metal tops. Gauge plugs were placed in the boxes on the original CRCP and above the boxes across the same cracks. Before overlaying, crack widths were read with a graduated microscope. The data are given in Table 2.

During construction, field tests were performed. They included testing for concrete and air temperature, concrete air value, slump test, and casting of beams for the flexural strength test. After construction, 4-in. field core samples were taken for laboratory testing. The tests were to determine CRCP-TBCO interface shear strength using a modified shear collar, and splitting tensile strength.

TABLE 2 Selected Crack Width Measurements With Microscope at Quarter Point Within Each Section, Before Roto Milling

Location	Distance from Outside Edge (in.)	Microscope Reading[a] (divisions)	Crack Width (in.)
1	18	7	0.014
2	39	17	0.034
3	37	12	0.024
4	34	21	0.042
5	32	15	0.030
6	25	6	0.012
7	32	8	0.016
8	39	10	0.020
9	37	13	0.026
10	34	14	0.028
11	34	8	0.016
12	35	11	0.022
13	31	12	0.024
14	39	10	0.020
15	31	8	0.016
Mean	—	11.47	0.023
SDEV	—	4.09	0.008

Note: Average temperature was 80°F; SDEV = standard deviation. Same cracks were instrumented for Berry strain gauge measurement.

[a] One division on microscope equals 0.002 in.

THE LOOP 610 EXPERIMENT CONSTRUCTION

Construction began on July 22, 1983, and was completed on August 27, 1983. After a 6-day curing period for the last pour, all four lanes were opened to traffic. Much of the delay incurred is attributable to waiting out hurricane Alicia, which struck the Houston-Galveston area on August 18, 1983, and the subsequent lack of ice used to control concrete placement temperature. Construction proceeded in two phases: (a) phase 1 consisted of the placement of overlays on lanes 1 and 2 (the inside two lanes); and (b) phase 2 consisted of the placement of overlays on lanes 3 and 4 (the outside two lanes).

Traffic Handling

For approximately 1 mi in advance of the project location, high visibility flashing signalization was used in addition to appropriate traffic signs to notify the drivers of the closure of two lanes along with portable arrows to indicate which lanes to use. Portions of the existing 10-ft asphalt shoulders were temporarily used. Barrels partially filled with sand, often surmounted by caution flags effectively closed off three lanes at a time. Removable 4-in., white, lane delineators were used and speed limits posted. Traffic lanes were reduced from 12 to 10 ft.

In phase 1, the inside two lanes were closed to traffic and an additional lane was used for separation and protection of workers from traffic. This lane was also useful in expediting construction. In this way, approximately a 25-ft width of pavement was available for construction.

In phase 2, the outside two lanes were closed to traffic. Traffic was rerouted on part of the inside asphalt shoulder and the completed overlay pavement. There was no accident reported for the duration of the construction. Note that a similar scenario was used later for monitoring the test sections.

Sequence of Operations

Surface preparation consisted of Roto milling to a nominal depth of .250 in., which proved to be the minimum attainable given the equipment and pavement material. Dust control was a problem when it was windy. An estimated three passes were required to cover the width of pavement to overlay. After milling, the pavement surface was swept with a stiff-bristle broom to remove all chippings. Thereafter, the longitudinal joint sealing material was removed by using jack hammers. Finally, the surface was thoroughly sand-blasted to remove all contaminants.

At this stage, clean, sound concrete was exhibited. Transverse cracks that had had a bad appearance at the surface, now looked tightly closed; this was a sign that the original CRCP was structurally adequate. It was also revealed that the polymer concrete patching material had indeed penetrated deeply into the cracks.

The last phase of the pavement surface preparation consisted of air-blasting as close as possible to the grouting and paving operations. Following air-blasting, double polyethylene sheet protection was spread in the middle of the two lanes to overlay. Concrete ready-mix trucks were then allowed to back up on these sheets. In this way, the prepared pavement surface was free from their tire imprints and engine and transmission oil drippings. It should be noted that no repair work (e.g., joint or crack sealing, deep patching, and slab jacking) was necessary on the prepared CRCP surface, which appeared to be in excellent condition.

Immediately before paving, a water and cement grout was uniformly swept onto the full width of the prepared CRCP surface. The grout consisted of water, cement, and a water-reducing plasticizer. The water-cement ratio was approximately 0.62 by weight or seven gal of water per sack of cement. The plasticizer used gave the bonding grout a creamy aspect. The concrete was then batched at a central plant and hauled in ready-mix trucks to the construction site. The trucks were loaded at 6 yd^3, or less than 80 percent, of capacity. The concrete was dumped onto the grouted pavement surface and spread manually. A transverse concrete finisher guided by rails was used to consolidate and finish the concrete to grade. The inspector took frequent readings to insure that the nominal specified thicknesses were obtained. Surface texturing consisted of transverse metal tine finish (i.e., wire combing), and was accomplished by hand from a working bridge.

Following surface texturing, a white pigmented impervious curing component was spread uniformly onto the overlay surface from a second working bridge. Within 24 hr of a pour, the pavement edge and centerline longitudinal joints were saw cut. The centerline longitudinal joints were cut to a nominal 1-in. depth and sealed with a hot-poured asphaltic material.

In either phase of the construction, the last pour was allowed to cure for a minimum of 6 days before the lanes were opened to traffic.

ANALYSIS AND EVALUATION OF RESULTS

Concrete Field Tests

During overlay construction, a number of tests were conducted for concrete quality control. These included slump test, determination of concrete air content, concrete temperature, and casting of beams for a 7-day flexural strength test. The results of these tests are presented in Table 3 for both phases. Note that lanes are numbered outwardly from the median. Thus, lane 1 is the lane adjacent to the median and lane 4 is adjacent to the outside shoulder.

As can be seen, the flexural strength of concrete for the 7-day test is well above the specified 700 psi for the entire population, the mean flexural strength, $\bar{f}$, is 864 psi with a standard deviation, σ_f of 75 psi. Although no durability test (e.g., freeze - thaw) was performed, it can be inferred from the chase air value (2.4 - 5.3 percent) that this concrete property would most likely be adequate.

TABLE 3 Concrete Quality Control Data During Overlay Construction

Design Section	Avg Slump (in.)	Avg Flexural Strength (psi at 7 days)	Avg Chase Air Value (%)	Range of Concrete Temperature (°F)
Phase 1: Lanes 1 and 2 (inside lanes)				
2-in. NR	3.6	889	4.1	75-82
2-in. R	4.5	878	2.4	76-78
3-in. R	5.5	992	3.0	79-85
3-in. R	5.2	870	5.3	79-85
2-in. R	5.1	920	4.6	79-83
Phase 2: Lanes 3 and 4 (outside lanes)				
2-in. NR	3.4	730	3.8	77-82
2-in. R	4.1	798	4.2	78-83
3-in. R	3.7	840	3.1	75-82
3-in. F	5.0	838	4.9	72-78
2-in. F	4.3	898	5.1	80-84

Note: NR = nonreinforced, F = fiber reinforced, and R = reinforced.

Workability, as measured by the concrete slump, varied between 3.4 and 5.5 in. This made for a concrete that could easily be placed. The fiber sections did not present any particular difficulty in that respect. In general, the fibrous concrete was easily cast and surface-finished. The metal tine finish that was adopted was particularly appropriate in that it would rearrange the steel fibers at the surface in a direction perpendicular to traffic, thus, effectively eliminating any potential tire-steel fiber interaction problem.

Interface Shear Strength

After construction, a sample of 4-in. cores was taken through the overlay and CRCP for laboratory testing. Because effective bonding between CRCP and TBCO is critical, it was first decided to test the interface in shear. A sliding two-part shear collar similar to the one used in Iowa (7) was used with one major difference: in this study, the shear force is induced in compression instead of tension. The summary statistics for these data are given in Table 4. As can be seen, the interface shear strength varied from 79 to 377 psi with a grand mean, μ, of 201 psi and a standard deviation, σ, of 100 psi. Under the worse scenario, researchers at the Texas A&M University at Austin concluded that a shear stress of 64 psi could be expected for a bridge deck overlaid with 2-in. bonded concrete subjected to impact loading (8). The calculations using elastic-layered theory show that a maximum of 24 psi can be expected under a standard 18 kips single-axle load on dual tires at the interface of a 2-in. TBCO and a Highway CRCP on weak foundation. This leads to the conclusion that once the bonding is achieved, the bonding capacity is usually not a problem.

Finally, it should be noted that the wide range of shear strength data suggests capping the 4-in. core samples with a thin, high-strength gypsum plaster to smooth out surface irregularities before testing; this has been shown to reduce variability resulting from testing in the case of indirect tensile strength test, and resulting in a lower coefficient of variation overall (9).

Profile Data

Road profile measurements were conducted with the old GMR profilometer in all four lanes. The analog data thus obtained was subsequently digitized at the Center for Transportation Research and finally processed through the computer program VERTAC, version 4. The VERTical ACceleration program computes road profile statistics and estimates the serviceability index (SI), which is a user-oriented performance measure based on combined information obtained under both trailing wheels of the profilometer.

Table 5 affords a comparison of the mean SI obtained for two consecutive runs of the profilometer before and after overlay construction. In general, a decrease of SI has occurred after construction, ranging from 6 to 44 percent. Only two units show an increase. This, it appears, can be attributed to lack of stringent grade control during construction, shorter "as-constructed" transitional sections, and relatively small sections that may have induced sampling error. Also note that the adopted surface

TABLE 4 Summary Statistics of Shear Strength Data—Loop 610-Houston

Interface Bonding Condition	Concrete Overlay Type Plain (2-in.) Inside Lane	Plain (2-in.) Outside Lane	Plain (3-in.) Inside Lane	Plain (3-in.) Outside Lane	Reinforced (2-in.) Inside Lane	Reinforced (2-in.) Outside Lane	Reinforced (3-in.) Inside Lane	Reinforced (3-in.) Outside Lane	Fiber-Reinforced (2-in.) Inside Lane	Fiber-Reinforced (2-in.) Outside Lane	Fiber-Reinforced (3-in.) Inside Lane	Fiber-Reinforced (3-in.) Outside Lane
Grout and Daraweld-C	238	m=377 s=42			m=243 s=118	165	79	m=106 s=15	m=103 s=11	m=207 s=57	130	
No grout		m=219 s=31										

Note: Grand Mean, μ (m) = 201 psi, Standard deviation, σ, (s) = 100 psi, and Total number of cores, n = 19.

TABLE 5 Mean SI Change Before and After Construction

Lane No.	Design Section	SI Before	SI After	SI Decrease (%)
1	2-in. NR	2.37	3.49	−47
	2-in. R	3.67	3.35	9
	3-in. R	2.68	2.78	−4
	3-in. F	3.57	2.44	32
	2-in. F	4.22	2.36	44
2	2-in. NR	3.70	3.66	1
	2-in. R	3.58	2.96	17
	3-in. R	3.72	3.23	13
	3-in. F	3.77	3.33	12
	2-in. F	4.42	3.03	31
3	2-in. NR	4.11	3.07	25
	2-in. R	3.93	3.23	18
	3-in. R	3.90	3.45	12
	3-in. F	4.08	2.62	36
	2-in. F	4.44	3.25	27
4	2-in. NR	3.30	3.19	3
	2-in. R	3.62	3.40	6
	3-in. R	3.94	3.11	21
	3-in. F	3.95	2.70	32
	2-in. F	3.93	3.24	18

Note: Minus sign indicates an SI increase; lane numbers increase from median to outside shoulder; NR = nonreinforced, R = reinforced, and F = fiber reinforced.

texturing technique may have had an impact; for the original CRCP, surface texturing was achieved by burlap drag, whereas for the TBCO, it was achieved by metal tine (i.e., wire combing). Note however, that the SI values in all units are still high (greater than 3.0 in most cases), which indicates an overall good riding pavement.

Dynaflect Deflection Data

The Dynaflect test points were located with respect to an expansion joint at the approach slab of the Calais Street overpass bridge (i.e., at the end of the design sections). The test points were located approximately on the centerline of each lane. Nine to twelve points were selected both at cracks and midspans within each section (Table 6). For each lane, the test points were located using a rolling tape. The objective was to test the same points before and after construction. Because the interior loading position was selected for this experiment, no temperature correction was required.

As can be seen from Table 6, the number of test points for the total population was 410 and the number of test points by lane was as follows:

Lane Number	Number of Test Points
1	100
2	104
3	104
4	102

The number of test points by section was as follows:

Section	Number of Test Points
2-in. nonreinforced	74
2-in. reinforced	92
3-in. reinforced	80
3-in. fiber-reinforced	88
2-in. fiber-reinforced	76

The number of test points at time of cracking was 205 at crack (c) and midspan (m).

To analyze the data thus obtained, two methods were used: (a) hand calculations of mean deflections before and after overlay construction, and of the percent reduction achieved; and (b) a multivariate analysis of variance using a statistical computer package, SPSS, which provided a further check on the hand calculations.

The weighted means deflections at cracks and at midspans were calculated for the before and after

TABLE 6 Factorial Design for Dynaflect Deflections Data Interpretation: Number of Test Points

Design Section Cracking Lane No.	2" NR C	2" NR M	2" R C	2" R M	3"R C	3"R M	3"F C	3"F M	2" F C	2" F M
1	9	9	11	11	9	9	11	11	10	10
2	10	10	11	11	10	10	11	11	10	10
3	9	9	12	12	11	11	11	11	9	9
4	9	9	12	12	10	10	11	11	9	9

construction conditions, respectively. From this set of calculations, the data were further aggregated by section and by lane. Finally, the percent reduction in deflections was calculated for all five sensors of the Dynaflect. This information is given in Table 7 for the five design sections and in Table 8 for the four lanes.

From Table 8, the effectiveness to reduce surface deflections of the various TBCO designs used in this experiment can be ascertained. This, in turn, could be related to fatigue life of the pavement structure. As is apparent from examining Table 7, the greatest reduction in deflection is achieved in the 3-in., steel-reinforced section at cracks for all five sensors of the Dynaflect. Also note that the maximum deflection as recorded by sensor 1 ranges from 10 to 24 percent, indicating that, overall, the various TBCO designs resulted in significant increases in pavement remaining life.

TABLE 7 Percent Reduction in Mean Deflections per Design Section

Design Section	Dynaflect Sensor		Cracking Condition	
			Cracks	Midspan
2-in. nonreinforced	$\%\bar{X}_1$	=	13	10
	$\%\bar{X}_2$	=	9	8
	$\%\bar{X}_3$	=	6	4
	$\%\bar{X}_4$	=	4	3
	$\%\bar{X}_5$	=	1	−3
2-in. reinforced	$\%\bar{X}_1$	=	20	17
	$\%\bar{X}_2$	=	18	17
	$\%\bar{X}_3$	=	18	13
	$\%\bar{X}_4$	=	10	8
	$\%\bar{X}_5$	=	9	8
3-in. reinforced	$\%\bar{X}_1$	=	24	21
	$\%\bar{X}_2$	=	22	19
	$\%\bar{X}_3$	=	17	15
	$\%\bar{X}_4$	=	14	11
	$\%\bar{X}_5$	=	10	8
3-in. fiber reinforced	$\%\bar{X}_1$	=	17	15
	$\%\bar{X}_2$	=	15	13
	$\%\bar{X}_3$	=	10	10
	$\%\bar{X}_4$	=	8	7
	$\%\bar{X}_5$	=	5	3
2-in. fiber reinforced	$\%\bar{X}_1$	=	12	11
	$\%\bar{X}_2$	=	9	9
	$\%\bar{X}_3$	=	7	7
	$\%\bar{X}_4$	=	6	5
	$\%\bar{X}_5$	=	3	−0.1

TABLE 8 Percent Reduction in Mean Deflections per Lane

Lane No.	Dynaflect Sensor		Cracking Condition	
			Cracks	Midspan
1	$\%\bar{X}_1$	=	14	5
	$\%\bar{X}_2$	=	10	4
	$\%\bar{X}_3$	=	5	1
	$\%\bar{X}_4$	=	1	−4
	$\%\bar{X}_5$	=	−0.2	−7
2	$\%\bar{X}_1$	=	14	15
	$\%\bar{X}_2$	=	12	13
	$\%\bar{X}_3$	=	14	11
	$\%\bar{X}_4$	=	9	9
	$\%\bar{X}_5$	=	7	5
3	$\%\bar{X}_1$	=	23	22
	$\%\bar{X}_2$	=	21	20
	$\%\bar{X}_3$	=	16	16
	$\%\bar{X}_4$	=	13	13
	$\%\bar{X}_5$	=	9	10
4	$\%\bar{X}_1$	=	19	16
	$\%\bar{X}_2$	=	16	15
	$\%\bar{X}_3$	=	13	11
	$\%\bar{X}_4$	=	11	9
	$\%\bar{X}_5$	=	7	5

Table 8 gives the main effect "lane." The percent reduction per lane ranges from -.07 to .23. It appears that lane 3 exhibits the greatest reduction in deflection, thus indicating that it may be the heaviest-trafficked lane at the project site, which would confirm an informal observation of traffic.

The multivariate analysis of variance was conducted with two main objectives: first, to check the hand calculations and second, to make inference on the effectiveness of the design sections from a statistical point of view. The first objective was fulfilled by running subprogram ANOVA of the SPSS library. By requesting three-way interaction terms in the model, tables of means were generated and checked against hand calculations. Also, it was found at this stage that only the two-way interaction "lane by section" was significant at the 5-percent confidence level.

Finally, subprogram MANOVA of the SPSS library was run with the difference from "before" deflections minus "after" deflections and a few contrasts were studied. Basically, MANOVA uses the general linear hypothesis model to fit a plane to all five Dynaflect sensor deflections simultaneously. Four test statistics were used to make multivariate tests of significance for each effect in the model as follows:

1. Pillai's criterion,
2. Hottelling's trace,
3. Wilk's lambda, and
4. Roy's largest root criterion.

The effect section was partitioned into single degrees of freedom and the unique sum-of-square feature was used to account for all of the effects in the design model when any particular effect was being investigated. Again, it was found that the 3-in. reinforced TBCO was the most effective design for a surface deflection criterion.

6-MONTH PERFORMANCE REPORT

Performance as measured by the condition survey variables is presented herein. The method used for the visual condition survey was the small section method. The survey team walked onto the pavement in the lane to be surveyed throughout the project length (1,000 ft). In doing so, cracks were mapped, spalls counted, and their severity noted. The condition survey was conducted within all four lanes (eastbound) before and after overlay construction. The results are presented in two forms: as sorted by sections, and as sorted by lanes. The first form primarily indicates the effectiveness of the various designs (Tables 9 and 10). Table 9 gives the lineal feet of cracking. As can be seen, a significant reduction in cracking has been achieved, ranging up to 99 percent after 6 months' worth of traffic. Percent reduction is calculated as

"before"   "after"   before
construction - construction ÷ construction
deflection   deflection   deflection

and is expressed as a percentage (i.e., a departure from initial conditions). Note that the 3-in. fiber has performed best for longitudinal cracking, and the 2-in. fiber for transverse cracking. Table 10 gives the amount of spalling before and after overlay construction. As can be seen, no spalls had been

TABLE 9 Cracking in the Various Design Sections

	Longitudinal Cracking (ft)			Transverse Cracking (ft)		
Design Section	Before (May 1983)	After (February 1984)	Reduction (%)	Before (May 1983)	After (February 1984)	Reduction (%)
2-in. nonreinforced	323	245	24	264	81	69
2-in. reinforced	200	202	−1	305	116	62
3-in. reinforced	291	247	15	289	223	23
3-in. fiber reinforced	393	4	99	288	28	90
2-in. fiber reinforced	348	60	83	119	11	91

TABLE 10 Spalling in the Various Design Sections (actual count)

	Minor Spalling		Severe Spalling	
Design Section	Before (May 1983)	After (February 1984)	Before (May 1983)	After (February 1984)
2-in. nonreinforced	17	0	109	0
2-in. reinforced	18	0	82	0
3-in. reinforced	9	0	103	0
3-in. fiber reinforced	15	0	87	0
3-in. fiber reinforced	4	0	17	0

noticed thus far, indicating an overall good performance of the project.

As sorted by lane in the second form of presentation, the data primarily indicate the effect of traffic (Tables 11 and 12). Note that in Table 11, the percent reduction in cracking is more homogeneous than in the first form, especially for transverse cracking where a narrow range (i.e., 58-66 percent) is observed. The data indicate that the TBCO project was effective in that it achieved a high percent reduction in cracking (about 60 percent) and also that traffic was fairly uniformly distributed across the four lanes.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been drawn from this study:

1. The constructibility of the various TBCO designs has been amply demonstrated; with current paving materials and equipment, it is possible to build TBCO of rigid pavements as a viable rehabilitation alternative.
2. In TBCO construction, water and cement grout is an adequate bonding agent.
3. Once bonding has been achieved, bonding ca-

TABLE 11 Cracking in the Various Lanes

	Longitudinal Cracking (ft)			Transverse Cracking (ft)		
Lane No.	Before (May 1983)	After (February 1984)	Reduction (%)	Before (May 1983)	After (February 1984)	Reduction (%)
1 (innermost)	149	102	32	283	118	58
2	402	363	10	319	108	66
3	602	146	76	344	121	65
4 (outermost)	402	147	63	319	112	65

TABLE 12 Spalling in the Various Lanes (actual count)

	Minor Spalling		Severe Spalling	
Lane No.	Before (May 1983)	After (February 1984)	Before (May 1983)	After (February 1984)
1	11	0	139	0
2	12	0	131	0
3	19	0	51	0
4	21	0	77	0

pacity, as determined by the interface shear strength test, is usually not a problem.

4. In this experiment, significant reduction occurred in surface deflections as measured by the Dynaflect device. Maximum deflection measured at sensor Number 1 decreases from 10 to 24 percent, indicating a substantial increase in fatigue life.
5. The 3-in. steel-reinforced design was most effective in reducing Dynaflect surface deflections.
6. The fiber sections were most effective in reducing cracking.
7. Plastic shrinkage seems to be the leading cause of cracking after 6 months; reflection cracking is not yet a problem.

The following recommendations have been drawn from this study:

1. TBCO projects should be monitored for a minimum of 3 years or until performance variables stabilize.
2. To improve the quality of ride as measured by the GMR profilometer, stringent grade control requirements should be included in the specifications and equipment capable of delivering the desired pavement smoothness.
3. Concrete mixes for TBCO should be designed to minimize plastic shrinkage cracks; also, construction during hot and windy weather conditions should be restricted.
4. Interface bond strength testing procedure and equipment should be standardized, so that results for various TBCO projects can be compared on the same scale. Such a standard should incorporate a provision to cap the concrete cores when a rough surface exists in order to reduce variability resulting from testing.

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