Use of Shear Connectors to Improve Bond in Concrete Overlays

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Abstract:

A full-scale experimental bonded concrete overlay (BCO) was constructed under relatively severe environmental conditions existing near El Paso, Texas. The condition of the overlay was monitored in terms of drying shrinkage cracking, interface strength development, and propagation of delaminated interfaces. In the BCO, good bond (1,360 kPa or higher in tension) was developed in the slab interior region but interface delaminations and low bond strengths were found near cracks, slab corners and edges. In two of eight test sections, two different types of shear connectors were used to improve bond and shear transfer between old and new concretes. Test sections with shear connectors performed significantly better than comparable sections without connectors in terms of overlay drying shrinkage cracking and interface bond strength development. The study results were used to make recommendations regarding the use of special large powder-driven shear connectors in a proposed BCO test section for I-10 in downtown El Paso.

Introduction

An experimental BCO was constructed to examine the feasibility of rehabilitating a 30-year-old continuously reinforced concrete pavement (CRCP) using bonded concrete overlays (BCOs) on I-10 in downtown El Paso, Texas. The BCO was constructed under relatively severe local climate conditions, which consist of low humidity, high wind, and large temperature fluctuations, in the summer of 1995. Interface delaminations may occur under such adverse environmental conditions. Interface strength, drying shrinkage cracks in the overlay, and interface delaminations were closely monitored for a six-month period immediately following the overlay placement. Previous studies (Neal, 1983, Lundy et al., 1991) suggest that interface shear stress concentration due to shrinkage-related contraction or temperature change-induced contraction or expansion of one layer with respect to the other layer is the likely cause of the overlay delamination near the slab edge or cracks. Two different types of shear connectors were installed along the slab edges in two of eight test sections in an attempt to improve shear transfer and bond between old and new concrete layers.

The research objectives were as follows:

1) Determine the extent of overlay delamination, if any, in a BCO constructed under the relatively severe climate conditions existing in El Paso, Texas;

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2) Compare the performance of test sections constructed with and without shear connectors;
3) Assess the advantages of using shear connectors for the expedited BCO construction using high early-strength concrete.

Research Significance

The current research provides data on the development of overlay drying shrinkage cracks and the interface bond strength in a full-scale experimental bonded concrete overlay constructed near I-10 in El Paso, Texas. Crack surveys were conducted and the interface strengths were determined using pullout tests on cores for a six-month period after the overlay construction. The pullout test results on cores revealed that good bond was developed in the slab interior region but interface delaminations and low bond strengths were found near drying shrinkage cracks and slab corners and edges. Test results also revealed that the shear connectors can be used to control the development of the overlay drying shrinkage cracks at early ages and to ensure the proper development of interface bond strength.

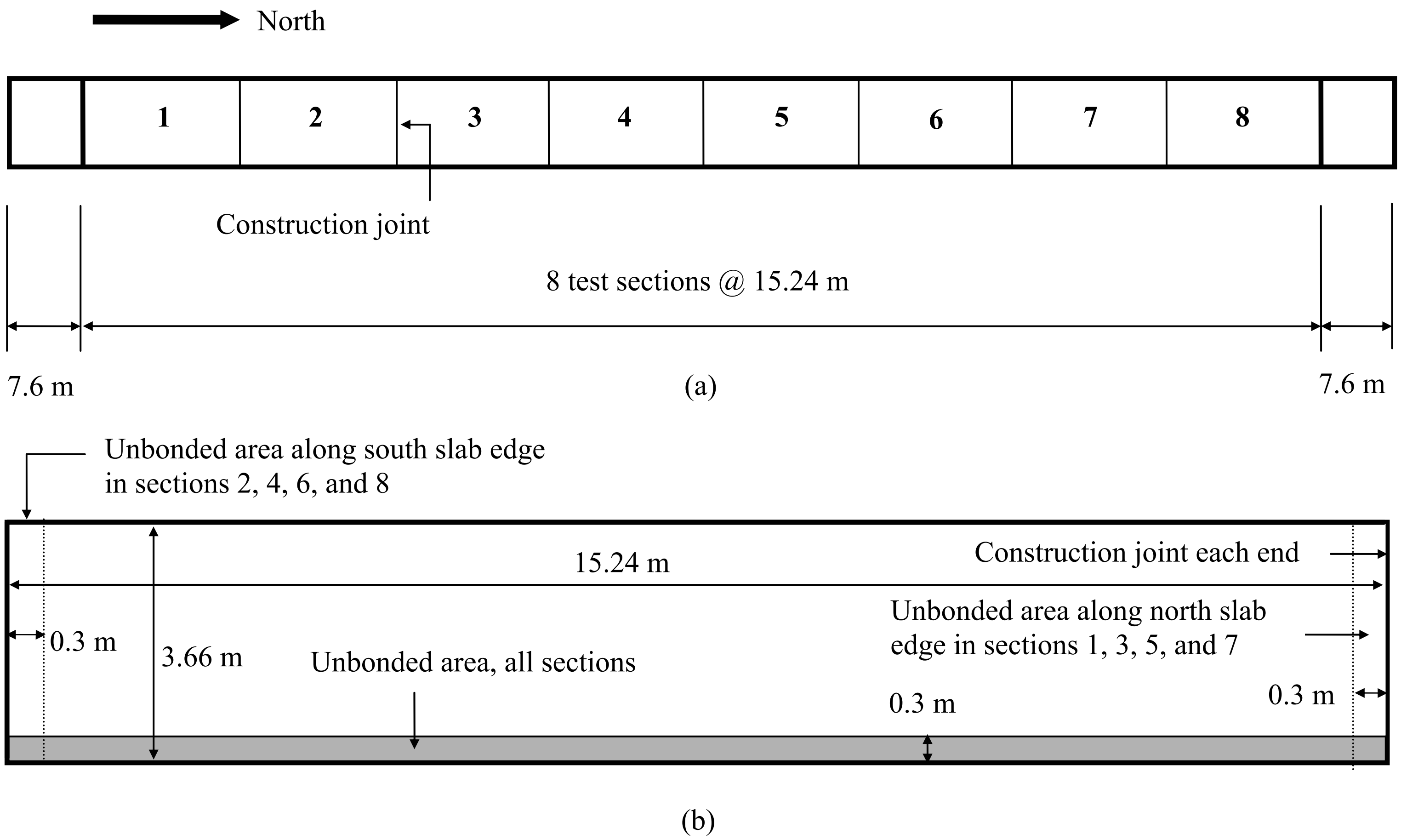
Experimental Program

Construction of bonded concrete overlay

Base Slab --- A new CRCP base slab section was cast for this research project, and was one month old when the overlay test sections were placed. The base slab was 137 m long with a thickness of 200 mm and a width of 3.66 m. The longitudinal reinforcing steel (16-mm diameter, U.S. # 5 bars) was placed at 190 mm on center (o.c.) at the slab mid-depth while the transverse steel (13-mm diameter, U.S. # 4 bars) was placed at 760 mm o.c. The original mixture proportions for I-10 were duplicated for the base slab. The 28-day compressive strength was 30 MPa. The entire base slab except for a 7.6-m length at the north and the south ends was overlaid as shown in Fig. 1. Eight test sections were constructed end to end. The length and width of each test section were 15.24 m and 3.66 m.

Interface Preparation --- Shotblasting and hydrocleaning were used for the interface preparation. The interface of seven test sections (all test sections except section 7) was roughened by shotblasting while section 7 was prepared by hydrocleaning, which was investigated as a potential alternative to the more conventional shotblasting. The average texture of the roughened interface was measured by the sand patch method (ASTM E 965, 1990). The average texture of the shotblasted interfaces ranged between 1 mm and 1.5 mm. A slightly rougher interface was created by hydrocleaning. Concrete debonding agent was applied on the prepared interface along the east longitudinal edge of the base slab over a 300-mm width to create an unbonded interface as shown in Fig. 1. The debonding agent was also applied either along the south or the north edge of each test section for the same width. The reason for creating an unbonded interface along the slab edge was to determine if interface delamination would extend with time.

Shear Connectors --- Two different types of shear connectors were used across the interface of old and new concretes.



(a)

(b)

Fig. 1---Full-scale experimental bonded concrete overlay: (a) Layout of test sections; (b) A typical test section

1) Powder-driven shear connector: The shear connectors were about 120 mm long and 10 mm in diameter and were installed using a special gun with an explosive charge to force the connector into a predrilled hole. About half the length protruded above the interface after installation. The pullout capacity of a connector is approximately 38 kN when installed in normal strength concrete (compressive strength, f'c = 32 MPa) while the ultimate shear capacity of a connector is about 50 kN (Choi et al., 1999).

2) Epoxy-bonded dowel bar: The pullout capacity of epoxy-bonded dowel bars, 200 mm long and 12 mm in diameter, is approximately 30 percent higher than that of a powder-driven shear connector. Dowel bars protruded 80 mm above the interface after installation.

Both shear connectors were installed along the east and the west longitudinal slab edges in sections 4 and 5 before the overlay placement. Each test section was divided into four subsections of equal length (3.81 m). Powder-driven shear connectors were installed in three subsections using three different installation spacings: 380 mm, 510 mm, and 760 mm. Epoxy-bonded dowel bars were installed using 510-mm spacings in one subsection in sections 4 and 5, respectively. All connectors were installed 150 mm from the slab edge. A total of 94 shear connectors was installed in sections 4 and 5 by a two-man crew. The average installation time was 2.2 minutes for a special powder-driven connector and 4.2 minutes for a epoxy-bonded connector. More drilling (deeper holes) and extra time for application of the epoxy accounted for the longer installation time for the conventional epoxy-bonded dowel bars. The connectors are shown in figure 2.

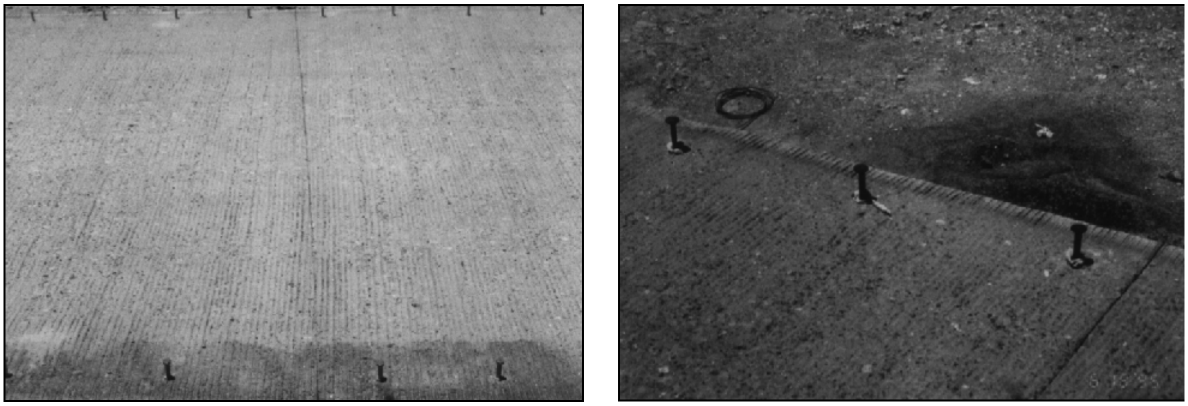


Fig. 2---Installed shear connectors – powder driven nails (left) and epoxied bolts (right)

Overlays --- The longitudinal reinforcing steel (13-mm diameter, U.S. # 4 bars) in sections 1 through 4 was placed at 150 mm o.c. while the transverse steel (U.S. # 4 bars) was placed at 460 mm o.c. directly on top of the roughened interface without using chairs. Longitudinal reinforcing steel was discontinued at the end of each test section where a construction joint was placed. No reinforcing steel was used in sections 5 through 8. Plain concrete was placed in section 1. Depth of the high early-strength overlay, which developed over 50 MPa compressive strength in three days, was 165 mm. The concrete used in section 2 was the same as that in section 1 but polypropylene fibers were added to control shrinkage cracking. Steel fibrous concrete was placed in all other sections (sections 3 through 8). Details of the mixtures are provided in Delatte et al. (1996). The concrete placement for the day-cast sections began early in the morning at the south end of section 1 and progressed north ending at section 7. Section 8 was constructed at night on the same day. Overlays were finished with tining in the transverse direction, and white pigmented curing compound was applied on the top surface of the overlay shortly after casting. Truck traffic was allowed on the BCO six days after the overlay placement. Table 1 is a summary of the test variables of the experimental BCO.

Table 1---Test variables of experimental BCO

Section no.	Interface preparation	Shear connectors	Overlay reinf.	Concrete	Casting time
1	Shotblast	--	Steel	Plain^{+}	5:30 a.m.
2	Shotblast	--	Steel	Pfrc^{++}	6:30 a.m.
3	Shotblast	--	Steel	Sfrc$^{\$}$	8:40 a.m.
4	Shotblast	Yes$^{!}$	Steel	Sfrc	9:30 a.m.
5	Shotblast	Yes$^{!}$	--	Sfrc	10:30 a.m.
6	Shotblast	--	--	Sfrc	11:10 a.m.
7	Hydroclean	--	--	Sfrc	11:40 a.m.
8	Shotblast	--	--	Sfrc	10:00 p.m.

$^{!}$ Powder-driven shear connectors and epoxy-bonded dowel bars; $^{+}$ Plain concrete; $^{++}$ Polypropylene fibrous concrete; $^{\$}$ Steel fibrous concrete using 60-mm-long steel fibers with hooked ends.

Instrumentation and field monitoring

Previous research (Whitney et al., 1992) suggests that the potential for delamination in a BCO increases if the overlay is placed on a day when the ambient temperature change shortly after overlay placement is more than 14 ^{o}C and the water evaporation rate from freshly placed concrete exceeds 1 kg/m^{2}/hr. The evaporation rate can be determined using a nomograph (PCA, 1988) which requires the input of wind velocity, air and concrete temperatures, and relative humidity. A weather station with a data logger was installed near the experimental BCO to record the weather data. A thermocouple was placed at the interface in each test section to measure the concrete temperatures.

The condition of the BCO was surveyed six times during a six-month period immediately following the overlay placement. Table 2 is a summary of test types and dates. The development of transverse cracks in the overlay due to restrained shrinkage of concrete was investigated through crack surveys. The location of each crack was recorded while the crack width was measured using a crack comparator. The interface bond strength was determined using pullout tests on cores. A 100-mm-diameter core was drilled into the BCO past the interface to an approximate depth of 190 mm. A steel cap was epoxied on the top surface of the core. The pullout device was connected to the steel cap and the pullout force was applied until the core failed in tension at the interface. An attempt was made to extract cores for shear testing, but it proved impossible to drill all the way through the overlay and base and extract a 370 mm core.

Table 2---Field surveys conducted on BCO

Index	Date	Test type	
		Crack survey	Pullout test (no. of cores)
1	June 23~25	Yes	25[!]
2	July 25	Yes	--
3	Aug. 28	Yes	--
4	Sept. 17~19	Yes	19[!]
5	Nov. 22	--	14[+]
6	Dec. 9~11	--	33[+]

[!] Pullout tests conducted in sections 1 through 6; [+] Pullout tests conducted in unreinforced sections 5 and 6 only.

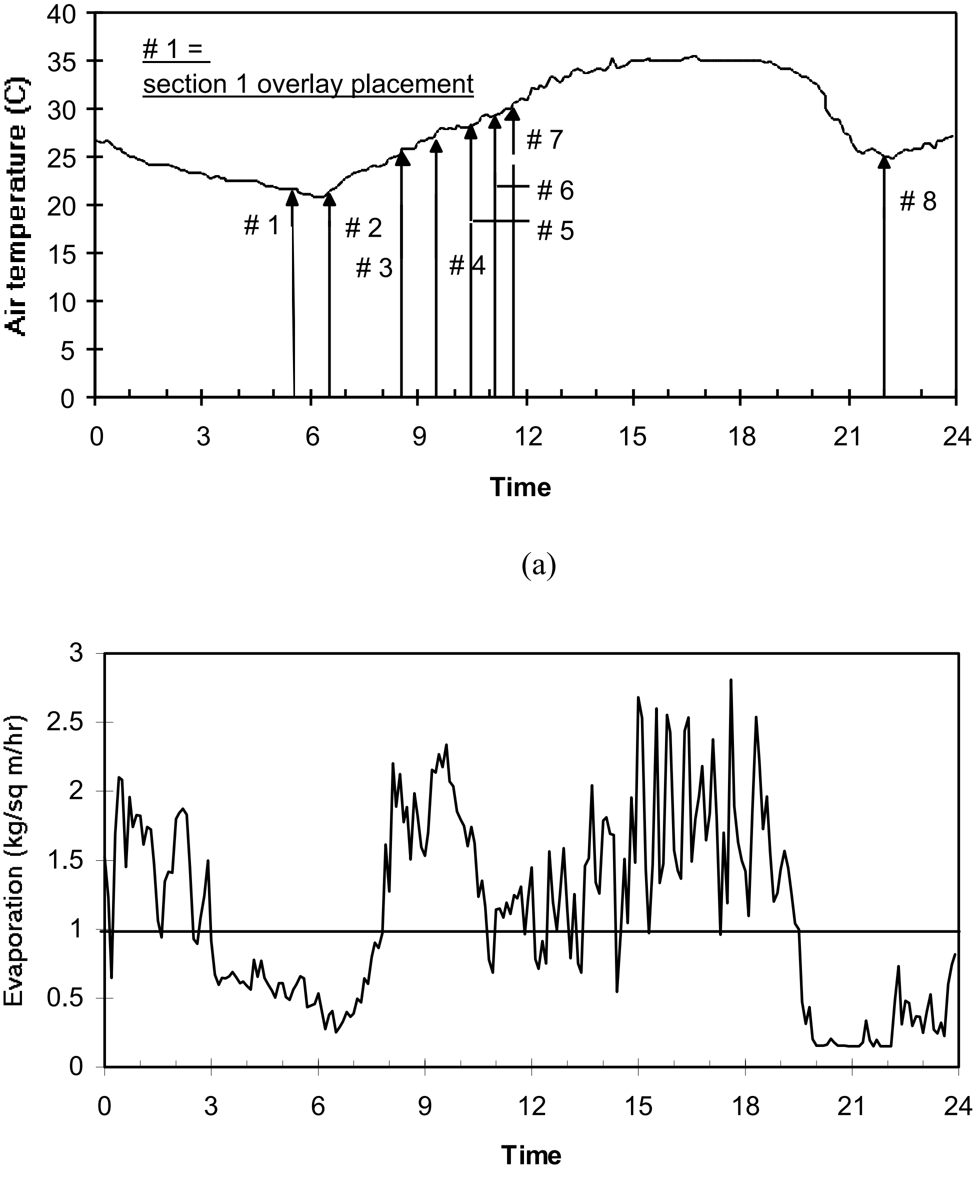
Test Results

Weather conditions

The lowest air temperature (21 °C) for the day of overlay placement, June 22, was recorded in the morning approximately one hour after overlay placement of section 1 started. The highest temperature (36 °C) was recorded in the afternoon approximately five hours after placing the last day-cast section. The relative humidity was 30 percent or higher early in the morning and then began to decrease rapidly. The relatively humidity was 15 percent or lower for the most of the afternoon. The wind velocity remained between 6 and 19 kph during most of the day. The air temperature and water evaporation rate from the overlay determined using the recorded weather data are shown in Fig. 3(a) and (b). Fig. 3(b) shows that a high evaporation potential existed for test sections cast later in the morning and in the afternoon.

Crack survey results

In the three crack surveys, data were collected at approximately one-month intervals after the overlay placement. Average crack spacing in the overlay one and three months after the overlay placement was 1.8 m and 1.2 m, respectively. The cumulative and average widths of all cracks in each test section are shown in Fig. 4(a) and (b). The cumulative crack width is the sum of the widths of all cracks within a section. Crack widths in sections 1 and 2, cast very early in the morning when the air temperature was the lowest of the day, are smaller than those in sections cast later in the morning, as shown in Fig. 4. Crack width increased in test sections cast later in the morning (sections 3 through 7) while that in the night-cast section (section 8) was the smallest.

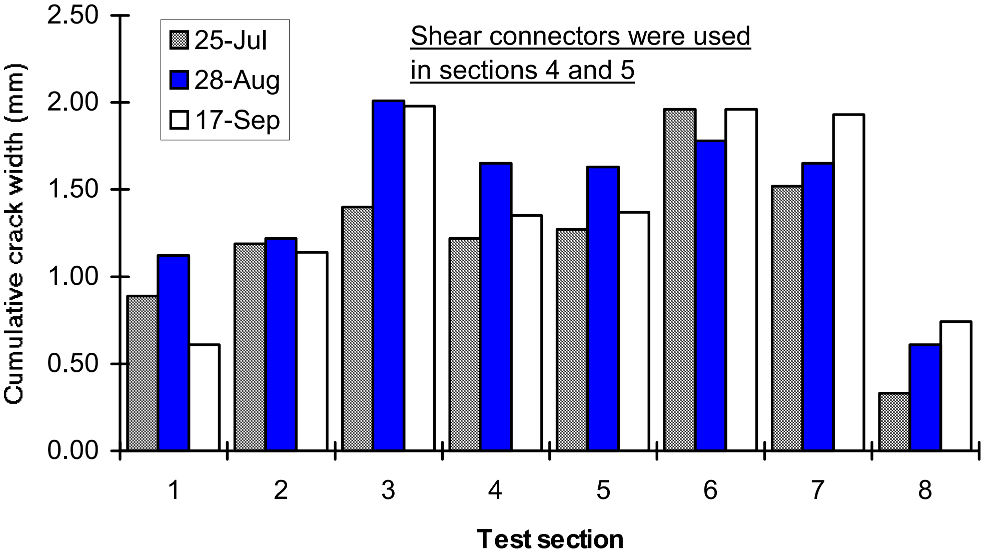


(a)

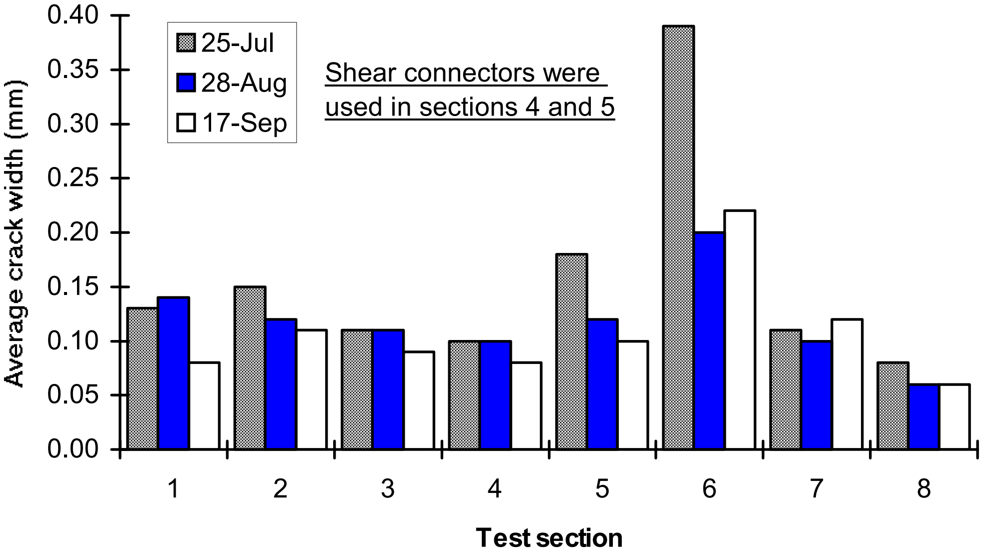
(b)

Fig. 3---Weather conditions on June 22: (a) Air temperature; (b) Evaporation rate vs. time

The crack widths in the four test sections cast later in the morning, sections 3 through 6, were compared. Sections 3 and 4 (or sections 5 and 6) had the same test variables except for the shear connectors. The cumulative widths of cracks in the two sections with shear connectors, sections 4 and 5, one month after casting are significantly smaller than comparable sections 3 and 6 without connectors. The results of crack surveys performed later also revealed similar results. The crack widths in sections 4 and 5 are significantly smaller than those in sections 3 and 6 two and three months after casting. The mean of the cumulative crack widths in sections 4 and 5 is 1.3 mm while that in sections 3 and 6 is 1.7 mm one month after casting in Table 3.



(a)



(b)

Fig. 4---Development of overlay drying shrinkage cracks: (a) Cumulative width of cracks; (b) Average width of cracks

The mean of the cumulative crack widths in sections 4 and 5 is 1.4 mm while that in sections 3 and 6 is 2 mm three months after casting. Test results indicated that the shear connectors helped to control the development of drying shrinkage cracks in the overlay probably because the shear connectors improved shear transfer and distributed stresses from the overlay to the base slab more uniformly. It is noteworthy that the cumulative and the average crack widths in section 6, where neither the overlay reinforcement nor the shear connectors were used, were much larger than those in section 5 with shear connectors.

Table 3---Results of crack surveys

Section no.	No. of cracks	Average crack spacing, m	Average crack width, mm	Cumulative crack width, mm	Remarks
1	7 - 8 – 8[!]	1.9 - 1.7 - 1.7[!]	0.13 - 0.14 - 0.08[!] (0.12)[+]	0.89 - 1.12 - 0.61[!] (0.87)[+]	
2	8 - 10 - 10	1.7 - 1.4 - 1.4	0.15 - 0.12 - 0.11 (0.13)	1.19 - 1.22 - 1.14 (1.18)	
3	13 - 19 - 22	1.1 - 0.8 - 0.7	0.11 - 0.11 - 0.09 (0.1)	1.40 - 2.01 - 1.98 (1.8)	
4	12 - 16 - 16	1.2 - 0.9 - 0.9	0.10 - 0.10 - 0.08 (0.09)	1.22 - 1.65 - 1.35 (1.41)	Shear connectors
5	7 - 14 - 14	1.9 - 1.0 - 1.0	0.18 - 0.12 - 0.10 (0.13)	1.27 - 1.63 - 1.37 (1.42)	Shear connectors
6	5 - 9 - 9	2.5 - 1.5 - 1.5	0.39 - 0.20 - 0.22 (0.27)	1.96 - 1.78 - 1.96 (1.9)	
7	14 - 16 - 16	1.0 - 0.9 - 0.9	0.11 - 0.10 - 0.12 (0.11)	1.52 - 1.65 - 1.93 (1.7)	
8	4 - 11 - 13	3.1 - 1.3 - 1.1	0.08 - 0.06 - 0.06 (0.07)	0.33 - 0.61 - 0.74 (0.56)	

[!] Crack survey results conducted on July 25, August 28, and September 17, respectively; [+] Average of three crack surveys.

Development of the drying shrinkage cracks in the overlay for the different connector spacings in sections 4 and 5 was compared. A comparison of the crack survey results between subsections in section 5 revealed that more cracks of smaller width developed with a smaller connector spacing. Similar results were also determined for section 4.

Results of pullout tests on cores

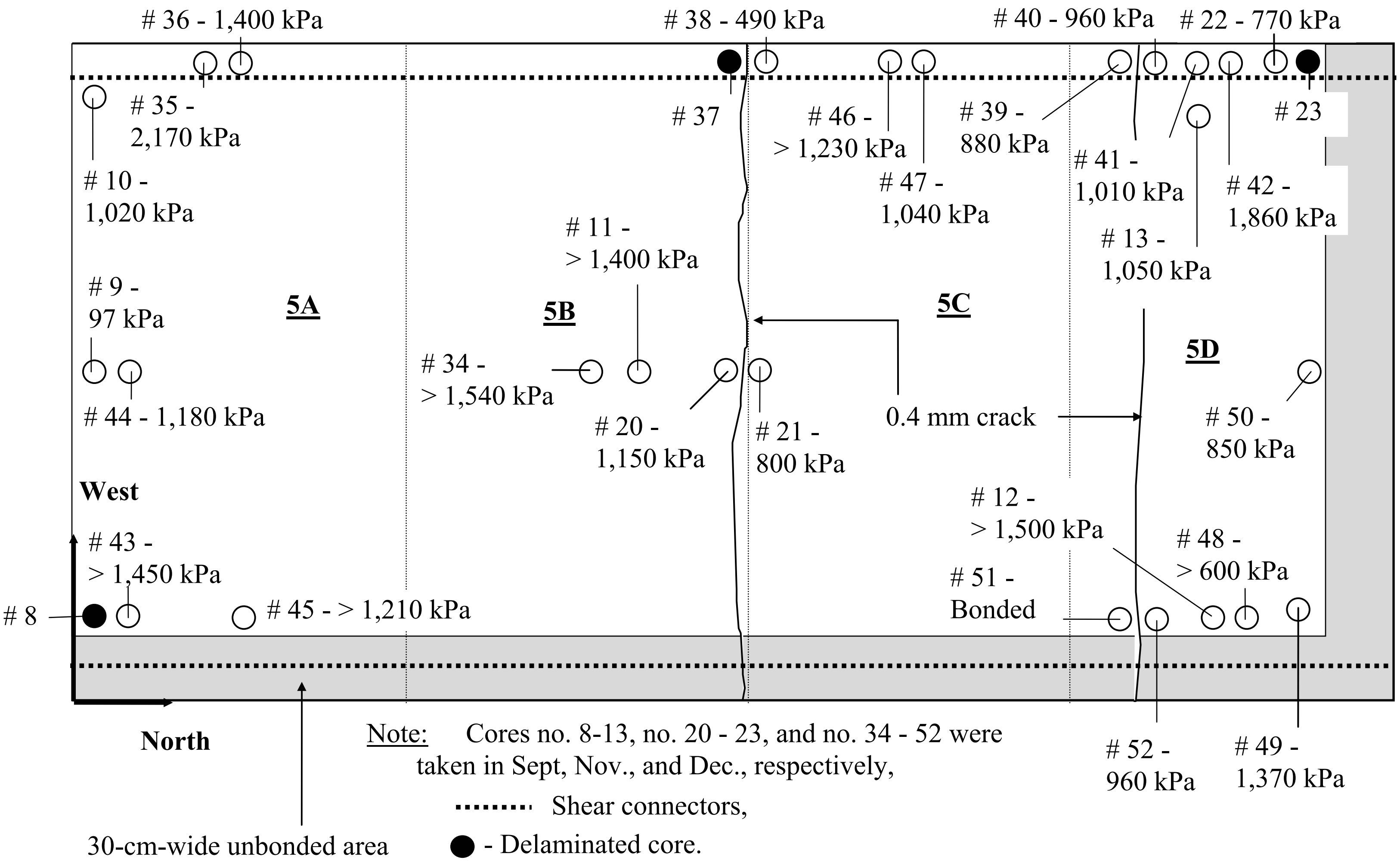
Approximately 25 pullout tests were performed on cores when the overlay was between 16 and 50 hours old to determine development of the interface tensile strength at early ages. Reliable test results were not obtained due to many technical problems encountered during the coring and the pullout tests. Problems included difficulties in coring due to the presence of the overlay reinforcing steels in sections 1 through 4 and difficulties with relatively deep coring at early ages when the interface bond strength was low. Test results achieved from several successful pullout tests indicated that the interface strength in tension was approximately 550 kPa or higher 30 hours after the overlay placement.

Nineteen additional cores were taken to determine the development of the interface tensile strength three months after the overlay placement. Coring attempted in reinforced sections 1 through 4 was again not successful because all cores failed at the interface due to the severe vibrations when the core bit cut through reinforcing steel placed on top of the interface. Figure 5 shows all pullout test results in section 5. A control pullout test (no. 11) was conducted in the interior region. The epoxy failed during the test but a pullout strength of at least 1,400 kPa was reached before epoxy failure. Three pullout tests (no. 8 through 10) were performed in subsection 5A along the south slab edge where the shear connectors were installed at 380-mm spacing. No significant pullout strength was found in core no. 8 where the pullout test was performed very close to the intentionally unbonded area, while a very low pullout strength (97 kPa) was determined in core no. 9. Delamination did not seem to have occurred along the entire edge since a high pullout strength (1,020 kPa) was found in core no. 10 at the southwest corner. Two more tests were made in subsection 5D near the slab edge where the shear connectors were installed at 760-mm spacing. A high pullout strength of 1,050 kPa was developed in core no. 13. The epoxy failed during the test of core no. 12 but an interface strength of at least 1,500 kPa was found even though the core was very close to the intentionally unbonded region.

Figure 5 also shows the test results of twenty-three cores taken in section 5 (no. 20 through 23 and 34 through 52) approximately five and six months after the overlay placement. Interface delaminations were found in two cores near the intentionally unbonded area and near a 0.4-mm-wide shrinkage crack. The delamination may have spread from the intentionally unbonded northwest corner in one core (no. 23) and the development of the interface bond appears to have been influenced by the stresses developed on the interface neighboring the crack in the other core (no. 37). The pullout test results of all other cores in section 5 with shear connectors indicated the development of relatively good interface bond.

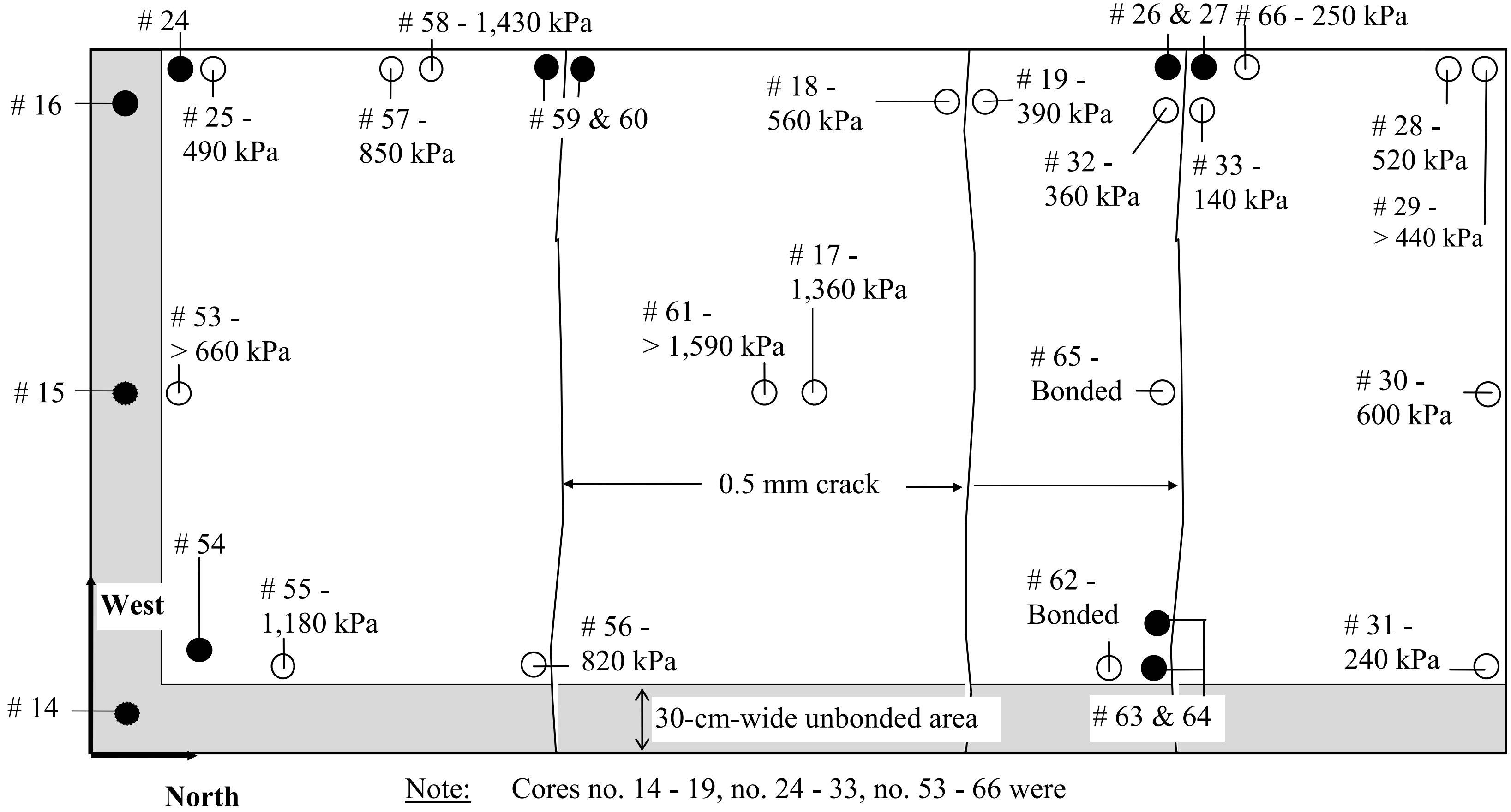
Figure 6 shows all pullout test results conducted in section 6. The pullout strength of 1,360 kPa was determined at the middle of section 6 (no. 17) three months after the overlay placement. Three pullout tests were conducted in the intentionally unbonded area along the south edge which revealed that the applied bond breaker successfully prevented bond from developing between the two concrete layers. Two more pullout tests (no. 18 and 19) were made very close to a relatively wide crack (0.5 mm). Relatively low pullout strengths of 560 kPa and 390 kPa were found in cores no. 18 and 19, respectively. The development of shrinkage in the concrete neighboring the crack seems to have influenced the strength development.

Figure 6 also shows the test results of twenty-four additional cores (no. 24 through 33 and 53 through 66) in section 6 approximately five and six months after the overlay placement. Interface delaminations were more often found in section 6 constructed without shear connectors than in section 5 with shear connectors. Delaminated interfaces were found in six cores taken near 0.5-mm-wide cracks (no. 26, 27, 59, 60, 63, and 64). The interface delaminations appear to have spread along the crack for less than a 300-mm width starting from edges. Delaminated interfaces were also found at the southeast and southwest corners (no. 24 and 54), and cores taken at two north-side corners had very low pullout strengths in Fig. 5.



Note: Cores no. 8-13, no. 20 - 23, and no. 34 - 52 were taken in Sept, Nov., and Dec., respectively,

Fig. 5---Pullout test results in Section 5



Note: Cores no. 14 - 19, no. 24 - 33, no. 53 - 66 were taken in Sept., Nov., and Dec., respectively,

● - Delaminated core.

Fig. 6---Pullout test results in Section 6

In addition to the delaminated cores, cores taken near the slab edges typically had significantly lower pullout strengths than the control cores taken in the interior region away from cracks. It must be noted that the interface strengths of cores taken in section 6 without shear connectors were often significantly lower than those in section 5 with shear connectors at similar locations.

Conclusions

The development of overlay drying shrinkage cracks and the interface bond strength in a full-scale experimental BCO was investigated. Crack surveys were conducted for all test sections. Interface strengths were mostly determined in unreinforced sections 5 and 6 using pullout tests on cores. The interface strengths of sections 7 and 8 need to be further investigated. The current test results lead to the following conclusions.

Overlay drying shrinkage crack development

1) Restrained drying shrinkage of overlays resulted in the development of cracks in the overlay in the transverse direction in the experimental BCO.
2) The overlay shrinkage crack development rate was highest during the first month following the overlay placement.
3) Overlay crack development was closely related to the time of the day the overlay was placed. Cumulative and average widths of cracks in a night-cast section were significantly smaller than those in day-cast sections. Cumulative crack widths in test sections cast early in the morning were also smaller than those in test sections cast later in the morning.
4) Shear connectors effectively controlled development of the overlay drying shrinkage cracks at early ages. Drying shrinkage cracks which developed in test sections with shear connectors were evenly distributed and the width of cracks was typically smaller than in sections without connectors. However, there were more cracks.
5) More cracks of smaller width developed with a smaller connector spacing.

Interface bond strength development

1) Interface tensile strength of 550 kPa or higher developed 30 hours after overlay placement and 1,360 kPa or higher strength developed three months after overlay placement.
2) Interface delaminations occurred in the experimental BCO. Delaminated interfaces were typically found near relatively wide (0.4 or 0.5 mm) overlay drying shrinkage cracks. The shrinkage of the overlay adjacent to the crack seems to have caused the interface delamination.
3) Delaminated interfaces were also found in cores taken very close to the intentionally unbonded area in the corner region. Interface delaminations appeared to spread from the unbonded area.
4) Interface strengths of cores taken along the edge, at corners, and close to cracks were often significantly lower than those of cores taken in the interior region away from cracks.

5) Interface strength of cores taken in a test section with shear connectors (section 5) was significantly higher than that of cores taken at similar locations in a comparable test section without connectors (section 6).

Acknowledgements

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