Portland Cement Concrete Test Strip Pavement
At The FAA National Airport Pavement Test Facility (NAPTF)

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Abstract

An 11 inch thick Portland Cement Concrete (PCC) test strip was constructed on an existing econocrete subbase, at the NAPTF, to investigate the effects of slab size, mix design, and curing procedures on shrinkage and curling of the PCC slabs. Two slab sizes: (4.5 by 4.5 meter (15 by 15 feet) and 6 by 6 meters (20 by 20 feet) were used on the test strip. The econocrete subbase had previously been constructed on a granular lower subbase over a low strength subgrade (4-5 CBR). A three-part optimized concrete mix was placed on half of the test strip, and the original two-part mix design was used on the other half. Both mixes complied with the FAA P-501 specification. Special attention was given to the curing stage. In addition to watering, the effect of thermal blankets was investigated. After the curling studies were completed the slabs were trafficked to failure.

Introduction

The National Airport Pavement Test Facility (NAPTF), located at the Federal Aviation Administration's (FAA) William J. Hughes Technical Center, was constructed to investigate, through full-scale testing, the relative effects of the new generation of heavy civil transport aircraft on typical pavement structures. This effort will lead to the development of reliable failure criteria for new design procedures for airport pavements.

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The rigid pavements in the first construction cycle at the NAPTF developed corner cracking during the early stages of traffic testing. At this point the pavements were considered to be inadequate for normal life cycle testing since failures attributed to non-structural mechanisms could affect the test data obtained for development of structural failure criteria. More NAPTF rigid pavements are scheduled for reconstruction and testing in 2003, and it is essential for the new rigid sections to perform as required, i.e., by experiencing defined structural failure before secondary failures occur. Several primary factors were believed to be responsible for the slab curling that caused the corner cracking (McQueen, 2002):

- Use of a shrinkage prone mix during the original construction;
- Intermittent wetting and drying of the slab surface during curing;
- Unfavorable temperature gradient between subbase and ambient temperatures during placement and initial cure period;
- Unfavorable aspect ratio for slab curling (i.e., slabs too large for thickness); and
- Since the slabs were constructed indoors, an extended period (1 year) elapsed with little additional moisture available to the concrete.

The PCC Test Strip

Before reconstructing the full-scale test items, the FAA required a demonstration, with instrumentation and load testing, that curling was not going to occur at least to the extent that would cause premature corner cracking. A PCC test strip consisting of 12 slabs was designed to address the following concerns:

- Comparison of PCC mix designs, slab sizes 4.5 meters and 6.0 meters (15 ft. and 20 ft.) and curing methods to minimize the risk of corner cracking;
- Evaluation of removal and replacement methods;
- Measurement of pavement response related to curling; and
- Traffic for failure model.

Laboratory Shrinkage Tests

Differential drying shrinkage was believed to be the predominant factor contributing to slab curling and corner cracking, based on literature search results, mixes with a limiting shrinkage of 0.04% were sought. Laboratory shrinkage tests conducted in accordance with ASTM C 157, a matrix of 16 concrete mixes were evaluated for coarse aggregate size, aggregate type, aggregate proportioning, and water/cement ratio, revealed:

- The maximum size of the coarse aggregate (No. 57 or No. 467) did not influence the shrinkage.
- The use of high range water reducers (HRWR) increased shrinkage. Shrinkage greater than 0.04% in mixes with HRWR, and less than 0.04% in mixes without HRWR.
- The mix used for the original concrete mix (50% coarse aggregate and 50% sand blend; 0.50 water/cement ratio; No.57 coarse aggregate) had measured shrinkage of 0.08%.

Optimized Mix Design

Shrinkage and workability were the most important variables considered for the optimized mix design, particularly due to the instrumentation and the fact that "indoor" construction made machine placement impractical. The method employed by the U.S. Air Force as discussed by Lafrenze and the State of Iowa were used to optimize mixture proportioning (after Shilstone). Both methods look at obtaining a well graded aggregate blend by optimizing the "coarseness factor" (combined percent retained above 9.5 mm sieve divided by combined percent retained above 2.36 mm sieve) and the "workability factor" (combined percent passing 2.36 mm sieve) among other factors. Meeting the coarseness and workability guidelines necessitated adding an intermediate size crushed fine aggregate meeting New Jersey Department of Transportation No. 9 (i.e., 9.5 mm maximum aggregate size).

A total of six laboratory mixes was tested using the dolomite and traprock aggregate at cement contents of 204 kg. (450 lbs.), 215 kg. (475 lbs.), and 227 kg. (500 lbs.), holding water constant to yield water/cement ratios of 0.47, 0.44, and 0.42, respectively. The mixes were tested for shrinkage, slump, air content, flexural strength, and compressive strength. The mixes were batched with and without water reducing agents to optimize the slump at 8 cm to 10 cm (3 inches to 4 inches) for hand placement at the NAPTF. Of these, a candidate mix, designated as Clayton No. 2, was selected for trial batching. This laboratory mix had a water/cement ratio of 0.44, 215 kg (475 lbs) of cement, 8 cm (3 inches) slump, and 0.05% shrinkage. Although the shrinkage slightly exceeded the set guidelines, it was consistent with results for the other candidate mixes and considered acceptable. The flexural results were near the mid-range of 6 MPa (870 psi) to 8 MPa (1,150 psi) recorded for all the mixes.

However, during trial plant batches, the selected mix achieved a maximum slump of 2.5 cm (1 inch). The minimum practical slump considered was 7 cm to 8 cm (3 inches), HRWR was added to the mix to reach 8 cm (3 inches) slump. No improvement in the mix workability was observed. Trial batches were necessary to optimize the mix design. The mix design selected for construction of the test slabs consisted of:

No. 57 Coarse Aggregate	:	658 kg. (1,450 lbs.)
No. 9 Intermediate Aggregate	:	358 kg. (790 lbs.)
Concrete Sand	:	508 kg. (1,120 lbs.)
Water	:	105 liters (231 lbs.)
Type 1 Cement	:	238 kg. (525 lbs.)
Air	:	4.9%
HRWR	:	0.3 liter per 45 kg. (10 oz per 100 lbs.)
Slump	:	7 cm (3-inches)
Water/Cement Ratio	:	0.44
Yield	:	0.77 cubic meters (27.1 cubic yards)
Workability	:	34.1%

Coarseness : 58.4%
Mortar : 53%

Test Strip Construction

The plan called for careful removal of the existing cracked concrete slabs and placement of new 28 cm (11-inch) thick PCC slabs on the existing econocrete subbase. Both the 6 x 6 meters (20 x 20 feet), the size of the original slabs, and the 4.5 x 4.5 meters (15 x 15 feet) test slabs were constructed to evaluate the effect of different slab sizes in controlling curling.

The test strip south lane (slabs S) was placed on November 27, 2001, using the new optimized mix design (3-part mix). The 2-part mix, same as in the original construction, was placed in the test strip north lane (slabs C) on November 30, 2001. The layout of the test strip is shown in Figure 1.

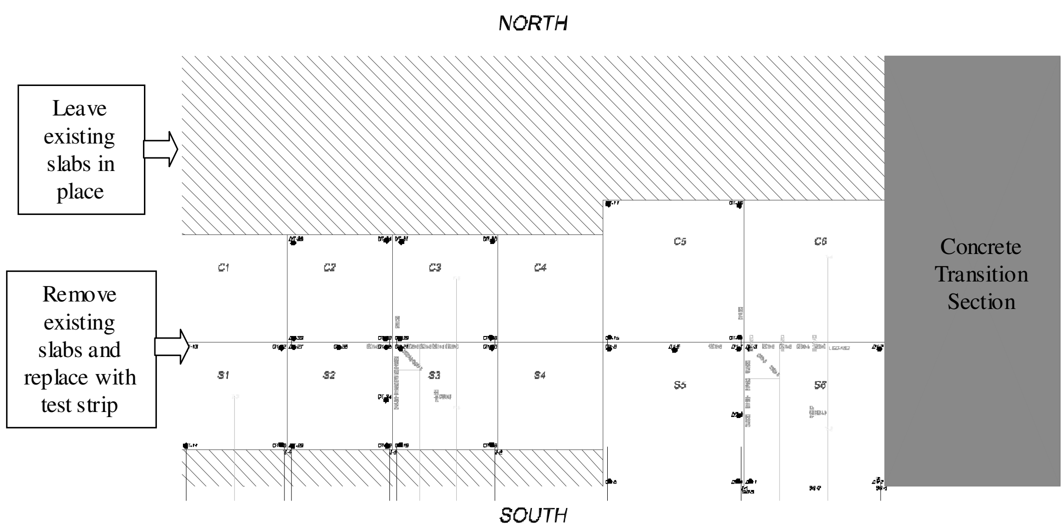


Figure 1. PCC Test Strip Layout

Test Strip Curing

Poor curing procedures were suspected for the early corner cracks in the original construction cycle due to the NAPTF being an enclosed facility. Special curing procedures were included in the test plan to prevent any possible curling due to lack of proper curing. The slabs in both lanes were covered with burlap for a 28-day wet cure period to fully hydrate the cement in a moist environment. Additionally, insulating blankets were placed on two 4.5 x 4.5 meters (15 x 15 feet) slabs (C1 and S1). The blankets were left in place to achieve and maintain no more than a 5 - 8 ºC (10 – 15 ºF) temperature differential between top and bottom of the slabs for the first three days. The blankets were placed to establish a favorable thermal gradient to induce the slabs to assume a "curl down" shape, thereby promoting full support at the slab corners. A layer of plastic was also placed over slabs C1 and S1 to reduce moisture loss. At the completion of the 28-day wet cure, a liquid sealing membrane was applied to slabs C1 and S1.

Test Strip Instrumentation

The Data Acquisition System retrieves and processes data from dynamic and static sensors placed in and around the concrete. The tests slabs were instrumented with both static and dynamic sensors, grouped as follows:

- Dynamic
  - 36 Displacement Transducers (DT)
  - 28 Concrete Strain Gages (CSG)
  - 4 Joint Gages (J)
  - 3 Slide Gages (SG)
  - 3 Instrumented Dowels (D)
- Static
  - 7 Thermister Trees (T)
  - Moisture Sensors
  - 2 Vibrating Wire Strain Gages (VSG)

During the paving operation, FAA personnel hand placed the concrete around the sensors to safeguard them from accidental damage. The paving contractor then placed the concrete, forming the slabs, on the existing econocrete base. Figure 2 shows the instrumentation in slab S3.

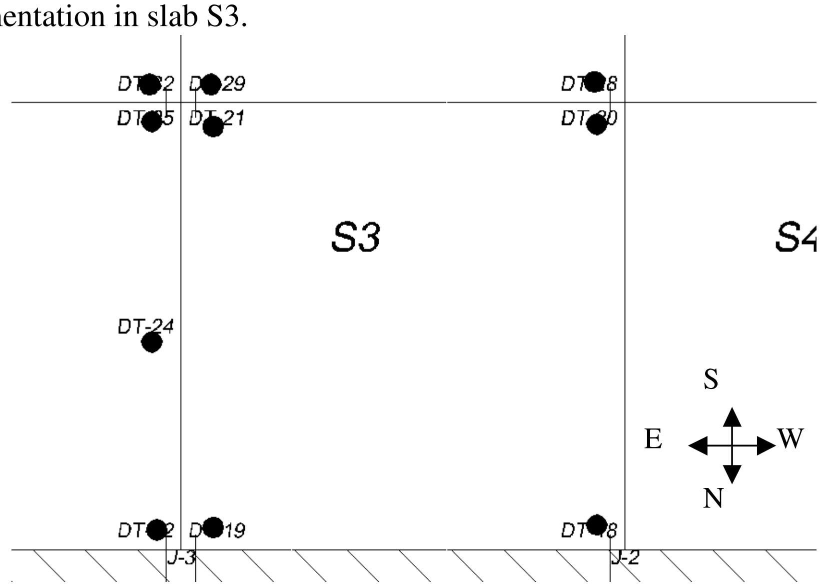


Figure 2. Instrumentation in Slab S3

Joint Formation

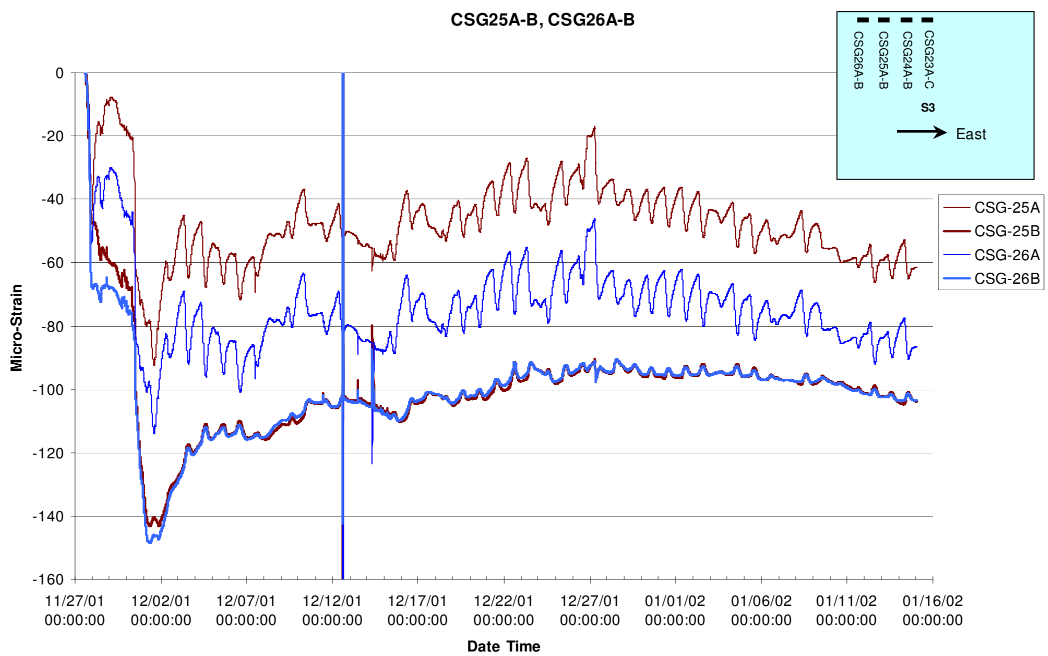
Test vehicle loading was used to initiate transverse joint formation (joint cracking). The joint formation was verified using the measured Heavy Weight

Deflectometer (HWD) responses at center and edges of the slabs and the readings from the concrete strain gages installed in the test strip.

A crack was first observed in joint J45 (joint between slabs 4 and 5) north lane the morning of December 24, 2001. Sensor records show that the entire joint J45 (See Figure 6 for diagram of joint locations) north and south (N & S) was formed naturally between 7:20am to 8:20am, on December 27, 2001, (Figure 3), before any load was applied on the test strip. This indicates that the in-plane initial stress was high. It is supposed that this crack was observed first because it was located between two different size slabs, causing stress concentration.

The doweled longitudinal joint between the S and C slabs made the joint J23 (See Figure 6 for diagram of joint locations) the next probable location for joint formation since the in-plane initial stress was the highest at that location. To crack the joints, the load was applied on the C-slabs since the vehicle could only reach the free edge of the C-slabs. A hairline crack from the slab top was first observed at joint J23(N) (See Figure 6 for diagram of joint locations) after the two-wheel gear with a 26 tonnes (58,000 lb) wheel load was slow rolled on the test strip, January 29, 2002. The load was then increased to 30 tonnes (66,000 lb) and applied for 2 minutes. There was no visible change in the crack. To investigate further, HWD testing was conducted at the east and west side of joint J23(N) (See Figure 6 for diagram of joint locations). The HWD maximum deflection under the 7,264 kg (16,000 lb) load was 0.011 cm (4.5 mils). The deflection indicated that the joint was not yet formed.

Figure 3. Joint J45 – First Joint Crack Formation



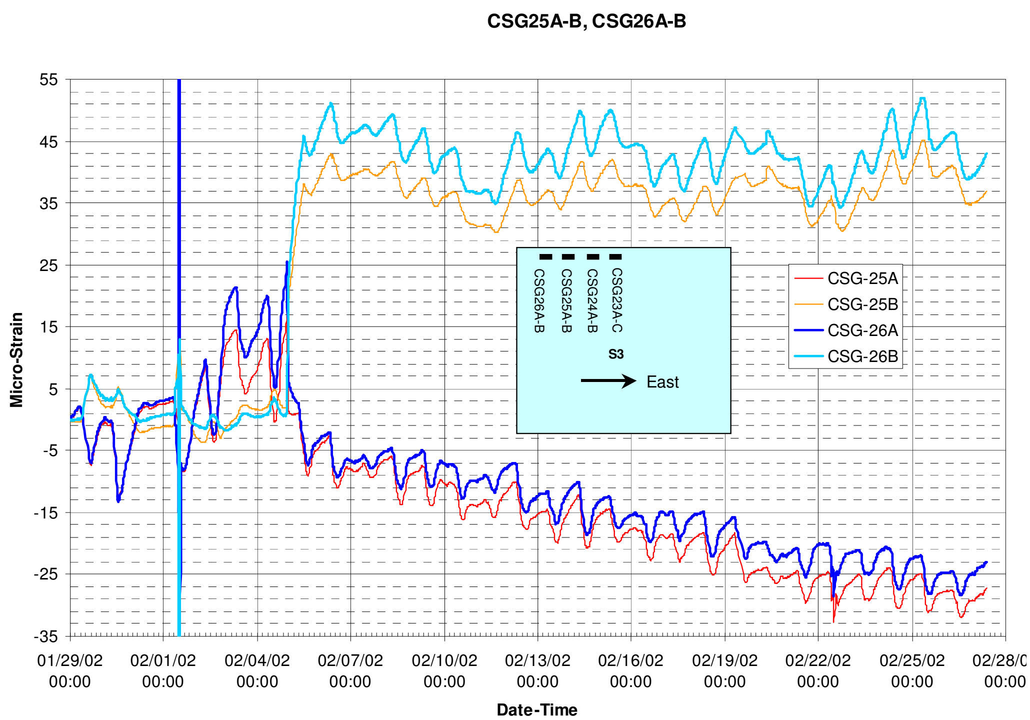


Figure 4. Concrete Strain Gage, Normal Readings
Figure 5. Concrete Strain Gage, Joint Crack Readings

In Figure 4 are presented the sensor readings for the Concrete Strain Gages (CSG) 25 and 26 (slab S3). Before joint formation, the readings on top (A) and bottom (B) showed similar behavior for both sensors. However, once the joint formed the sensor readings at the top (A) and bottom (B) "split" and "jumped," as shown in Figure 5.

After January 29, the air temperature at night dropped . New HWD testing was conducted on February 5, resulting in evidence of joint formation along J23 (C and S slabs). The hairline crack observed previously had propagated through the slab thickness. Sensor records showed that the joint J23 was completely formed as of 11pm on February 4. The joint gage J3 showed about a 12 mil jump. Many strain gages perpendicular to the joint showed unusual readings indicative of joint formation at the same time.

A hairline crack was also observed at joint J34(N), on Feb 4, but it required 40 additional wander passes of 27 tonnes (60,000 lb) per wheel load in a two-wheel gear configuration to form J34(N) (Feb 19, 2002). Joints J12(N) and J56(N) were also formed on the same date. HWD testing was conducted to verify the joint formation at those locations. Deflections under the sensor distance "zero" (D0) were approximately 0.018 cm (7 mils) at both sides of each joint.

The morning of February 26, a crack was observed in joint J56(S). Sensor records show that J56(S) was formed between 2:30 am and 3:30 am on February 24. On March 2 a crack was observed in joint J34S. Sensor records show that J34S was formed between 5 am and 6 am, and joint J12S between 2:30 am and 3:30 am on March 1. Figure 6 shows the progression of joint formation in the test strip.

HWD Testing on PCC Test Strip

On February 26, 2002, HWD testing was conducted to compare the deflections at the slab edges along both sides of the test strip (north and south lanes). A total of 28 locations were tested on slabs 1, 2, and 3. Four HWD drops with a maximum load of 7,264 kg (16,000 lbs) were conducted. From the HWD measured deflections, at sensor distance "zero" (D0) shown in Figure 7, the following was observed:

- The measured deflections on the "C" slabs (north lane) show evidence of joint formation. However, the deflections on the "S" slabs indicate that joint J12 has not yet been formed.
- The deflections on the "S" slabs (new concrete mix) are consistently larger than the deflections on the "C" slabs (original concrete mix), which can be interpreted as more "curling" occurrence in the "S" slabs.

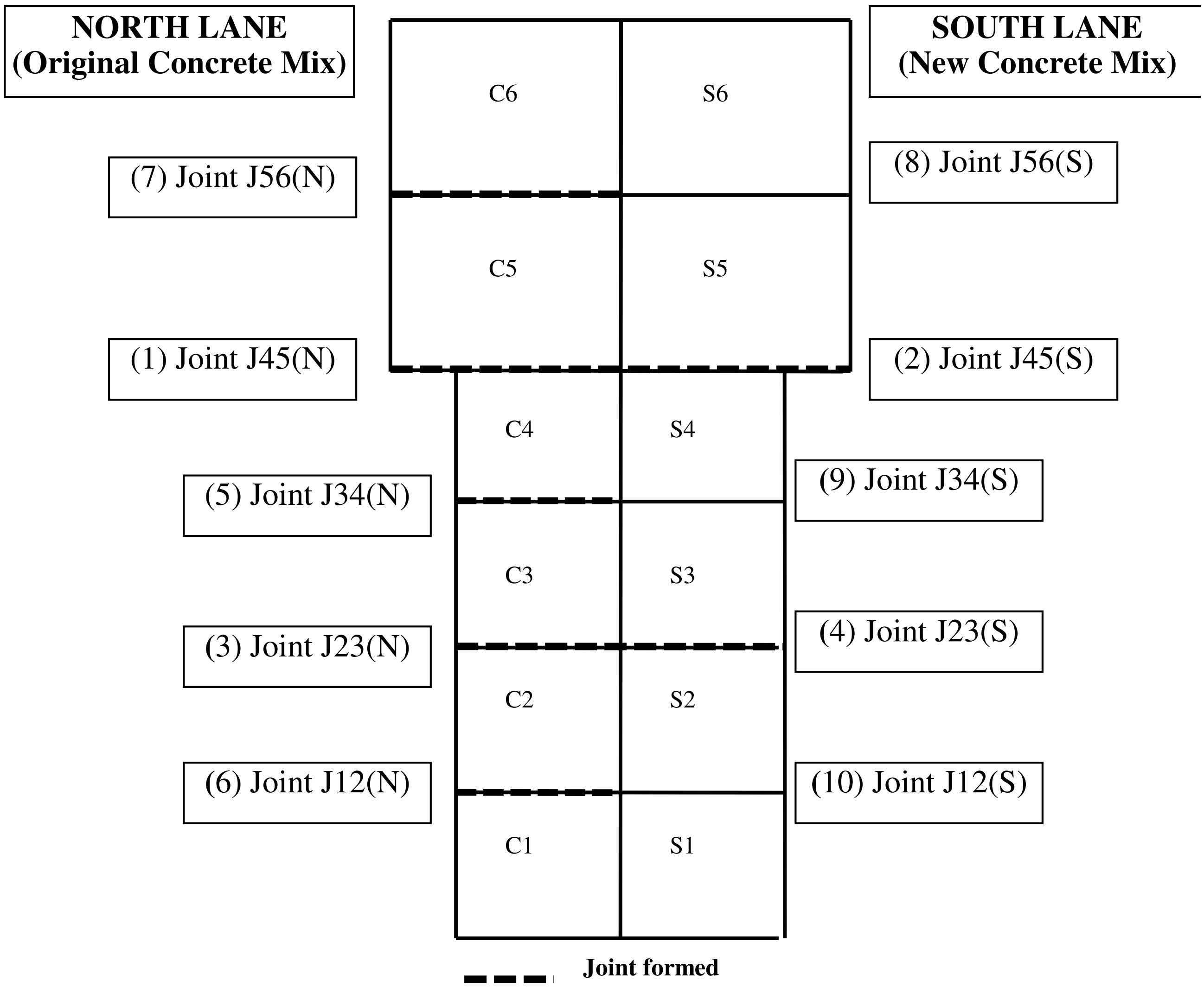


Figure 6. Progression of Joint Formation

Curling on PCC Test Strip

From March 6 to 7, 2002, using the available instrumentation, a static test was conducted on the test strip to determine the slab curling, based on load-deflection relationships, for the different slab sizes. A static load was applied at different locations in the 4.5 meter (15 feet) and 6 meter (20 feet) slabs. A two-wheel gear with 112 cm (44 inches) dual spacing was used with a maximum tire load of 23 tonnes (50,000 lbs). The load was increased from 0 to 23 tonnes (50,000 lbs), maintained for 10 seconds, and then released in a repetitive sequence (3 cycles).

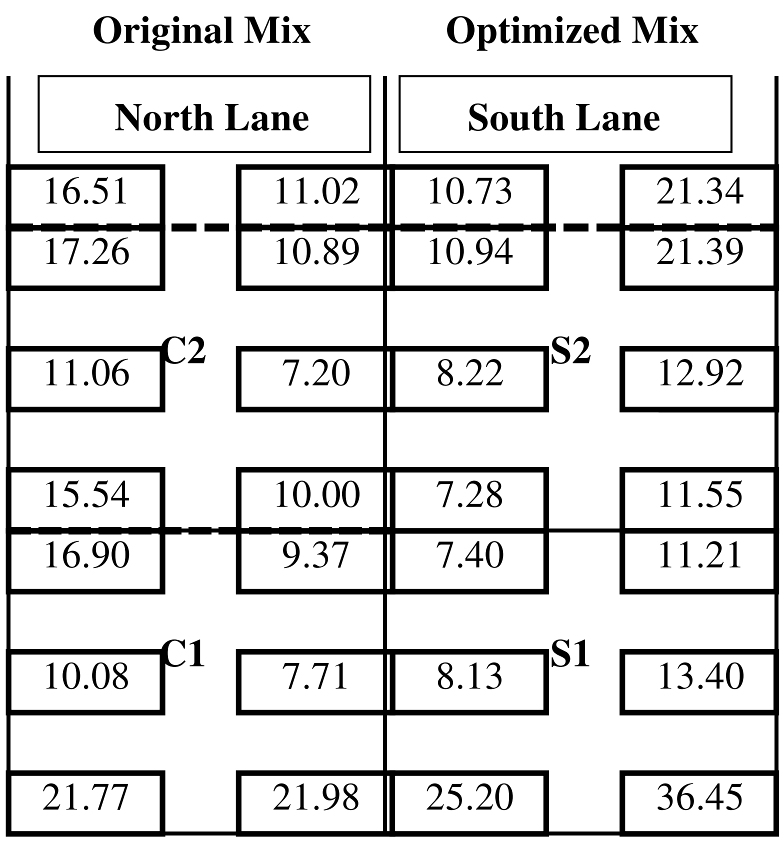


Figure 7. HWD Measured Deflection (D0) Comparison (mils)

On March 18, the static tests conducted on March 6, 7 were repeated because the deflection transducers (DT) readings showed two-digit deflections in most of the tested slabs (from 24.1 to 46 mils) except at the edge of slabs C5 and C6, where the deflection readings were in single digits (from 6.2 to 7.9 mils). Load transfer was evident between slabs C5, C6 and the original PCC pavement. The longitudinal joint between the original and new concrete mix north of slabs C5 and C6 was saw-cut up to 25.4 mm (10 inches) depth to avoid any load transfer which could have affected the 6 x 6 meter (20 x 20 feet) slabs curling behavior under study. The deflection transducer readings after the "saw cut" increased and are shown in Figure 8. The 4.5 x 4.5 meter (15x15 feet) slabs showed smaller deflections than the 6 x 6 meter (20 x 20 feet) slabs.

Additional slow rolling tests were conducted on March 15 to verify the location of critical responses under a four-wheel gear with 112 cm (44 inches) dual spacing and 148 cm (58 inches) tandem spacing. The load per wheel was 23 tonnes (50,000 lbs). The tests were conducted at a speed of 2.5 miles per hour (0.5 feet per second) and positiones to pass exactly over sensors CSG 5 and 6 located in slab S5 and CSG 18, 19, and 20 located in slabs S2, S3 and S4.

Flexural Strength on PCC Test Strip

To determine the flexural strength at the slab top and bottom edges, a maximum static load of 34 tonnes (75,000 lbs) per wheel was applied on the north edges of the "C" slabs. The tests were conducted on April 9. Additional external sensors installed on slabs C5 and C6, required the vehicle wheel outer edge to be located 15 cm (6 inches) inside the slab edge. The dual-wheel gear load with 137 cm (54 inches) dual spacing was increased from 0 to 34 tonnes (75,000 lbs) and was maintained for 10 seconds at every test location. The test was repeated on April 11. Table 1 shows the deflection readings comparison for the tests on both dates. After the initial testing (April 9) a crack developed from the bottom of slab C2. On April 11, the crack expanded and changed direction without reaching the slab top (about three fourth's of slab thickness). A second crack initiation was observed at the bottom of slab C2 on the same date.

Table 1. Deflection Comparison for Static Tests

			Static Test – Load 34 tonnes (75,000 lbs)	
Slab	Sensor	Load Location	April 9, 2002	April 11, 2002
			Deflection, cm (mils)	
C6	CT-40	NE corner	0.187 (73.70)	0.195 (76.79)
C5	CT-11	1.5 meters (5 feet) west of J56	0.032 (12.60)	0.044 (17.38)
C4	CT-38	NW corner	0.026 (10.30)	0.050 (19.53)
C3	CT-37	1.5 meters (5 feet) east of J23	0.054 (21.40)	0.060 (23.70)
	CT-37	Midpoint		0.033 (13.09)
C2	CT-34	1.5 meters (5 feet) west of J23	0.071 (28.00)	0.074 (28.97)
	CT-34	Midpoint		0.050 (19.68)
C1	CT-36	NW corner	0.118 (46.30)	0.120 (47.24)

Trafficking PCC Test Strip

Traffic tests started March 18 using a four-wheel gear with 112 cm (44 inches) dual spacing and 148 cm (58 inches) tandem spacing. The load was 25 tonnes (55,000 lbs) per wheel moving at a speed of 4.023 km/h (3.667 ft/sec). The trafficking started following a wander pattern consisting of 66 positions designed to simulate a normal traffic distribution. After 46 passes, the slab surfaces were checked for cracks. Two corner cracks were visible, one at the northeast corner of slab S6 and one at the southeast corner of slab C6. The traffic was stopped. On March 19, two cores were taken from each crack location. The cracks extended from the slab top through three fourths of the slab thickness in both cases. The trafficking continued following the wander pattern described above. Specifics of the wander pattern are available at NAPTF's web site.

The test strip trafficking was completed on April 11, 2002 after 8,087 repetitions. The 4.5 meter (15 feet) slabs exhibited fewer corner cracks for equal passes than the 6 meter (20 feet) slabs. Corner cracks developed after 46 passes under the 25 tonnes (55,000 lb) load in slabs C6 and S6. Figure 9 presents the trafficking results for the test strip (passes for the first crack). Although corner cracks were developed first in most of the test strip, the 4.5 meter (15 feet) slabs using the optimized mix (S2, S3 and S4 slabs) developed edge cracks before corner cracks after 4,000 to 5,000 passes.

Figure 10 shows the test strip crack mapping. The wander path extension is shown as a darker gray area. The number assigned to each crack corresponds to the order in which the cracks were visible.

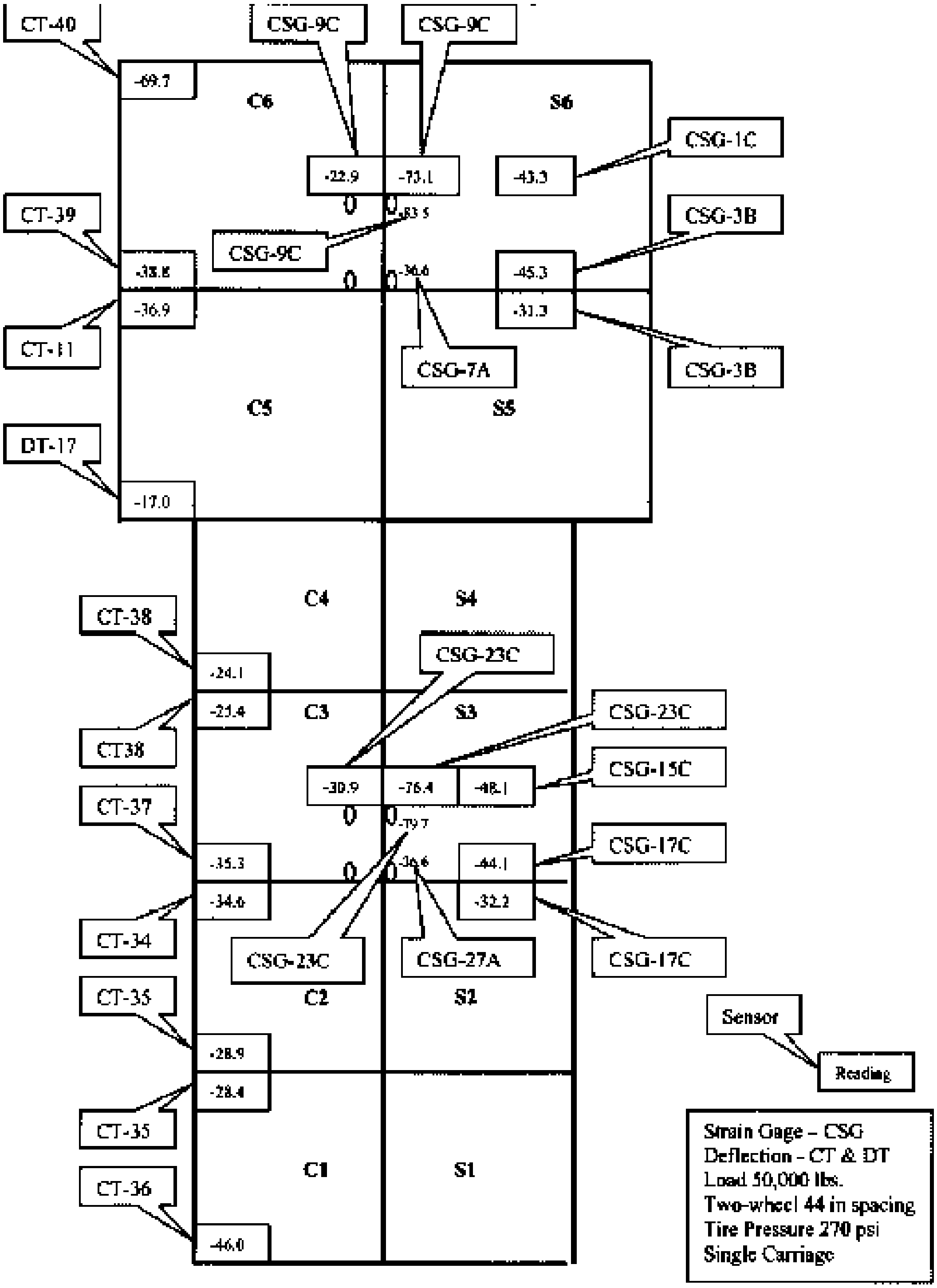


Figure 8. PCC Test Strip Instrumentation Response

Denotes # of Passes for First Crack							
	500	3000	2300	1700	800	50	← C-slabs, old mix
	800	*Edge Cracks Formed Before Corner After 4000 – 5000 Passes*			800	50	← S-slabs, optimized

Figure 9. Trafficking Results

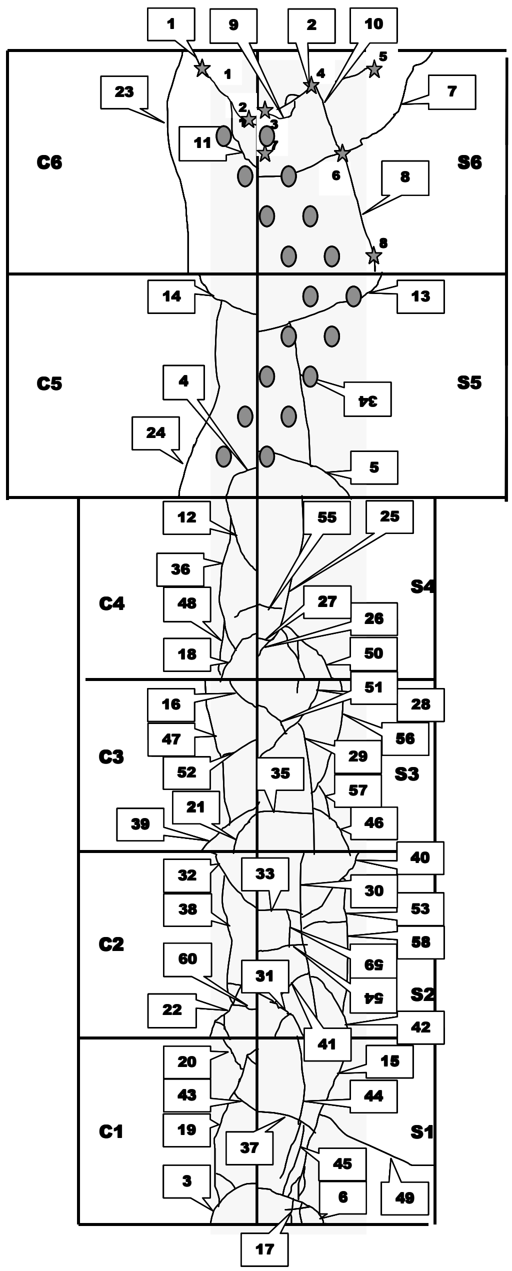


Figure 10. Map OF Cracking Sequence in PCC Test Strip

Summary

The two concrete mixtures used in the test strip- the 3-part optimized concrete mix and the original 2-part mix design-showed approximately the same levels of curling in the slabs.

Because the NAPTF is an enclosed facility, the test strip has proven the importance of the curing process (28-days wet burlap). The use of thermal blankets did not improve the curing.

The concrete strain gauge readings proved valuable for detecting the exact time of the joint formation in the test strip. The HWD testing was used to verify the findings.

It was observed that the 4.5 meter (15 feet) slabs curled less than the 6 meter (20 feet) slabs under similar test conditions.

The 6 meter (20 feet) slabs (C6, S6) were the first to exhibit corner cracks, regardless of the concrete mix used. However, the 4.5 meter (15 feet) slabs (S2, S3, and S4) placed using the new optimized mix (3-part) exhibited edge cracks before corner cracks.

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