DEVELOPMENT OF MATERIAL REQUIREMENTS FOR PORTLAND CEMENT CONCRETE PAVEMENTS AT THE FAA NATIONAL AIRPORT PAVEMENT TEST FACILITY

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ABSTRACT

The National Airport Pavement Test Facility (NAPTF) is located at the Federal Aviation Administration’s (FAA) William J. Hughes Technical Center. The facility was constructed to obtain data on pavement performance that can be used to investigate the relative effects of four- and six-wheel aircraft gear loads, and to develop reliable failure criteria that can be used for development of mechanistic design procedures for airport pavements. In order to meet these basic objectives, prototypical test pavements were constructed consistent with actual in-service pavements. A basic requirement for the test pavements was to ensure that structural failure would occur at the desired location in the controlling pavement layer. For rigid test pavements, failure was defined in terms of structural cracking initiating at the joints at the bottom of the Portland cement concrete (PCC) layer. The thickness designs for the concrete slabs were predicated on these structural cracks forming as a result of the full-scale applied loading. Therefore, cracks or failures attributed to nonstructural mechanisms needed to be avoided in order to obtain the basic data for development of structural failure criteria.

Although the pavements were constructed to exacting standards, corner cracks developed soon after full-scale gear loads were applied to the slabs. This form of cracking was not anticipated, since the NAPTF pavements were housed in a building and large temperature gradients in the slabs were not expected. In fact, temperature data acquired before and during application of the gear loads of less than ½ degree F per inch depth indicated that the corner cracking could not be due to slab warping from temperature gradients within the slabs. The crack mechanism is believed to be primarily due to differential drying shrinkage between the top and bottom of the slabs, possibly exacerbated by unfavorable temperature differences within the slabs during curing. Since the NAPTF rigid pavements are scheduled for reconstruction and testing in 2002, it is essential for the new rigid sections to perform as required, i.e., by experiencing defined structural failure before secondary failures occur.

For the new rigid pavements, shrinkage tests were performed on concrete mixes batched with different aggregate types, sizes and proportions, including the mix used for the original construction. The primary purpose of these tests was to screen out potentially shrinkage-prone aggregates and to size the coarse aggregates for the next construction cycle. This was followed by detailed mix designs on several candidates, using mix optimization techniques to minimize shrinkage and maximize workability, and plant trials to further optimize the mix design.

After selecting the candidate mix, a test strip was placed to investigate the effect of the slab size, concrete properties, and curing procedures on curling of the test slabs and corner cracking. The test strip slabs were instrumented to measure concrete strains, temperature, joint performance, and curling. Slab size, material requirements, and curing procedures for the full scale rigid test items planned for the next construction cycle will be based on the performance of, and data collected on, the test strips.

BACKGROUND

During the first construction cycle of the NAPTF, a total of forty-five, 6- by 6-meter (20- by 20-ft.) PCC slabs were placed in three test items as part of the overall test pavement. Fifteen of the slabs were 280 mm (11 inches) thick, fifteen were 250 mm (9¾ inches) thick, and the remaining fifteen were 230 mm (9 inches) thick. These slabs were constructed for low-, medium-, and high-strength subgrades, respectively (McQueen [1]). All pavements were constructed on 150-mm (6-inch) econocrete base and 150-mm (6-inch) granular subbase.

During the early stages of traffic testing, cracking occurred in the slabs. The cracks were located primarily at the slab corners and were evident over most of the test pavement. At this point, the PCC pavements were not considered to be suitable for further traffic testing. Figure 1 depicts the crack pattern recorded on the PCC slabs constructed on the medium-strength subgrade. Similar crack patterns, albeit at different crack densities, were recorded for the PCC slabs constructed on the low- and high-strength subgrades. Test vehicle loadings were positioned so that the maximum number of loads in each wander cycle were applied along the edge of the outside lanes, with a wander pattern approximately 2 meters wide.

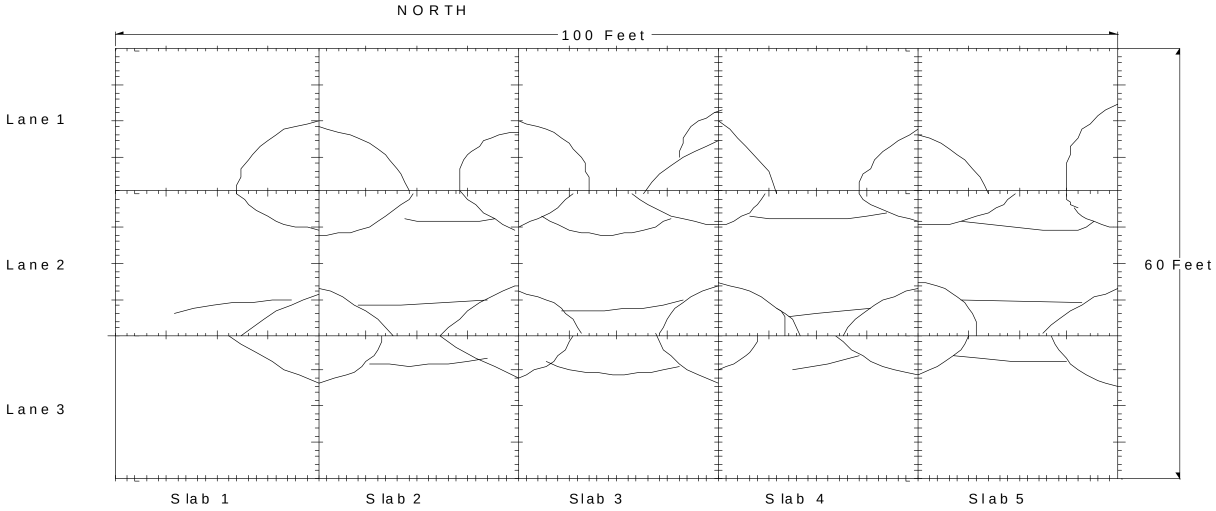

Figure 1. Concrete Cracks on Medium-Strength Subgrade Rigid Test Item

It should be noted that, although it might have been possible to minimize or eliminate the corner cracking by constructing thicker slabs, constructing smaller slabs, or using a nonstabilized base (or by any combination of the three), this was not done for the following reasons:

- Temperature-induced warping was not anticipated since the pavements were constructed indoors.
- Structural failure needed to occur in a reasonable time period; hence, the need for thinner, rather than, thicker slabs.
- Six-meter (20-ft.) square slabs and using stabilized base under concrete slabs represents typical U.S. construction practice.

To prevent a reoccurrence of the corner cracks on future rigid pavement construction, a plan consisting of the following basic elements was developed:

- Identify significant factors that contribute to differential shrinkage and dimensional instability;
- Perform laboratory tests to quantify the shrinkage potential of various aggregates and concrete mixes;
- Optimize mix designs to minimize shrinkage and maximize workability;
- Perform plant trial batches on the best candidate mix and adjust the design, as necessary;
- Construct test slabs at different dimensions and demonstrate with instrumentation and load testing that the magnitude of curling will not result in corner cracking; and

- Use the results to finalize materials, curing, slab dimensions, and construction requirements for new full-scale rigid test items, planned for the next construction cycle.

PRIMARY FACTORS AFFECTING CURLING

Several possible causes for the cracking were investigated by a team of FAA, U.S. Army Corps of Engineers, and industry experts. These included differential drying shrinkage, warping due to temperature gradients in the slab, carbonation, and unfavorable temperature differences between the top of the econocrete subbase and the air during concrete curing. After the study, it was generally agreed that the cracking was primarily due to early-age curling caused by differential drying shrinkage of the concrete. Several primary factors were believed to be responsible for the slab curling that caused the corner cracking. These include:

- Using a shrinkage-prone mix during the original construction;
- Intermittent wetting and drying of the slab surface during curing;
- Unfavorable temperature gradient between base and ambient temperatures during placement and initial cure period;
- Borderline aspect ratio for slab thickness (i.e., slabs too large for thickness), compounded by the stiff econocrete base; and
- Since the slabs were constructed indoors, an extended period (1 year) elapsed with no additional moisture available to the concrete.

As discussed below, the investigative and experimental program was established to address these factors.

LABORATORY SHRINKAGE TESTS

Early-age differential drying shrinkage was believed to be the predominant factor contributing to slab curling and corner cracking. It was believed that if the absolute magnitude of concrete shrinkage could be controlled, then the magnitude of the differential shrinkage between the top and bottom of the slab would be reduced, thereby reducing the potential for excess curling and corner cracking. Based on literature search results (e.g., Bognacki [2]), mixes with a limiting shrinkage of 0.04 percent were sought.

Laboratory shrinkage tests were conducted in accordance with ASTM C 157 on a matrix of 16 concrete mixes to evaluate such variables as coarse aggregate size, aggregate type, aggregate proportioning, and water/cement ratio. The tests were conducted on mixes with ASTM C 33, No. 57 (38-mm maximum aggregate size) and No. 467 (64-mm maximum aggregate size) coarse aggregates; traprock, argillite, and dolomite aggregates; water/cement ratios of 0.42 and 0.50; with and without high-range water reducers (HRWR); cement contents of 181 kg. (400 lbs) and 226 kg. (500 lbs.); and 65:35 percent and 50:50 percent aggregate:sand blends. (It should be noted that the local aggregates and Type 1 cement used in the local area typically result in high flexural strengths in excess of 5.5 MPa (800 psi); hence, the relatively low cement factors.)

The results of the laboratory shrinkage tests revealed the following:

- The maximum size of the coarse aggregate (No. 57 or 467) did not influence the shrinkage.
- The use of HRWR increased shrinkage. Mixes without HRWR generally had shrinkage results less than 0.04 percent, while mixes with HRWR generally had shrinkage results greater than 0.04 percent.

- The mix used for the original rigid pavement construction (50 percent coarse aggregate/50 percent sand blend; 0.50 water/cement ratio; No. 57 coarse aggregate) had a measured shrinkage of 0.08 percent.

OPTIMIZED MIX DESIGNS

Based on the results of the shrinkage tests, laboratory testing was initiated to optimize mix designs using traprock and dolomite coarse aggregates and No. 57 coarse aggregate grading. Since there were no measured differences in shrinkage between the No. 467 and 57 aggregates, the smaller size aggregate will facilitate concrete placement around the instrumentation required for the test pavements. The argillite aggregate was eliminated due to potential problems with thermal instability.

There are several methods that can be used to optimize a concrete mix design with respect to shrinkage, workability, and strength. Although strength was not a problem for the candidate mixes, shrinkage and workability were considered very important, 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 Lafrenz [3] and the State of Iowa [4], were used to optimize mixture proportioning (after Shilstone [5]). 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 sample gradation plot and a workability chart for one of the mixes that was investigated are shown in Figures 2 and 3, respectively.

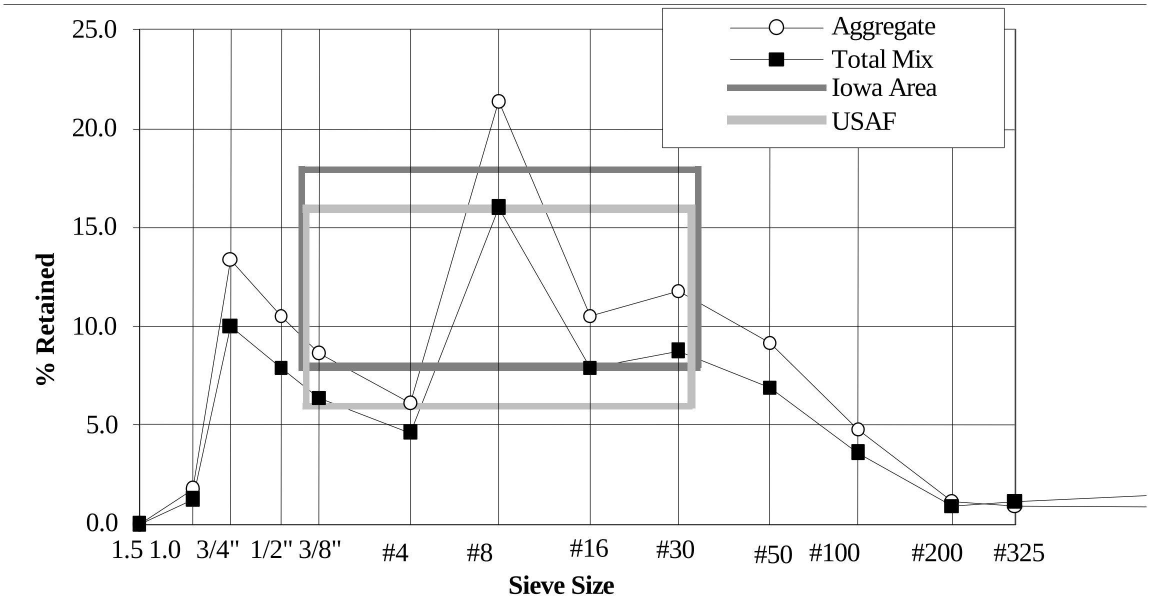

Figure 2. Gradation Plot

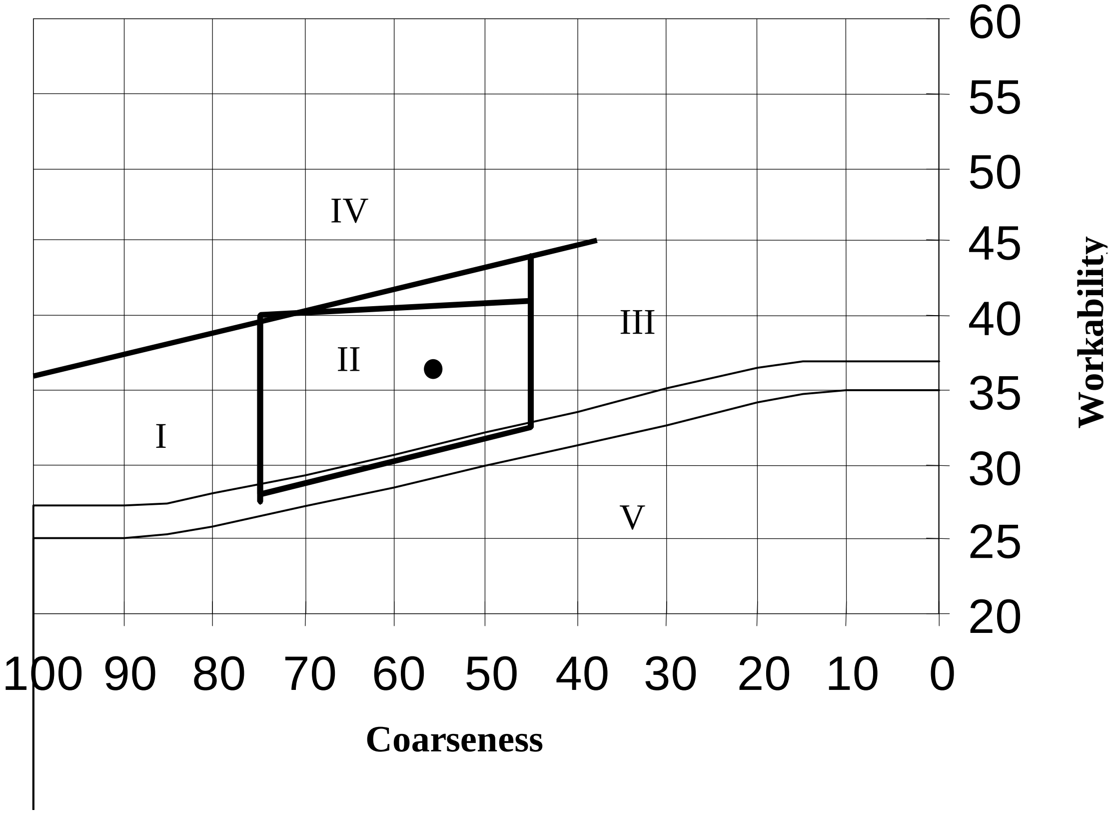

Figure 3. Workability Chart

Using the optimization guidelines, a total of six laboratory mixes were 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, and flexural 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 in 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/m of cement, 8-cm slump, and 0.05 percent shrinkage. Although the shrinkage slightly exceeded the 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, after several attempts to duplicate the mix design using plant trial batches, the maximum attainable slump was only 2.5 cm (1 inch). A 7-cm to 8-cm slump was considered the minimum practical slump for hand placement around the instrumentation. Therefore, 0.3 liters per 45 kg. of cement (10 oz. per 100 lbs. of cement) of a high-range water reducer (HRWR) was added to achieve a slump of 8 cm. However, the resulting mix was harsh and had poor workability. This necessitated further trial batches with higher cement and water (to increase the workability by increasing the cement paste content of the mix). Therefore, while the mix design was beneficial in establishing preliminary proportioning, the trial batches were necessary to optimize mix design. The following mix design was selected for construction of the test slabs:

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 percent
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 percent
Coarseness : 58.4 percent
Mortar : 53 percent

TEST STRIP

Before constructing the full-scale test items, the FAA required that the revised concrete mix design, construction practices, and curing procedures be tested on the low-strength subgrade section. The plan called for careful removal of the existing cracked concrete slabs and placement of new 11-inch slabs on the existing econocrete base. Both 6-meter (20-ft.) square (the size of the original slabs) and 4.5-meter (15-ft.) square test slabs were constructed to evaluate the effect of different slab sizes in controlling curling. The layout of the test slabs is shown in Figure 4.

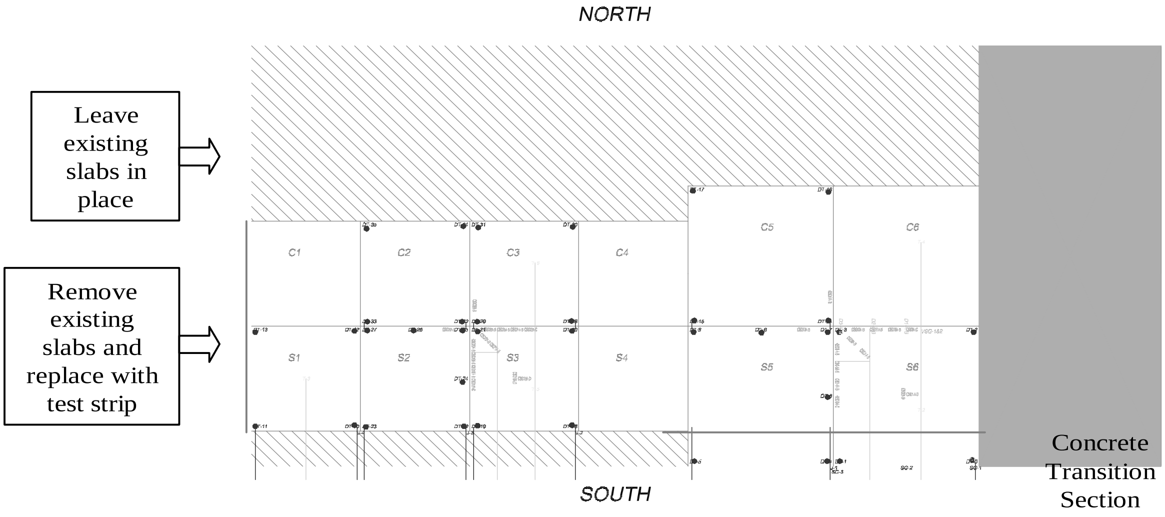

Figure 4. Test Strip Layout

The test slabs were instrumented with both static and dynamic sensors, grouped as follows:

- Dynamic
    - Displacement Transducers
    - Concrete Strain Gages
    - Joint Gages
    - Slide Gages
    - Instrumented Dowels

- Static
    - Thermistor Trees
    - Moisture Sensors
    - Vibrating Wire Strain Gages

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. The contractor covered the slabs with burlap for a 28-day wet cure period. The reason for a 28-day wet cure was to fully hydrate the cement in a thoroughly moist environment. This will aid recovery of any subsequent drying shrinkage to the fullest extent by re-wetting the concrete.

Additionally, thermal blankets were placed over slabs S1 and C1. The blankets were left in place to achieve and maintain no more than a 5° to 8°C (10° to 15° F) temperature differential between top and bottom of the slabs for the first two 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.

Further, in order to more fully understand the reasons for the early cracking on the original slabs, one-half of the slabs were placed with the optimized mix (south half) and one-half were placed with the mix used for the original construction (north half). This could help identify whether the initial failures were related to the mix or the curing procedures used for the original construction.

Monitoring during the curing period was critical relative to any curling tendencies, particularly during the first few days after placement. It was hoped that by controlling concrete temperatures, any upward curling will be minimized or eliminated, particularly since shrinkage at the bottom of the slab will be resisted by friction against the econocrete base.

The displacement transducers will directly measure any curling. The concrete strain gages and instrumented dowels will be used to supplement the displacement transducers. Since formation of cracks at joint locations will release built-up stresses in the concrete, joint gages will be used to detect joint separation and slide gages will be used to indicate movement of the slab relative to the base. The thermister trees will measure thermal gradients within the concrete to monitor the potential for slab warping.

The monitoring process during curing was developed to answer the following questions:

- Has slab curling occurred?
- Where did it occur?
- When did it occur?

- Have the transverse joints formed?
- Where did the joint cracks occur?
- When did they occur?
- Has joint formation revealed curling?

These data will help in evaluating the effect of the mix characteristics, curing methods, and slab sizes on concrete curling.

Finally, after curing, the slabs will be subjected to full-scale loads using the NAPTF test vehicle to observe the behavior of the slabs under load and to measure load-induced strains at the top and bottom of the concrete slabs.

RESULTS OF TEST PROGRAM

Since the test slabs were placed at the end of November 2001, the results were not available at the time this paper was prepared. It is expected, however, that the results will be available by February 2002, in time for presentation.

The results will be used to finalize the requirements for rigid pavement test items planned for the next construction cycle on medium- and high-strength subgrades. At this writing, the planning is for construction of the following four test items on both the medium and high strength soils:

- Concrete slab on econocrete base (medium and high strength subgrades); and
- Concrete slab on granular subbase (two medium strength subgrades)

The results from the test slabs will be used to optimize the design and construction requirements for the rigid test items with respect to:

- Slab thickness design;
- Slab dimensions;
- Concrete mix design; and
- Concrete curing methods.

ACKNOWLEDGMENTS/DISCLAIMER

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