Monitoring of Strength Development in Portland Cement Concrete With High Fly-Ash Content at the FAA's National Airport Pavement Test Facility

Navneet Garg[1], Lia Ricalde[2]

Abstract

Construction Cycle 2 (CC2) at the FAA's National Airport Pavement Test Facility (NAPTF) included construction of three concrete test items MRC, MRG, and MRS on three different support conditions (crushed-stone subbase, slab on grade, and econocrete stabilized subbase). All three test items were constructed on a CBR 7-8 subgrade. The existing econocrete subbase (P-306) from CC1 test item MRS was used for CC2 MRS. Concrete was placed in the test items using a concrete pump into fully formed 15 ft. (4.57 m) by 15 ft. (4.57 m) slabs. Test results are presented and discussed in this paper. Test results include concrete placement details (slump, air content, concrete temperature), compressive strengths, flexural strengths, elastic modulus from free-free resonance tests on concrete beams and cylinders, portable seismic pavement analyzer (PSPA) tests, and strength results from sawed beams and cored cylinders taken from untrafficked test slabs. Concrete specimens included both laboratory cured and field cured specimens. PSPA tests were performed on the test item slabs at the age of one day and on regular intervals after that, coinciding with the laboratory testing of beams and cylinders. The test results showed good correlation between elastic modulus (from free-free resonance and PSPA tests) and strength values (compressive and flexural strengths) and demonstrated the application potential of a testing device such as PSPA for assessing the early-age strength of concrete.

Introduction

The Federal Aviation Administration's (FAA) National Airport Pavement Test Facility (NAPTF) is located at the FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The primary objective of the NAPTF is to generate full-scale pavement response and performance data for development and verification of airport pavement design criteria. It is a joint venture between the FAA

---

[1] Navneet Garg, Ph.D., Airport Technology R&D Branch, FAA's William J. Hughes Technical Center, Atlantic City Intl. Airport, NJ 08405, U.S.A, Email: navneet.garg@faa.gov

[2] SRA International Inc., 3120 Fire Road, Egg Harbor Township, NJ 08234, U.S.A, Email: Lia_Ricalde@sra.com

and the Boeing Company and became operational on April 12, 1999. The test facility consists of a 900 ft (274.3 m) long by 60 ft (18.3 m) wide test pavement area, embedded pavement instrumentation and a dynamic data acquisition system (20 samples per second), environmental instrumentation and a static data acquisition system (four samples per hour), and a test vehicle for loading the test pavement with up to twelve aircraft tires at wheel loads of up to 75,000 lbs (334 kN).

A typical construction cycle (CC) at the NAPTF is shown in Figure 1:

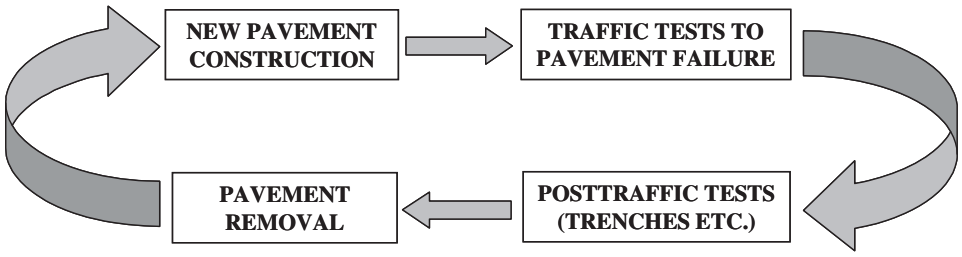

FIGURE 1. Construction Cycle At The NAPTF.

CC1 consisted of six flexible test items (two each on low-, medium-, and high-strength subgrade) and three rigid test items (one each on low-, medium-, and high-strength subgrade). Traffic testing started in February of 2000 with all of the test items loaded at 45,000 lbs (200 kN) per wheel. The "north" traffic lane was loaded by a six-wheel triple dual tandem (TDT) configuration at 54 in (1.372 m) dual spacing and 57 in (1.449 m) tandem spacing; and the "south" traffic lane was loaded by a four-wheel dual tandem configuration at 44 in (1.118 m) dual spacing and 58 in (1.473 m) tandem spacing. The three rigid pavements experienced substantial corner cracking (top-down cracking) after 28 passes had been completed. Traffic testing was halted to determine cause of the early corner cracking. The cracking was caused by a significant amount of upward curling combined with the relatively shallow thickness of the slabs compared to those of normal airport construction. A detailed description of CC1 rigid pavement responses and performance can be found elsewhere (Guo et al. 2002). A new construction cycle (CC2) was initiated and it included construction of three concrete test items MRC, MRG, and MRS on three different support conditions (M stands for medium-strength subgrade, R stands for rigid pavement, C stands for aggregate subbase, G stands for slab on-grade, and S stands for stabilized econocrete subbase). All three test items were constructed on the medium-strength subgrade (California Bearing Ratio CBR ≈ 7-8). For the test item MRS, the existing econocrete subbase (P-306) from CC1 test item MRS was used. CC2 consisted of three phases: test strip, free-standing slab, and complete medium-strength test section. A high amount (50-percent) of Class-C fly-ash was used in the concrete mix.

Extensive laboratory testing for strength characterization, early-age strength development, and non-destructive testing was conducted to characterize the CC2 concrete. The main objective of this paper is to present the test results from the concrete characterization phase. The research significance of this study is to

demonstrate the application potential of Portable Seismic Pavement Analyzer (PSPA) and Free Free Resonant Column (FFRC) tests for concrete characterization.

Construction Cycle 2 Test Strip

CC2-TestStrip and a free-standing slab were constructed to quantify the effects of different concrete mix designs on the curling behavior of slabs at the indoor testing facility (NAPTF). The test results from these two phases (Ricalde and Roy 2003, Guo et al. 2004, Hayhoe 2004*)* showed that:

- An optimized three-aggregate mix design did not provide any significant benefit in terms of curling behavior.
- The optimized three-aggregate mix and a conventional two-aggregate mix both resulted in higher flexural strengths, which would in turn result in thin slabs for the CC2 test item designs.
- Flexural strengths could not be significantly reduced so that thicker slabs could be used.
- Fly-ash can be used to replace cement to significantly reduce concrete flexural strength (in the short term).
- High fly-ash content (60 percent) did not have any adverse effect on the slab curling behavior.
- The slabs remained flat during curing (when the wet burlap remained on top of the slabs).

Construction Cycle 2 (CC2)

Based on the results discussed above, it was decided to use a two-aggregate mix with 50 percent flyash replacement for the CC2 test items. Class-C flyash was used because it is the only type available to the local concrete producers. The chemical composition of the Class-C flyash used is given in Table 1.

TABLE 1. Chemical Composition of Class-C Flyash Used During CC2.

Chemical Analysis	Result
Silicon Dioxide, SiO_2, %	33.95
Aluminum Oxide, Al_2O_3, %	19.09
Iron Oxide, Fe_2O_3, %	6.03
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	59.07
Calcium Oxide, CaO, %	26.27
Magnesium Oxide, MgO, %	6.05
Sodium Oxide, Na_2O, %	1.90
Potassium Oxide, K_2O, %	0.42
Sulfur Trioxide, SO_3, %	2.57
Moisture Content, %	0.20
Loss on Ignition, %	0.28

Target slump, air content and flexural strength were 3-inch (7.62 cm), 4.5-percent, and 750 psi (5171 kN/m^2) respectively. Slab size of 15 feet (4.57 m) by 15 feet (4.57 m) and thickness of 12 inches (30.5 cm) were used. Both longitudinal and transverse joints were dowelled. Concrete was placed in the plywood forms using a concrete pump. Air content and slump were measured before and after the concrete passed through the pump. In general, use of the concrete pump reduced the concrete slump and air content.

Concrete from Truck –			
Slump (inch):	Minimum = 2.0	Maximum = 4.5	Mean = 3.3
Air Content (%):	Minimum = 1.4	Maximum = 8.5	Mean = 4.9
Concrete from Pump –			
Slump (inch):	Minimum = 1.0	Maximum = 4.25	Mean = 2.5
Air Content (%):	Minimum = 1.4	Maximum = 7.9	Mean = 3.9

(1 inch = 2.54 cm)

In terms of uniformity and homogeneity, the variation in concrete properties (slump and air content) was similar in concrete from the truck and pump.

Concrete from Truck –			
Slump (inch):	Mean = 3.3	Standard Deviation = 0.67	COV (%) = 20
Air Content (%):	Mean = 4.9	Standard Deviation = 1.7	COV (%) = 34
Concrete from Pump –			
Slump (inch):	Mean = 2.5	Standard Deviation = 0.7	COV (%) = 26
Air Content (%):	Mean = 3.9	Standard Deviation = 1.3	COV (%) = 33.5

(1 inch = 2.54 cm)

Laboratory Testing

Each of the 60 slabs were individually formed, requiring the concrete to be placed in a checkerboard fashion. This means that each test item was constructed in two concrete placements. Beams and cylinders were cast from concrete placed in the ten middle row slabs of each test item. Therefore, for a given concrete placement, samples were taken from the middle five slabs. Concrete beams and cylinders were prepared as per ASTM C31/C 31M-03a (Standard Practice for Making and Curing Concrete Test Specimens in the Field). Beams and cylinders were divided into two groups – field cured and lab cured. A total of 286 beams and cylinders were cured in the laboratory under standard curing conditions, and 210 beams and cylinders were field cured. The field-cured samples were placed inside the test facility adjacent to the test slabs and were covered with wet burlap for the duration that the corresponding slabs were cured with wet burlap to mimic the slab curing conditions. Six beams and six cylinders were tested for strength on any given day. Three beams and three cylinders were lab cured, and three beams and three cylinders were field cured. For the compressive strength tests, ASTM C 39/C 39M-01 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) was followed. ASTM C 78-02 (Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading) procedure was used for the flexural strength tests. The lab-cured samples were tested at the ages of 2, 5, 7, 14, 28, 56, and 90 days. The field-

cured samples were tested at the ages of 7, 14, 28, 56, and 90 days. These beams and cylinders came from different slabs cast on the same day. The objective was to characterize the concrete strength and study the variability in the strength of a test item. The results from strength tests are summarized in Table 2. Each strength value in Table 2 is an average of three specimens tested.

TABLE 2. Summary of Flexural and Compressive Strength Test Results.

		MRC				MRG				MRS			
		Lab-Cured Specimens		Field-Cured Specimens		Lab-Cured Specimens		Field-Cured Specimens		Lab-Cured Specimens		Field-Cured Specimens	
	Age @ Testing, days	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2	Flexural Strength, kN/m^2	Compressive Strength, kN/m^2
FIRST PLACEMENT	2	1326	2252	-	-	487	1195	-	-	1648	5040	-	-
	3	-	-	-	-	-	-	-	-	2533	8088	-	-
	5	-	-	-	-	3144	10974	-	-	-	-	-	-
	7	4256	18616	4146	12925	4112	13943	2958	8738	5045	21259	4808	17274
	14	4753	21381	5599	19958	5040	19878	4532	17113	5047	24309	5493	23739
	28	5376	24957	6465	26301	5461	23982	3746	23534	5148	26097	4362	27193
	56	4990	26221	5932	30243	4886	26177	4403	23658	5222	30974	4576	28535
	90	4665	26867	5826	28331	5040	27273	5030	26503	5171	30569	4109	24997
SECOND PLACEMENT	2	-	-	-	-	-	-	-	-	3018	7237	-	-
	3	830	3323	-	-	788	1259	-	-	3399	10243	-	-
	5	2700	8333	-	-	3783	10285	-	-	-	-	-	-
	7	4360	13617	3507	8660	4052	14187	3128	7642	4132	16341	4148	15936
	14	4488	18862	5015	16097	4491	18657	4169	17276	4534	20608	4107	21461
	28	4886	23658	5355	23412	6021	24796	4695	23700	4383	22681	4420	23332
	56	4861	26016	4996	26586	5461	28983	5486	27558	4537	24796	4744	23578
	90	4916	28131	5137	24145	5757	31709	4551	25855	4532	24959	4341	23821

Effect of Lab/Field Curing of Specimens on Concrete Strength

Figure 2 shows the results from flexural strength tests for beam specimens (lab and field cured). No clear relationship was observed between the flexural strengths of field-cured and lab-cured specimens. Figure 3 shows the results from compressive strength tests for cylinder specimens (lab and field cured). In general, the compressive strengths for lab-cured cylinders were higher than those for the field-cured cylinders.

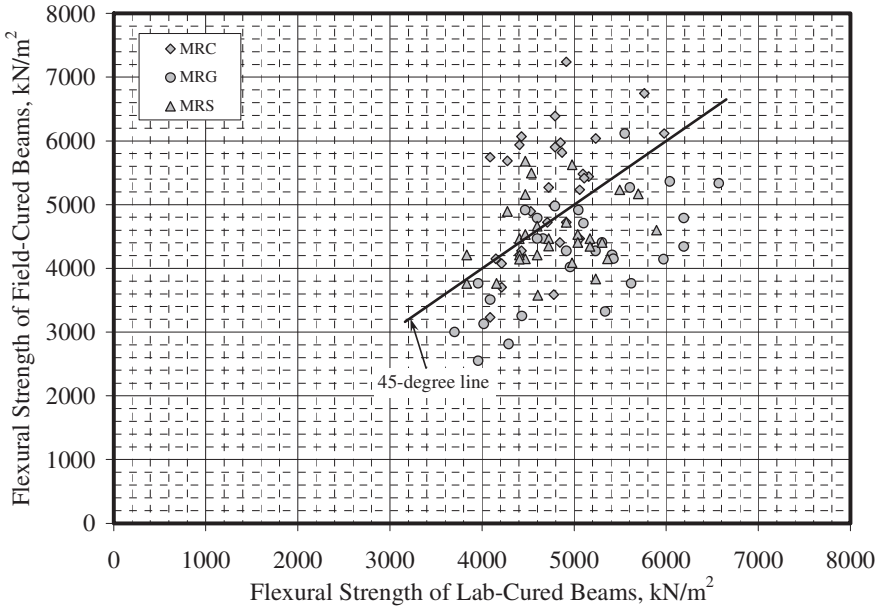

FIGURE 2. Flexural Strength of Lab-Cured and Field-Cured Beam Specimens.

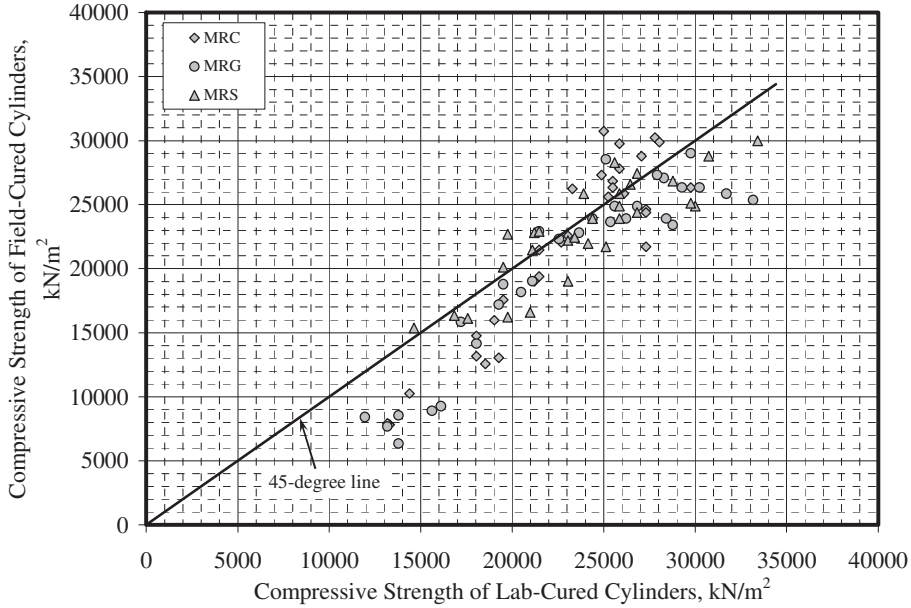

FIGURE 3. Compressive Strength of Lab-Cured and Field-Cured Cylindrical Specimens.

A fairly strong relationship was observed between the compressive strengths of field-cured and lab-cured specimens. The relationship is as follows:

CS (field-cured specimens) = 0.935 * CS (lab-cured specimens), and $R^2 = 0.78$ where CS is the compressive strength in psi.

A review of the literature shows that a relationship exists between flexural strength (modulus of rupture MR) and compressive strength (CS). The relationship is shown in equation-1:

$$MR = C_{FC} * \sqrt{CS} \qquad [1]$$

where C_{FC} is generally expected to have a value in the range 8 to 10 for normal strength concrete (Huang, 1993).

The NAPTF strength test data were analyzed and the following relationships were developed:

Considering only lab-cured specimens:

$$MR = 12.06 * \sqrt{CS} \qquad R^2 = 0.86 \qquad [2]$$

Considering only field-cured specimens:

$$MR = 12.19 * \sqrt{CS} \qquad R^2 = 0.33 \qquad [3]$$

Considering both lab-cured & field-cured specimens:

$$MR = 12.12 * \sqrt{CS} \qquad R^2 = 0.75 \qquad [4]$$

Equations 2, 3, and 4 show that there is not a significant difference in the relationship for lab-cured specimens, field-cured specimens, or both types of

specimens (irrespective of curing type). However, there is a significantly higher variability in the field-cured specimens compared to the lab-cured specimens. Also, the coefficient C_{FC} is outside the generally accepted range, maybe because of high amount of flyash used in the mix. The results are shown in Figure 4.

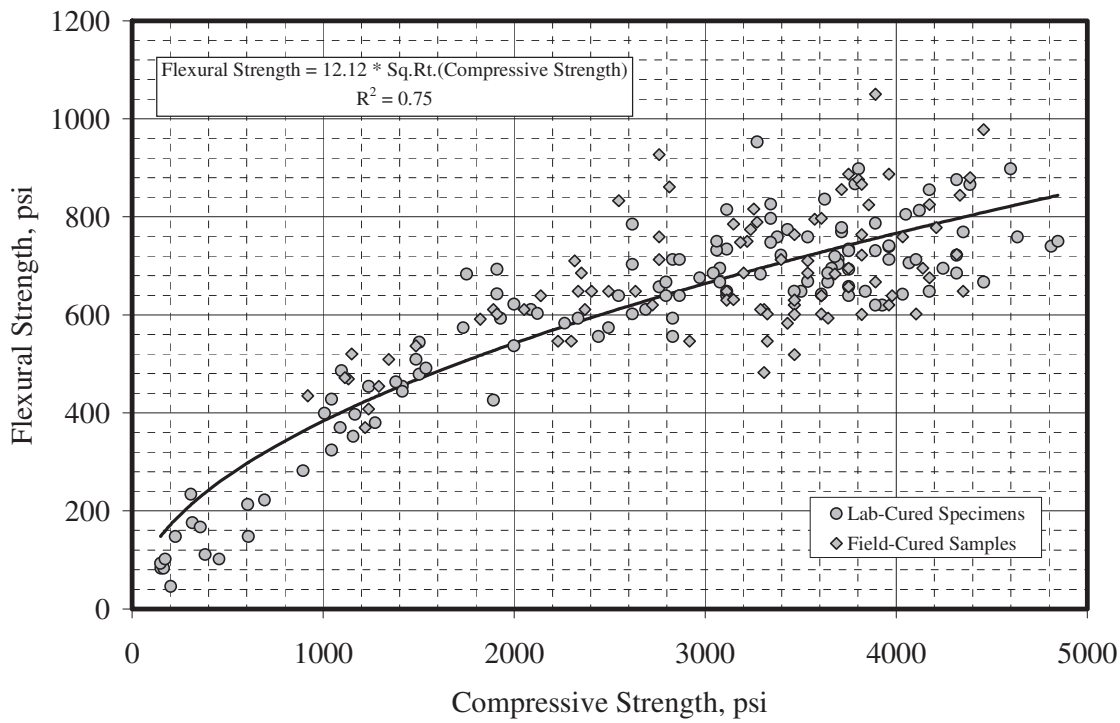

FIGURE 4. Relationship Between Compressive Strength and Flexural Strength. (1 psi = 6.894757 kN/m^2)

Non-Destructive Testing

Non-destructive testing was performed during CC2 to assess the early-age strength development in concrete slabs and also to estimate the modulus of concrete beams, cylinders, and slabs using seismic properties measuring equipment. The measurements were used to develop relationship between seismic modulus and strength (flexural and compressive). The data collected from these tests will provide necessary information for the FAA project currently underway "Early Opening of Newly Constructed Concrete Airport Pavements". Two types of non-destructive tests were performed – free-free resonant column (FFRC) tests on beams and cylinders, and portable seismic pavement analyzer (PSPA) tests on CC2 test item slabs. A brief description of test procedure and results from the two types of tests are discussed.

Free-Free Resonant Column Tests

The FFRC tests were performed in accordance with ASTM C215. This method is particularly suitable for determining the modulus of concrete samples in the laboratory using beams and cylinders. The modulus measured with this method is the low-strain seismic modulus. When a cylindrical specimen is subjected to an impulse load at one end, seismic energy over a large range of frequencies propagates within

the specimen (Yuan et al. 2003). Depending on the dimensions and stiffness of the specimen, energy associated with one or more frequencies is trapped and magnified (resonates) as the seismic waves propagate within the specimen. By determining the resonant frequencies, the modulus of the specimen can be calculated using principles of wave propagation in a solid rod (Richart et al. 1970). The test set-up is shown in Figure 5.

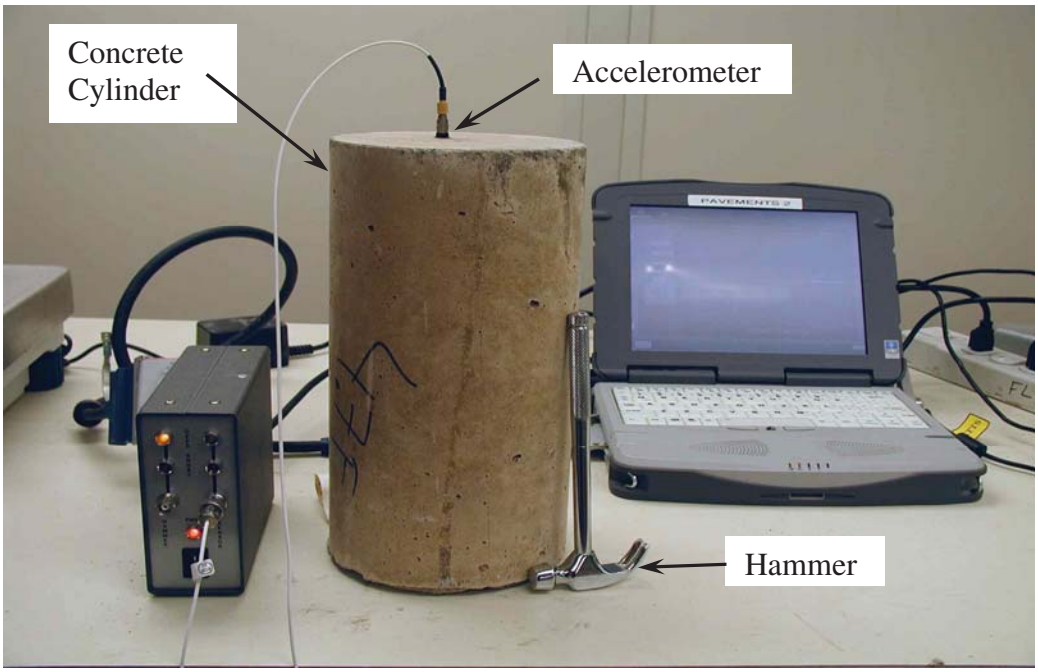

FIGURE 5. Free-Free Resonant Column Test Set-Up.

FFRC tests were performed on beams and cylinders (laboratory and field cured specimens). After performing the test, the beams were tested for flexural strength (ASTM C 78-02) and the cylinders were tested for compressive strength (ASTM C 39/C 39M-01). The results from the modulus measurements are shown in Figure 8. The results show that modulus values determined from beam samples are generally higher than the modulus values determined from cylinders (roughly 3 to 10 percent difference). The effect of specimen curing (lab or field) on concrete modulus is also shown in Figure 6. During the early age of concrete (less than 20 days old), the field-cured specimens (both beams and cylinders) showed higher modulus values than laboratory-cured specimens. When the concrete was more than 20 days old, lab-cured specimens showed higher modulus values than the field-cured specimens.

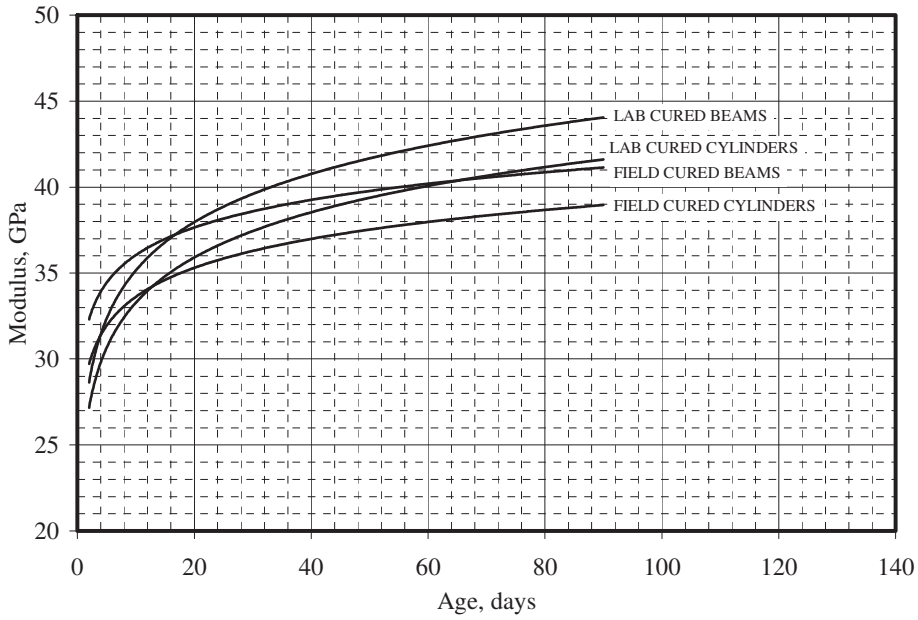

FIGURE 6. Results from FFRC Tests on Beams and Cylinders

Figures 7 and 8 show the relationship between concrete modulus and compressive strength and flexural strength respectively for laboratory and field cured specimens. A strong relationship was observed between compressive strength and the modulus of concrete (from free-free resonant column tests). As shown in Figure 7, the relationship is much stronger for laboratory-cured specimens compared to the field-cured specimens. If the data for field- and lab-cured specimens are combined, the modulus of concrete from the CC2 test items can be determined from the compressive strength as follows:

$$E = 437.68*(CS)^{0.309} \qquad [5]$$
$$R^2 = 0.93$$

where E is the elastic modulus of the concrete (ksi) and CS is the compressive strength (psi). The modulus relationship with flexural strength is fairly strong for the laboratory-cured beams (Figure 8), but a lot of scatter was observed in the data for the field-cured beams. The lab cured samples were subject to uniform temperature of 73±3 °F (23±2 °C), whereas the field cured samples were subjected to daily temperature cycling (field temperatures were less than lab temperatures). The difference in curing conditions could explain the variations noted above.

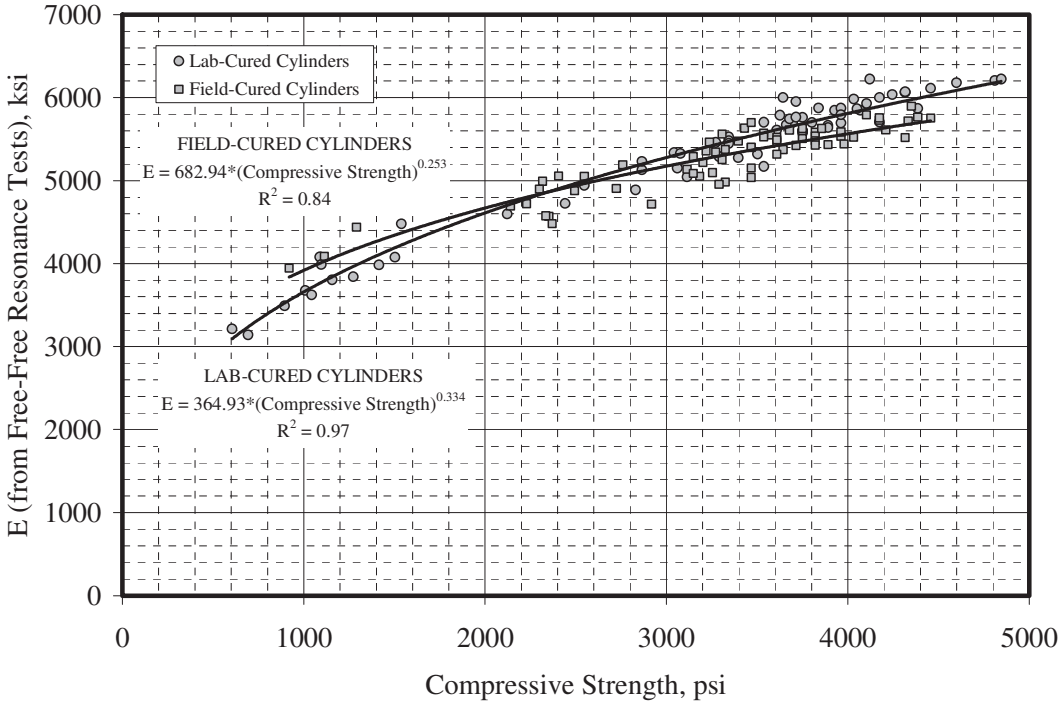

FIGURE 7. **FFRC Modulus and Compressive Strength Relationship (1 psi = 6.894757 kN/m^2).**

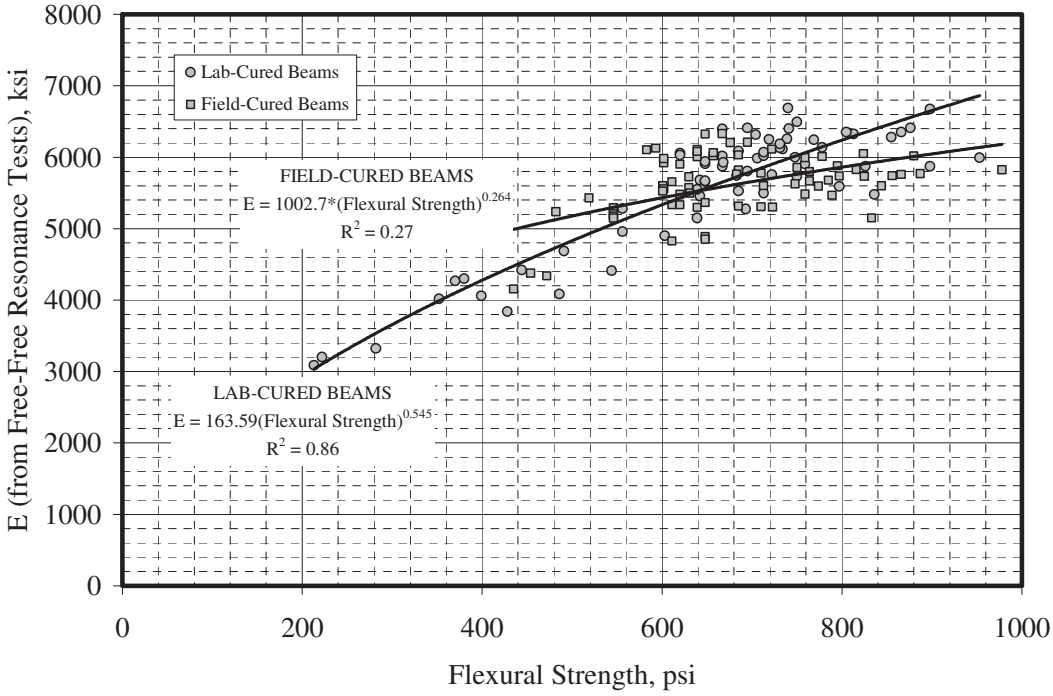

FIGURE 8. **FFRC Modulus and Flexural Strength Relationship (1 psi = 6.894757 kN/m^2).**

Portable Seismic Pavement Analyzer (PSPA) Tests
The tests described previously (destructive and non-destructive), are generally performed on beams and cylinders cast during the placement of concrete or on cores taken from the concrete slabs. Researchers are also interested in the characterization of concrete in situ slabs. The PSPA estimates the in situ seismic modulus of a concrete slab. Figure 9 shows the PSPA equipment.

FIGURE 9. Portable Seismic Pavement Analyzer (PSPA)

PSPA is a portable device and consists of two transducers (receivers) and a source. The device operates from a computer. The operating principle of PSPA is based on generating and detecting stress waves in a layered medium. The data collected by PSPA is processed by spectral analysis to determine the modulus of the layer. A more detailed explanation on theory and equipment can be found elsewhere (Yuan et al. 2003, Nazarian et al. 1995).

At the NAPTF, PSPA equipment was loaned by Dr. Soheil Nazarian (University of Texas at El Paso) just before the placement of test item MRS. Twenty-four hours after the placement of concrete in MRS, PSPA tests were performed close to the slab edge. Three tests were conducted at each location. After the first tests on the slab edge (conducted 24 hours after concrete placement), the remaining tests were performed at the center of the slabs at intervals of 3, 7, 14, 28 and 120-days after placement of concrete. Figure 10 shows the results from PSPA tests on test item MRS (second placement). The device had a very high degree of repeatability of test results.

Figures 11 and 12 summarize the results from the NAPTF CC2 concrete characterization testing program. Figure 11 shows the relationship between compressive strength and modulus values determined from PSPA tests on CC2 MRS concrete slabs, and free-free resonant column tests on concrete cylinders (used for compressive strength testing and concrete maturity study). Results show that the modulus values determined from the two methods are comparable and relate well to the compressive strength.

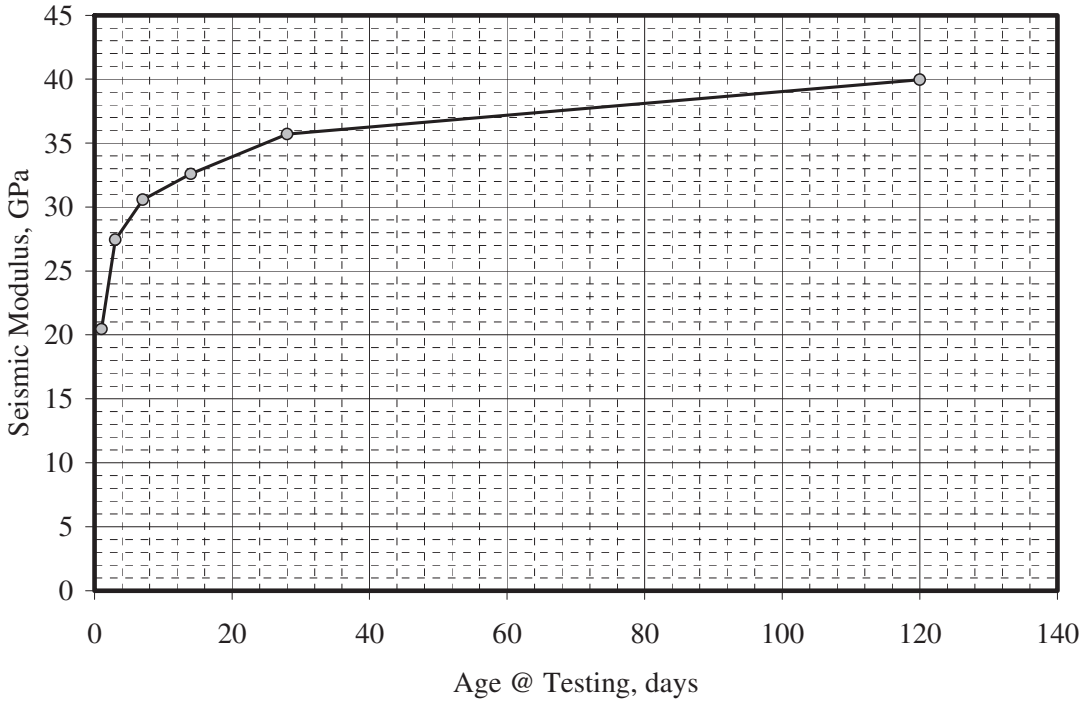

FIGURE 10. **Results from PSPA Tests on Test Item MRS**

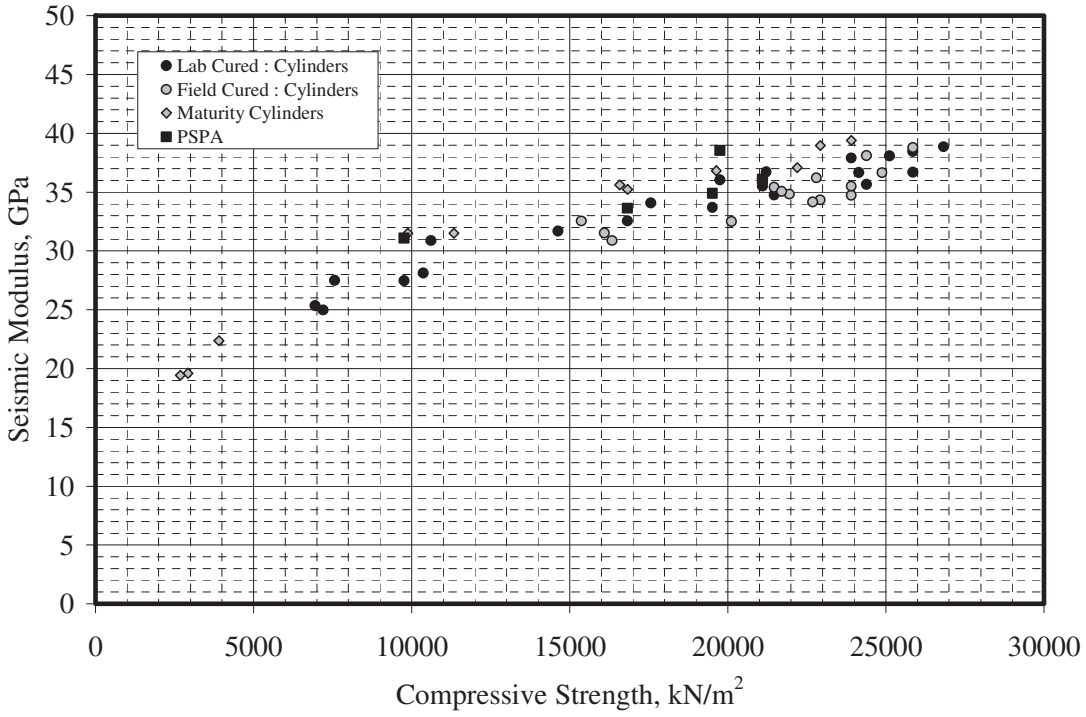

FIGURE 11. **Relationship Between Modulus and Compressive Strength.**

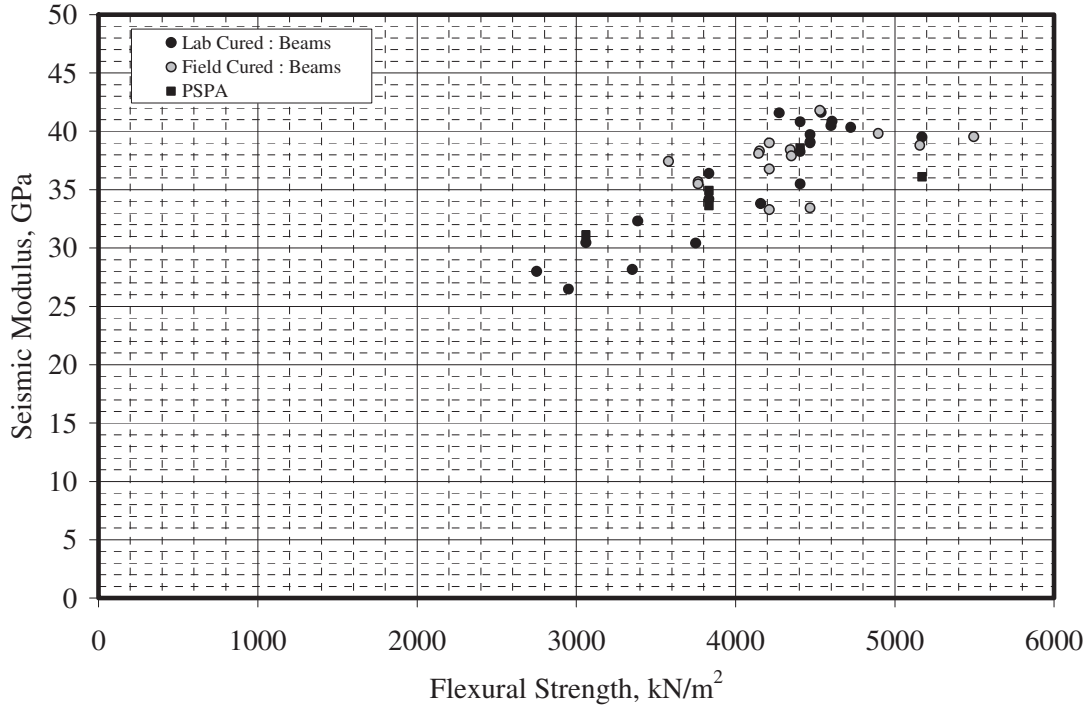

FIGURE 12. Relationship Between Modulus and Flexural Strength.

Figure 12 shows the relationship between flexural strength and modulus values determined from PSPA tests on CC2 MRS concrete slabs, and free-free resonant column tests on concrete beams (used for flexural strength testing). A reasonable relationship is observed between the modulus values determined by the two methods and the flexural strength of concrete.

One of the anomalies observed during the strength testing (beams and cylinders) was that the flexural strength of concrete at the age of 90 days was lower than the 56-day strength by about 5 to 8 percent for most of the specimens tested (for some it remained unchanged). Compressive strength also did not show any significant increase during that period.

Summary/Conclusions

The results from the concrete characterization phase for CC2 rigid test items at the NAPTF are presented. A concrete pump was used to place the concrete and a concrete mix design with high fly-ash content (50-percent) was used. Tests included both destructive and non-destructive tests. Destructive tests included flexural and compressive strength testing at different ages. The non-destructive tests included free-free resonant column tests and PSPA tests to determine the concrete's Young's modulus. The results can be summarized as follows:

- The effect of the type of curing of specimens (field-cured and laboratory-cured) was clearly observed in the case of the compressive strength results. The compressive strength of field-cured specimens was roughly 94 percent of the lab-cured specimens.

- Flexural strength results showed significantly higher variability than the compressive strength results.
- Specimen curing did not have any significant effect on the relationship between compressive strength and flexural strength.
- The non-destructive tests performed on beams and cylinders (free-free resonant tests) and concrete slabs (PSPA) demonstrated a high degree of repeatability. The tests were rapid and easy to perform.
- Moduli obtained with seismic tests correlated well with the traditional strength parameters such as compressive strength and flexural strength. Relationships were fairly strong in the case of compressive strength.
- Moduli obtained from PSPA and laboratory tests (FFRC) were comparable.

The strong relationship between the seismic modulus and concrete strength (compressive and flexural) demonstrated the application potential of PSPA and FFRC tests for concrete characterization for airport pavements.

Acknowledgements/Disclaimer

The work described in this paper was supported by the FAA Airport Technology Research and Development Branch, Manager, Dr. Satish K. Agrawal. The contents of the paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. The paper does not constitute a standard, specification, or regulation. The authors would like to thank Dr. Gordon Hayhoe and Dr. Soheil Nazarian for their valuable comments and inputs in the study.

References

1. Guo, Edward H., Hayhoe, Gordon F., and Brill, David R. (2002). "Analysis of NAPTF Traffic Test Data for the First-Year Rigid Pavement Test Items." *Proc., Federal Aviation Administration Technology Transfer Conference,* Atlantic City, New Jersey.
2. Ricalde, Lia, and McQueen, Roy D. (2003). "Portland Cement Concrete Test Strip Pavement at the FAA National Airport Pavement Test Facility (NAPTF)." *Proc., Airfield Pavements Challenges and New Technologies Conference*, Las Vegas, Nevada.
3. Guo, Edward H., Dong, May, Daiutolo, Hector, and Ricalde, Lia (2004). "Analysis of the Observed and Predicted Responses of a Curled Single Slab." *Proc., FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, New Jersey.
4. Hayhoe, Gordon F. (2004). *"Traffic Testing Results from the FAA's National Airport Pavement Test Facility." Proc., 2nd International Conference on Accelerated Pavement Testing,* University of Minnesota, Minneapolis, MN.
5. ASTM C31/C 31M-03a. Standard Practice for Making and Curing Concrete Test Specimens in the Field.
6. ASTM C 39/C 39M-01. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

7. ASTM C 78-02. Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Pount Loading).
8. Huang, Yang H. (1993). *Pavement Analysis and Design. Prentice Hall*, New Jersey, USA.
9. ASTM C215. Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens.
10. Yuan, D., Nazarian, S., and Medichetti, A. (2003). "A Methodology for Optimizing Opening of PCC Pavements to Traffic." *Research Report 4188-2.* The Center for Highway Materials Research, The University of Texas at El Paso, El Paso, TX.
11. Richart, Jr. F. E., Woods, R. D., Hall, Jr. J. R., *Vibrations of Soils and Foundations*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970.
12. Nazarian, S., Yuan, D., Baker, M. R., *Rapid Determination of Pavement Moduli with Spectral-Analysis-of-Surface-Waves Method,* Report Research Project 0-1243, The Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso, El Paso, TX, November, 1995.