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Comparison of Field and Laboratory Strengths of Concrete Slabs

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Abstract

The existing practice for acceptance of newly-constructed concrete pavements is usually based on the strength of specimens prepared and cured under ideal conditions. These tests can be used as a standard for acceptance, but they do not address the quality of the construction and/or the adequacy of the field curing process, differences in placement, compaction, or environmental conditions. Strength tests can also be performed on specimens extracted from the completed structure. However, coring operations are costly and specimens may experience internal damage.

Nondestructive technologies (NDT) in general and seismic methods in particular can be used to estimate the in-place strength of concrete slabs. These NDT methods rely on measuring the velocity of propagation of elastic waves within the concrete. Velocities can be converted to modulus of elasticity and relate it with high confidence to strength.

To complete this study, ten different concrete mixes or curing methods were investigated. Estimated field strengths were typically lower than those measured on lab-cured specimens prepared at the site with the same mixes. On average, differences of 15% with the 28 day strength were observed. The differences are significant enough that may impact the performance of the materials.

Résumé

La pratique existante pour la réception des chaussées en béton neuves est habituellement basée sur la résistance d'échantillons préparés et séchés dans des conditions idéales. Ces tests peuvent être utilisés comme standards pour cette réception, mais ils n'indiquent pas la qualité de la construction et/ou l'adéquation avec le séchage sur le terrain, les différences d'emplacement, le compactage ou les conditions environnementales. Les tests de résistance peuvent aussi être réalisés sur des échantillons extraits directement de la chaussée. Cependant, les opérations de carottage sont coûteuses et les échantillons peuvent subir des dégâts internes.

Les technologies non destructives en général, et les méthodes sismiques en particulier, peuvent être utilisées pour estimer la résistance des plaques de béton en place. Ces technologies non destructives s'appuient sur la mesure de la vitesse de propagation des ondes transversales dans le béton. Ces vitesses peuvent être converties en un module d'élasticité qui permet de faire le lien avec la résistance du béton, et ce avec un haut niveau de confiance.

Pour compléter cette étude, dix différents mélanges de béton ou méthodes de séchage ont été examinées. Les résistances estimées pour le terrain étaient en général plus basses que celles mesurées sur des échantillons séchés en laboratoire et préparés sur le terrain avec le même mélange. En moyenne, des différences de 15% de résistance au 28ème jour de séchage ont été observées. Les différences sont assez remarquables pour avoir un impact sur la performance des matériaux.

Keywords

Nondestructive, Seismic, Free-free, PSPA. Concrete pavements.

1 Introduction

Concrete strength has been usually obtained by performing conventional tests on prepared specimens that are cured under ideal conditions (in a water bath). These tests can be used as a standard for acceptance of the quality of a given mix as delivered. However, the in-place strength of the same material may differ due to the differences in placement, compaction, curing method and environmental conditions. Therefore, it may not be realistic to assume that the strength of the lab-cured specimens is always reflective of the actual strength of the slabs constructed from the same concrete. To remedy this aspect, strength tests can be performed on specimens extracted from the completed structure, but coring operations are costly and only a few samples can be obtained. Also a number of studies have shown that the specimens cored from a slab may experience internal damage.

Nondestructive methods (NDT) have been successfully employed to address these issues [1, 2]. Most of the existing NDT techniques are focused on maturity methods or seismic modulus. Maturity methods estimate the strength of concrete in the field; however, they do not provide any information on the construction quality. On the other hand, seismic methods are sensitive to construction-related factors that may impact the properties of concrete [3]. These NDT methods do not measure directly the concrete strength, but they can be related with high confidence to strength through a simple calibration process.

The first objective of this paper is to compare the methods proposed to measure modulus on lab and field. The next goal is to demonstrate that the seismic methods can reliably estimate the strength of in-place concrete and finally compare the in-place strength with that measured on specimens cured under the ideal conditions.

2 Seismic Methods Used in This Study

Seismic methods rely on generating, detecting and measuring the velocity of propagation of elastic waves within a medium and can be carried out in the laboratory or in the field. Three types of waves, compression, shear, and Rayleigh or surface waves propagate in elastic mediums [4]. The measured velocities can be converted to the modulus of elasticity (also called the seismic modulus) based on the theory of elasticity. Two methods are presented in this study, the free-free resonant column (FFRC) for the lab and Portable Seismic Property Analyzer (PSPA) for the field as shown in Figure 1.

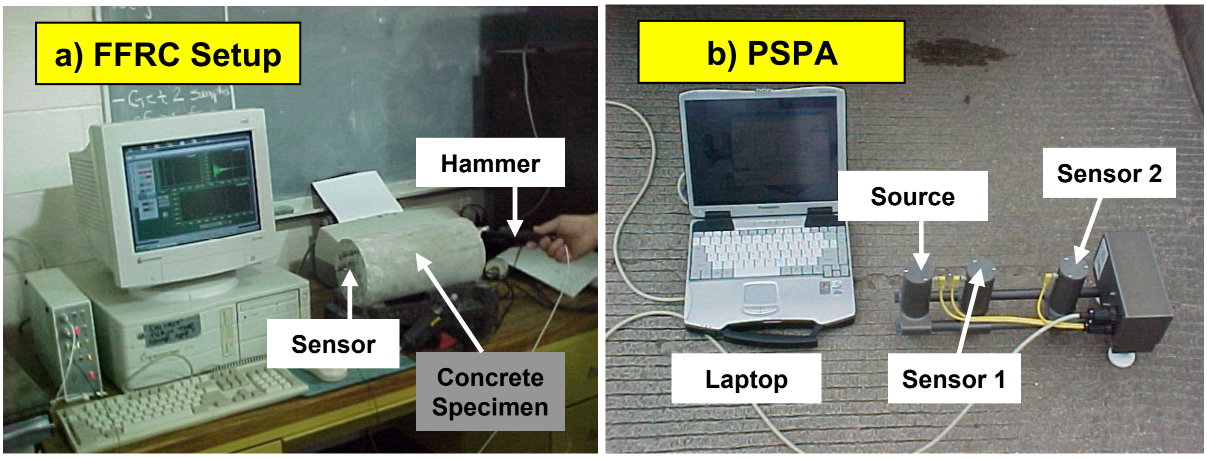

Figure 1. *Example of FFRC setup (a) and Portable Seismic Pavement Analyzer (b)*

2.2. Free-free Resonant Column (FFRC)

The FFRC test (ASTM C215) measures the seismic modulus of concrete specimens in the laboratory. In recent years, the test has been simplified and enhanced and a setup example is shown in Figure 1a. To conduct the FFRC tests, a cylindrical or prismatic specimen is subjected to an impulse load at one end. The energy of the signal generated propagates within the specimen over a large range of frequencies and it is measured on the other end of the specimen. The longitudinal resonant frequency f is trapped and resonates as it propagates within the specimen. With the fundamental value of this frequency, length of the specimen, L, and mass density, ρ, the lab seismic modulus, E_{lab}, is calculated with the formula:

$$E_{Lab} = \rho\left(2\,f\,L\right)^2 \tag{1}$$

2.3. Portable Seismic Property Analyzer (PSPA)

The PSPA (see Figure 1b) determines the variation in modulus with depth of the exposed layer on the field. The PSPA consists of two ultrasonic sensors or transducers and a source packaged into a hand-portable system, which can perform the Ultrasonic Surface Wave (USW) method and allows determining the modulus of the material [2]. The PSPA is operable from a laptop computer. The computer is tethered to the hand-carried transducer unit through a cable that carries power to the hammer and transducers and returns the measured signals to the data acquisition board in the computer. To collect data the user initiates the testing sequence through the computer. The high-frequency source is activated four to six times. The outputs of the two transducers from the last three impacts are saved and averaged (stacked). The other (pre-recording) impacts are used to adjust the gains of the pre-amplifiers to optimize the dynamic range.

The time records collected are subjected to signal processing and spectral analyses. In the USW method, the surface or Rayleigh wave velocity, V_R, is measured without an inversion algorithm. After V_R is measured, the modulus of the top layer, E_{field}, can be determined from

$$E_{field} = 2\,\rho\left[V_R\left(1.13 - 0.16\right)\right]^2\left(1 + \nu\right) \tag{2}$$

where ρ is mass density, and ν is Poisson's ratio. The two moduli, E_{lab} and E_{field}, are theoretically related through Poisson's ratio [4]. This relationship is in the form of

$$E_{field} / E_{lab} = \left(1 + \nu\right)\left(1 - 2\nu\right) / \left(1 - \nu\right) \tag{3}$$

Several studies have demonstrated that the modulus values measured with the PSPA and from FFRC tests are highly correlated in practice and the repeatability of seismic tests is significantly better than those carried out by traditional strength tests [5, 6].

3 Estimating Strength

Test protocols for estimating the in situ concrete strength with seismic methods were used in this study. The test protocol applied consists of the following phases [2]:

1. *Specimen Preparation*. For each mix about a dozen specimens should be prepared to conduct seismic and strength tests.
2. *Seismic Modulus Tests*. FFRC tests are carried out on specimens after 1, 3, 7 and 28 days.
3. *Strength Tests.* Compressive strength tests as per ASTM C39/C39M or flexural tests as per ASTM C78 are performed on two specimens at the dates specified in Item 2.
4. *Correlation Development.* Seismic modulus, E_{lab}, is correlated to the concrete strength, F, using a relationship in the form of

$$F = \gamma\left(E_{lab}\right)^{\delta} \tag{4}$$

where γ and δ are correlation parameters.

5. *Estimation of in-situ Strength.* Concrete strength can be predicted based on the in-place seismic modulus measured with the PSPA and the calibration relationship from Item 4.

Previous studies have shown that modulus measured with the PSPA on concrete slabs and modulus measured with the FFRC in the lab on cores and beams extracted from the same slabs are closely related with a high level of confidence. Differences between these moduli can be attributed to experimental errors, conservatism built in the PSPA analysis, and the damage to the cores and beams during drilling and saw cutting [2].

4 Case Study

A newly-constructed experimental concrete pavement site in Texas was used in this study. The site consisted of ten different concrete sections each 50 meters long. Different curing methods, type and concentration of fly ash, and charging sequences of materials during mixing were used on the sections. The variations of these parameters in the ten mixes are summarized in Table 1. For this site, no relative humidity was recorded, the temperature at pouring varied from 24°C and 29°C and the measured slump ranged from 40 to 100 mm.

PSPA tests were carried out on the sections at different curing times to measure the early age properties of the ten mixes. The average seismic moduli obtained with the PSPA for the first 4, 24 hours and after 28 days are summarized in Figure 2a. It can be observed that mix 1 (10% UFFA+15% fly ash with modified charge cured with high-reflective compound) exhibited the highest modulus both after 4 hrs and 28 days. It was also found that for the first 24 hours, the gain in modulus is quite rapid at the beginning where the concrete makes a transition from plastic to solid and then becomes more gradual.

***Table 1.** Concrete mix properties of the case study and correlation parameters*

Section #	Fly Ash Content (%)		Curing Type	Charging Sequence	Parameter γ	Parameter δ	R^2
	Ultra Fine	Class F					
1	10	15	HRC	Modified	3.010E-6	4.211	1.000
2	10	15	NC	Modified	2.085E-5	3.717	0.979
3	0	25	NC	Modified	4.177E-5	3.566	0.980
4	0	25	Wet Mat	Modified	6.022E-5	3.499	0.970
5	10	15	NC	Normal	3.285E-6	4.179	0.998
6	10	15	HRC	Normal	1.700E-5	3.786	0.994
7	0	25	HRC	Normal	2.649E-5	3.681	0.972
8	10	15	Wet Mat	Normal	4.497E-6	4.100	1.000
9	0	25	NC	Normal	1.182E-5	3.876	0.989
10	0	25	Wet Mat	Normal	4.923E-5	3.528	0.994

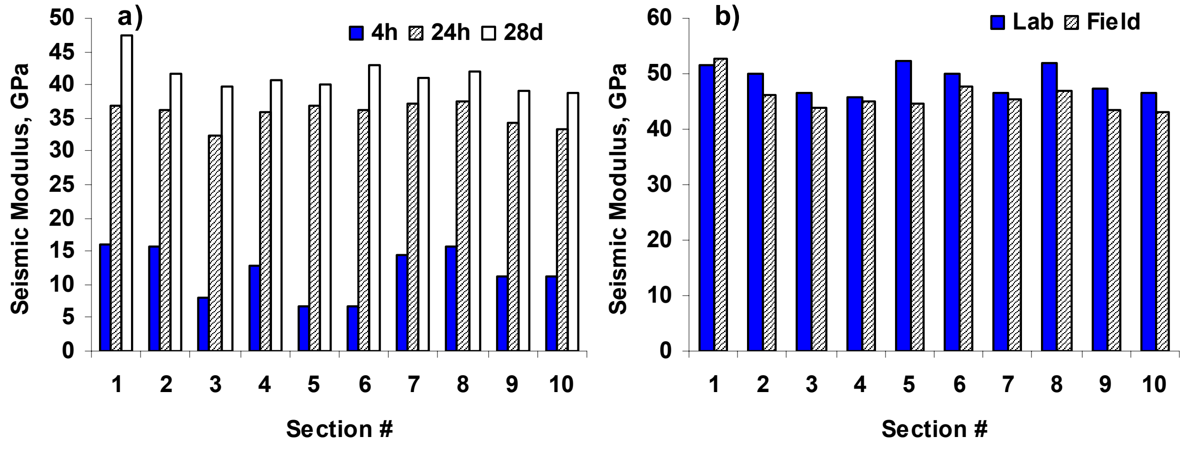

***Figure 2.** Comparison of field seismic modulus at different ages (a) and lab seismic modulus with field PSPA modulus after 28 days (b)*

Field seismic moduli obtained with the PSPA are compared to lab moduli with the FFRC tests in Figure 2b. The PSPA moduli are converted to E_{lab} using Equation 3. For the majority of the mixes the moduli on lab-cured specimens are consistently greater than those measured by the PSPA in the field.

For each of the sections, more than a dozen 100 by 200 mm cylinders were prepared for laboratory testing. The specimens were cured in a moisture room for up to 28 days. FFRC and compression tests were conducted on the specimens. Variations in the compressive strengths with time for the ten sections are shown in Figure 3a after 24 hours, 7 and 28 days of curing.

The seismic moduli from the FFRC tests measured in the lab for all ten mixes were related to the compressive strengths measured on the same samples according to equation 4. Results are shown in Figure 3b. The overall correlation is fairly good. This global relationship confirms the findings of Yuan [3] that seismic-modulus strength relationships are mainly affected by the nature of the coarse aggregates and, to a lesser extent, by other mix parameters. For more accurate results, the relationships for individual mixes could be used. These relationships (see Table 1) show R^2 values are in all cases greater than 0.97.

Following the approach discussed above, the average PSPA moduli from all points were converted to the compressive strengths using the global relationship between the strength and modulus. The measured lab strengths are compared with the estimated strengths from PSPA in Figure 4a. In many cases, the two strengths differ significantly. The differences can be attributed to the different curing conditions between the lab specimens and the in-place materials. These differences can also be observed in terms of higher seismic moduli measured in the laboratory compared to the modulus obtained with PSPA, as illustrated in Figure 2b.

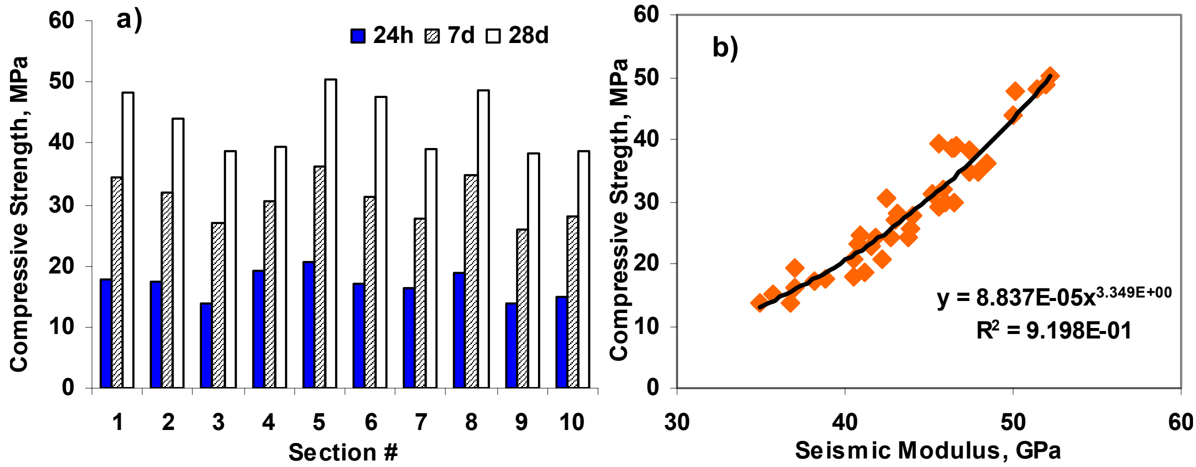

Figure 3. *Variations in compressive strength with time from lab-cured specimens (a) and correlations between compressive strength and lab seismic modulus (b)*

To better quantify the differences between the lab and in-place strengths, the cumulative distributions of the differences are shown in Figure 4b. On average, the strengths from the field are about 15% less than the lab values. Because of the main project restrictions, coring of the slabs could not be carried out for comparison. However, the trends observed in this study are quite similar to those reported by Yuan [2], where the compressive strengths of lab-cured specimens were compared with those from cores extracted from slabs at the same ages.

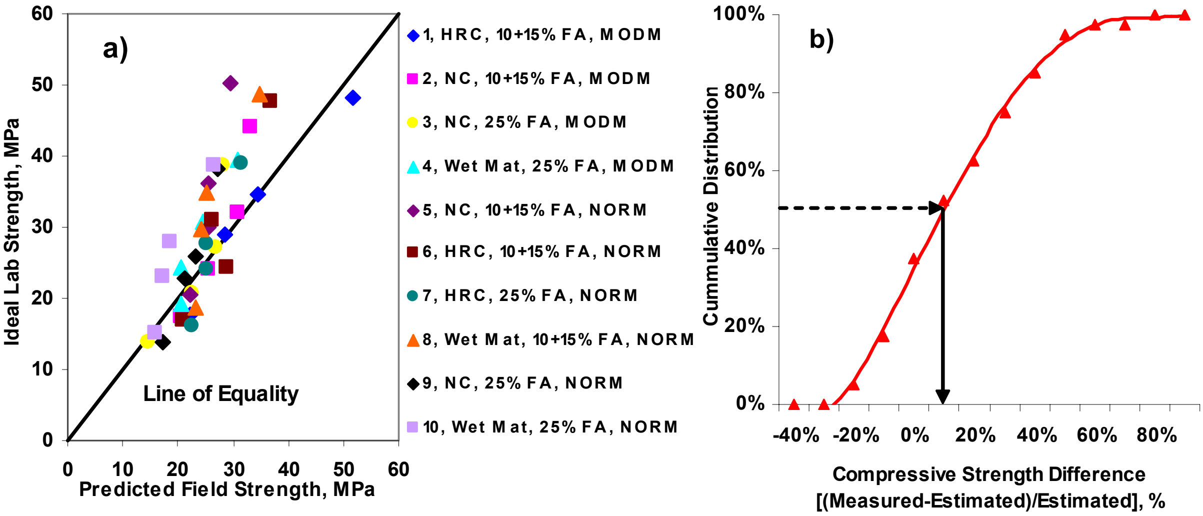

Figure 4. *Comparison of in-place strength with lab-cured specimens and differences between strengths measured on lab-cured specimens and estimated from field tests*

5. Conclusions

The differences between the strengths from lab-cured specimens and those measured on in-place slabs are discussed here. Ten newly-constructed concrete sections with different mix designs, curing methods and mixing sequences were evaluated to quantify these differences.

Estimated field strengths were typically lower than those measured on lab-cured specimens prepared at the site with the same mixes. On average, differences of 15% were observed. Differences in curing conditions between the lab specimens and the in-place material might explain these discrepancies.

Acknowledgements

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References

1. Malhotra, V. M. and Carino, N.J., (1990), “Handbook on Nondestructive Testing of Concrete,” CRC Press, Baco Rotan, FL.
2. Nazarian, S., Yuan, D., Smith, K., Ansari, F., Gonzalez, C., “Acceptance Criteria of Airfield Concrete Pavement Using Seismic and Maturity Concepts. “Innovative Pavement Research Foundation, Airport Concrete Pavement Technology Program. Report IPRF-01-G-002-02-2, May 2006.
3. Yuan D., Nazarian S. and Zhang D. (2003), “Use of Stress Wave Technique to Monitor and Predict Concrete Strength Development,” Airfield Pavement: Challenges and New Technologies, Proceedings of the Specialty Conference, Edited by Moses Karakouzian, ASCE, 2004, pp. 409-423.
4. Richart, Jr., F.E., Woods, R. D., Hall Jr., J.R. (1970), “Vibrations of Soils and Foundations,” Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
5. Alexander, D. R. (1996), "In Situ Strength Measurements with Seismic Methods,” Report from US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi for the US Air Force Civil Engineering Support Agency, Tyndall AFB, Florida.
6. Ramaiah, S., Dossey, T., McCullough, B.F. (2001), “Estimating In Situ Strength of Concrete Pavements Under Various Field Conditions,” Research Report 1700-1, Center for Transportation Research, The University of Texas at Austin.