Use of Maturity and Pulse Velocity Techniques To Predict Strength Gain of Rapid Concrete Pavement Repairs During Curing Period

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Rapid strength gain concrete repair mixtures that cure within 4 to 12 hr were used to carry out full-depth slab repairs on a section of Interstate highway. The mixtures included a calcium-chloride accelerated mix, a very early strength mix developed by the Strategic Highway Research Program, and a "fast-track" mix previously used for early opening of concrete intersections. Before carrying out the repairs, job materials and mix designs were obtained and used to develop correlations between pulse velocity, maturity, and early strength of concrete. Maturity functions based both on Nurse-Saul and Arrhenius (equivalent age) approaches were developed. To account for heat rise of the concretes in actual sections, laboratory correlations were carried out by curing test cylinders in a specially insulated curing box. Pulse velocity and maturity functions were used to predict in situ strength gain of concrete in instrumented test repair sections. Temperatures were monitored through the depths of the test slabs during the initial 8 hr of curing. Temperatures at mid-depth ranged from 60°C to 70°C (140°F to 160°F) for these mixes. After 4 hr of curing, the very early strength mix exceeded 14 MPa (2,000 psi) compressive strength, as determined by in situ methods. The other two mixes gained strength at a slower rate.

In recent years, early opening of concrete pavements to traffic has been given much emphasis. As documented in a synthesis (*1*) published by the Strategic Highway Research Program (SHRP), many recent developments in materials and processes for concrete paving focus on early opening. "Fast track" technology (*2*) allows concrete pavements to be constructed or repaired and opened to traffic within 4 to 24 hr. That is especially useful when full depth pavement repairs are being carried out along critical segments of highway where traffic disruption must be kept to a minimum.

In recognition of the importance of this technology, FHWA initiated a demonstration project on accelerated rigid paving techniques in 1988 to promote the development of fast track techniques. Several pilot projects have been completed with the assistance of the FHWA under this program. As a result of these advances, many states now allow early opening when fast track mixes are used (*3*). The high-early strength gain typically is obtained by using high cement content, a low water to cement ratio, and accelerating admixtures. A rich, low-water-content mix containing 1 to 2 percent calcium chloride produces adequate strength and abrasion resistance for opening to traffic in 4 to 5 hr at temperatures above 10°C (50°F) (*4*). Accelerators are added at either the ready-mix plant or at the jobsite, depending on the temperature and distance to the plant. Other admixtures commonly used in repair mixes include air-entraining agents, water-reducers, and superplasticizers.

Concrete used for rapid repair applications must meet minimum strength levels before the pavement can be opened to traffic. To obtain on-site estimates of strength gain rapidly, in situ techniques for strength measurement are very helpful, as it is not necessary to remove cores from the pavement—a time-consuming and destructive process.

A variety of methods for in situ strength measurement is available (*5*). Two methods that are widely used, pulse velocity measurements and maturity monitoring, were chosen for evaluation in this research program.

The use of ultrasonic pulse velocity measurements is described in the ASTM standard test method for pulse velocity through concrete. The method involves measuring the travel time of an ultrasonic pulse passing through concrete. Pulses are generated by an electro-acoustical transducer held in contact with one surface of the concrete being tested. The pulses are received and converted into electrical energy by a second transducer located a distance L from the transmitting transducer. The transit time is measured electronically, and the direct path length, L, between the transducers is divided by the travel time to obtain the pulse velocity through the concrete. Pulse velocity is proportional to the square root of the elastic modulus and inversely proportional to the square root of the density of concrete. Assuming the elastic modulus is proportional to the square root of compressive strength, pulse velocity is proportional to the fourth root of compressive strength.

Maturity monitoring is based on the fact that strength of concrete is the result of a chemical reaction (hydration) between cement and water. Because the rate of hydration depends on temperature, the strength of concrete may be evaluated from the concept of maturity, which is expressed as a function of time and curing temperature (*6*). By monitoring concrete temperature after casting, maturity can be calculated and compressive strength estimated—if a relationship between maturity and compressive strength for a given mixture has been established previously.

Maturity is most often calculated by the formulas first developed by Nurse (*7*) and Saul (*8*).

$$M(t) = \Sigma (T - T_o) \Delta t \quad (1)$$

Where

$M(t)$ = maturity at age t, degree-days or degree-hours;
Δt = time interval, days or hours;

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T = average concrete temperature during time interval (Δt, °C); and
T_o = datum temperature (°C).

Datum temperature is the temperature at which concrete ceases to gain strength in time (hydration stops). Datum temperature reportedly ranges from −10.6°C to 0°C (14°F to 32°F) but could fall outside that range depending on the specific materials used. The formula is based on the assumption that maturity increases linearly with temperature. However, it is known from chemical reaction kinetics that the rate of chemical processes increases with temperature, not linearly, but exponentially, according to the Arrhenius equation.

$$K = A \cdot \exp\left(\frac{-E}{RT}\right) \quad (2)$$

where

K = rate constant (1/time),
A = constant (1/time),
E = activation energy (J/mol),
R = gas constant (J/°K·mol), and
T = temperature (°K).

Based on this equation, the variation in maturity or the "equivalent age" at specified temperature can be computed (*9*)

$$t_e = \Sigma \exp -Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)\Delta t \quad (3)$$

where

t_e = equivalent age at a specified temperature T_s, days or hours,
Q = activation energy divided by the gas constant, °K,
T_a = average temperature of concrete during time interval Δt, °K,
T_s = specified temperature, °K and
Δt = time interval, days or hours.

Equations 1 and 3 are considered in ASTM standard practice for estimating concrete strength by the maturity method C 1074. To estimate the in-place strength of concrete in highway or other structures on the basis of maturity concepts, the concrete temperature should be monitored continuously, and the in-place maturity computed using either the temperature-time factor (Equation 1) or equivalent age (Equation 3). Temperature monitoring starts as soon as practicable after concrete placement; according to ASTM (C 1074), the recording time interval should be ½ hr or less for the time 48 hr, and 1 hr or less thereafter.

SCOPE OF INVESTIGATION

Field Site Description

A test site for installation of full-depth pavement repairs was located on I-20 west of Augusta, Georgia, between Mileposts 189 and 192. Test sections were added to a contract that was in progress for the full-depth repair of working cracks on I-20 in that vicinity. The project involved making full-depth repairs on existing 230-mm (9-in.) thick jointed plain concrete pavement with 9-m (30-ft) joint spacing. Repair lengths varied from 2 to 9 m (6 to 30 ft). Ongoing repairs were carried out each night, and the state required the road to be opened by 6 a.m. each morning. Work involved full-depth saw cutting, removal of the slab by lift-out, drilling of dowel holes by automatic ganged dowel bar drills, and dowel insertion and epoxy grouting. Plastic grout-retention disks were used. Approximately 20 patches were made each night. Concrete deliveries started about 10 p.m. and continued until about 2 a.m. Investigators used the first patch of each night for their main materials test program (*10*) allowing all testing and coring to be carried out before opening the highway.

Concrete Materials and Mixes

Materials used for pavement repair mixes at this site consisted of: (*a*) Type I and III cements; (*b*) an angular quartz natural sand having specific gravity of 2.68, absorption of 0.56 percent, and FM of 2.62; and (*c*) a crushed siliceous natural gravel having a maximum topsize of 19 mm ¾ in.), specific gravity of 2.66, and absorption of 0.5 percent. Admixtures included: (*a*) a chloride-free (nitrite-based) Type C accelerator, (*b*) an organic-acid salt-based air-entraining agent (*c*) a lignosulfonate-based Type A water reducer (*d*) a melamine-base Type F high-range water reducer, and (*e*) a 40 percent solution of calcium chloride.

Mixes used for the repairs are presented in Table 1. "Very Early Strength" (VES) concrete was developed by the investigators on an SHRP project (*11*) with the objective of opening concrete pavements approximately 4 to 6 hr after placement. "Fast Track I" was developed originally by Iowa DOT (*3*) for opening times of 12 to 24 hr. Finally, the mix being used by the contractor on the I-20 repair project, which was designed for opening 4 hr after placement of the last patch, was designated "GADOT" by the investigators.

Laboratory Correlations

Before carrying out the field experiment, representative materials were shipped from the Georgia ready-mix concrete supplier to the investigators' laboratories for preparation of trial batches. Mix quantities were adjusted to achieve the desired opening strengths [13.8 MPa (2,000 psi)] at 4 hr for VES and 13.8 MPa (2,000 psi) at 12 hr for fast track. Because the GADOT mix could not be changed, the mix was prepared using the supplied design. Compressive strengths of only 2.75 MPa (400 psi) were recorded for the GADOT mix after 4 hr, and the 13.8 MPa (2,000 psi) level was reached at 8 hr under laboratory curing conditions. However, it was noted during the subsequent field trials that the mix temperatures in Georgia were higher than 32 °C (90°F), which would tend to increase early strengths over those recorded in the room-temperature lab trial mixes. In all cases, cylinders were stored in an insulation box (*12*) constructed out of expanded polystyrene, which was cored to accept individual 100 × 200-mm (4 × 8-in.) cylinders immediately after casting. Each box holds a maximum of 28 such cylinders. This process served to simulate curing in a thick section of pavement.

A series of "correlation" batches was produced. From these batches, cylinders were cast to establish maturity relationships and relationships between pulse velocity and compressive strength. Mortar cubes also were prepared by wet screening mortar from the concrete batches from which datum temperature and activation energy were determined following ASTM C 1074 procedures. Temperatures monitored in the cylinders during curing in the insulation box were used to calculate maturity at the curing times chosen for the calibration: 4, 6, 8, 15, 18, 20, and 24 hr. Compressive strengths were determined also on the cylinders at these preselected times. For details of the maturity procedures, one is referred to the ASTM C 1074 method. Pulse velocity was determined on 100 × 200-mm (4 × 8-in.) cylinders using a commercially available pulse generator operating at 54kHz. Compressive strengths of the test cylinders were then determined after obtaining pulse velocity readings at the selected curing times noted previously.

Regression analyses were performed on each of the nine sets of data (i.e., three concrete mixes times three predictors). Various data transforms were applied to each data set to maximize the fit of the transformed relationships to a linear equation. Predictive equations developed by these techniques are presented in Table 2. The equations represent the best linearized fits obtained for each data set. Maturity values (MAT) for the Nurse-Saul approach were obtained using Equation 1, those for the Arrhenius predictor were obtained using Equation 3.

Field Instrumentation

After the first slab was removed each night, the open hole was instrumented to allow in-place testing to be carried out. Instrumentation for maturity monitoring consisted of a thermocouple tree containing thermocouples placed at depths of 13, 130, and 230 mm [0.5, 5 (i.e., mid-depth), and 9 in.] below the surface of the pavement. The thermocouple tree was positioned approximately 305 mm (12 in.) from the slab edges to minimize edge cooling effects. Additional thermocouples were placed in ambient air and in one of the test cylinders contained within the insulated curing box. Temperatures were monitored every 30 min using a portable datalogger. An average through-slab temperature was computed for each temperature increment for purposes of strength prediction from the maturity equations.

To facilitate pulse velocity measurements, expanded polystyrene blocks 152 × 152 mm (6 × 6 in.) in dimension were staked to the grade 200 mm (8 in.) apart. After the concrete had reached final set,

TABLE 1 Mixes Used at I-20 Full-Depth Pavement Repair Site

Material - Cubic Meter Basis	VES	Fast Track	GADOT
Cement (kg)	516[a]	439[a]	446[b]
Fine Aggregate (kg)	490	783	608
Coarse Aggregate (kg)	1,020	843	1,071
Water (kg)	199	155	169
Water reducer (ml)	(—)	1,301	(—)
Accelerator (L)	22.7	(—)	(—)
$CaCl_2$ solution (L)	(—)	(—)	6.0
HRWR (ml)	1,286	(—)	(—)
AE agent (ml)	1,286	355	290
w/c ratio	0.39	0.35	0.38

[a]Type III cement used.
[b]Type I cement used.
(—) Material not used in this mix.
Note: 1 m^3 = 1.308 yd^3 ; 1 kg = 2.205 lb ; 1 L = 0.264 gal ; 1 ml = 0.0338 fl.oz.

TABLE 2 Developed Predictive Relationships for I-20 mixes

Mix	Predictor	Equation	R^2
VES	Pulse Velocity	$\log f'c = 1.27 \times 10^{-4}\,PV + 1.844$	0.98
	Nurse-Saul	$1/f'c = 0.062/MAT + 1.72 \times 10^{-4}$	0.99
	Arrhenius	$1/f'c = 6.06 \times 10^{-3}/MAT + 1.68 \times 10^{-4}$	0.99
Fast Track	Pulse Velocity	$\log f'c = 5.47 \log PV - 19.09$	0.99
	Nurse-Saul	$f'c = -22.69 \times 10^{3}/MAT + 5161$	0.99
	Arrhenius	$f'c = -59.44 \times 10^{3}/MAT + 5163$	0.99
GADOT	Pulse Velocity	$1/f'c = 30.48PV - 1.91 \times 10^{-3}$	0.99
	Nurse-Saul	$\log f'c = -203.4/MAT + 3.717$	0.97
	Arrhenius	$\log f'c = -6.762/MAT + 3.705$	0.98

the blocks could be removed to leave square cavities in which to place an ultrasonic transmitter and receiver. As was done with the thermocouple trees, the blockouts were positioned away from slab edges to minimize edge cooling effects. The pulse velocity transmitter and receiver were placed at mid-depth of the slab in the cavities in order to obtain the direct transmission pulse velocity readings.

FINDINGS AND DISCUSSION

Temperature Development in Test Slabs

To estimate strength gain from maturity data, the temperature of the patches was monitored throughout the period of cure. Temperature profiles for the VES slab are shown in Figure 1. It can be seen that the mid-depth of the slab reached the highest temperatures at any point during the monitoring, as would be expected from the relatively stable nighttime air temperature range of 21°C to 26°C (70 °F to 80 °F), which allowed heat to escape from the top of the slab. The insulated cylinders at first lagged the slab, but then gained in temperature and eventually exceeded the slab temperature. About 5 hr after placement, the slab temperature stabilized at about 60°C (140°F) and then began to go downward, whereas the insulated cylinder temperature continued to rise to close to 70°C (160°F). Temperature profiles for the fast track slab are shown in Figure 2; peak temperatures are about 10°C (20°F) cooler than for the VES mix. That is to be expected considering the lower cement content and absence of accelerating admixtures. The fast track mix took longer to reach its peak (5.5 hr as opposed to 4 hr for VES). Again, the insulated box temperatures continued to rise after the slab had reached peak temperature. Finally, temperature profiles for the GADOT mix are shown in Figure 3. Peak temperature of 50°C (122°F) at 4 hr is very similar to that of the fast track mix.

Strength Gain Prediction Using Maturity and Pulse Velocity Techniques

Temperature data acquired from the test sections were used to develop plots of time versus predicted compressive strength using maturity and pulse velocity predictive functions (Table 2). Note that the strength that is predicted will be dependent on the location within the slab from which the temperature data are taken. As compressive strengths were to be compared with cores taken through the depth of the pavement, an average through-depth pavement temperature was calculated at each time increment. Two 100 × 200-mm (4 × 8-in.) cores were removed from each of two of the three test sections for field testing and comparison with predicted values. It was not possible to remove cores from the GADOT section, as construction activities prevented coring operations at this location.

Predictions of early compressive strength for the three mixes, VES, fast track, and GADOT are shown in Figures 4–6, respec-

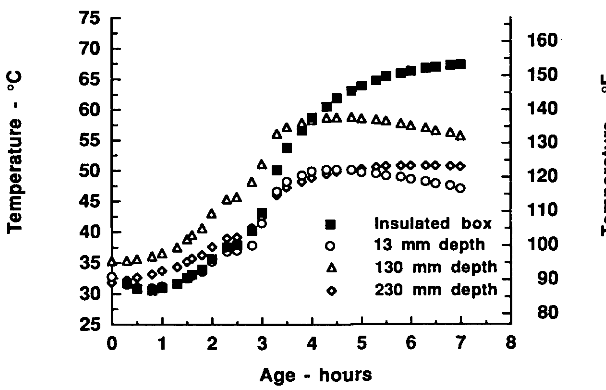

FIGURE 1 Temperature profiles for VES mix.

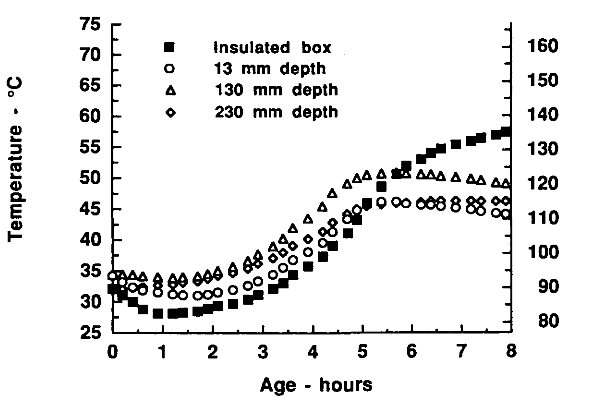

FIGURE 2 Temperature profiles for fast track mix.

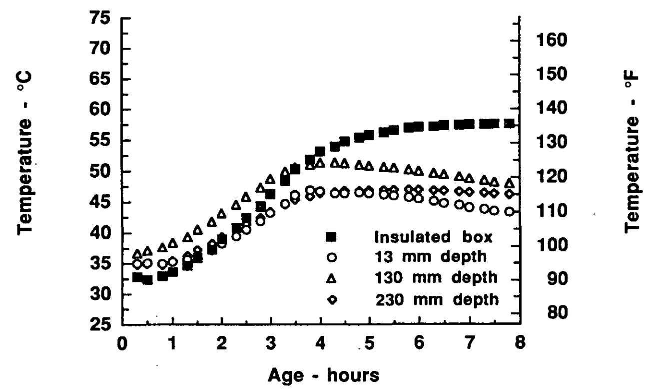

FIGURE 3 Temperature profiles for GADOT mix.

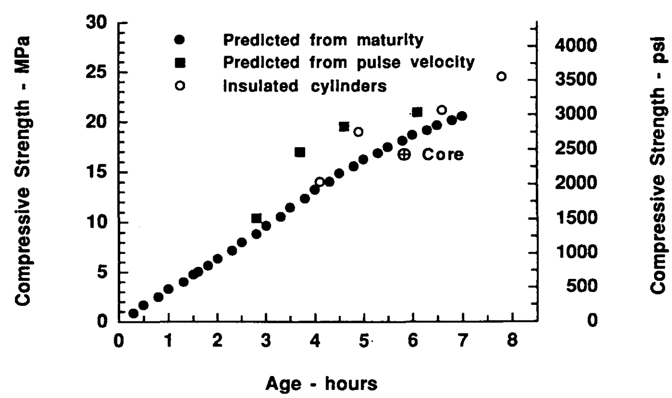

FIGURE 4 Compressive strength predictions for VES mix.

tively. Strengths predicted via maturity are shown for the approach (Equation 1 or 3) yielding the best prediction as measured by cores extracted from the test sections. For VES, the Nurse-Saul function (Equation 1) gave predicted values closest to core strengths. For fast track, the Arrhenius function (Equation 3) was more successful. Finally, for the GADOT mix, although no comparison core data were available, strengths predicted via the two approaches were within an average of 5 percent of each other. In addition to strengths predicted via maturity and pulse velocity, the strengths of cylinders stored in the insulated curing box are also presented.

For the VES mix (Figure 4) strengths predicted by maturity calculations were similar to strengths predicted by pulse velocity at early ages, but lower than both the pulse velocity predicted strengths and the strengths measured on cylinders taken from the insulated curing box at later times. At the time selected for sampling from this section (5.8 hr after casting), strength predicted from maturity was 18 MPa (2,600 psi) and that from pulse velocity was 20 MPa (2,900 psi). These values are 6 and 20 percent higher, respectively, than the measured core strengths of 17 MPa (2,450 psi). The somewhat higher strength predicted by the pulse velocity technique is reasonable, as pulse velocity transducers were placed near the middle of the pavement [a 130-mm (5-in.) depth], where the higher temperatures (Figure 1) would lead to a higher local strength at that elevation.

Similar data for the fast track mix are presented in Figure 5. There is a large discrepancy between the techniques at ages up to 8 hr. In fact, up to about 6 hr the maturity function predicts that the concrete will not gain any strength, although the ability to obtain pulse velocity readings on the actual slab indicates that the concrete as-placed was indeed gaining strength during that time. The reason for this most likely relates to the procedure used in the laboratory to establish the maturity function for this mix. As the fast track mix was placed into the 12- to 24-hr opening category in terms of the overall SHRP research project, initial strength measurements made for purposes of developing the maturity function (Arrhenius) were not obtained until after 12 hr of curing. Therefore, it appears that although the function should be applicable to all time/temperature combinations in theory, in actual practice, its range of applicability may be more restricted. Eight hr after casting, however, the methods tend to converge. At the time of sampling (7.8 hr) core strength was 8 MPa (1,150 psi), strength predicted by maturity was 7.6 MPa (1,100 psi), and strength predicted by pulse velocity was 10 MPa (1,450 psi). Again, as for the VES mix, the best predictor of strength appears to be the maturity function, as the core strength lies exactly on the line of prediction.

Finally, Figure 6 shows data developed on the GADOT mix. Here again, maturity predicts somewhat lower strengths at early ages, but after about 5 hr all methods fall within the same general band. Unfortunately, as previously noted, cores could not be retrieved from this slab.

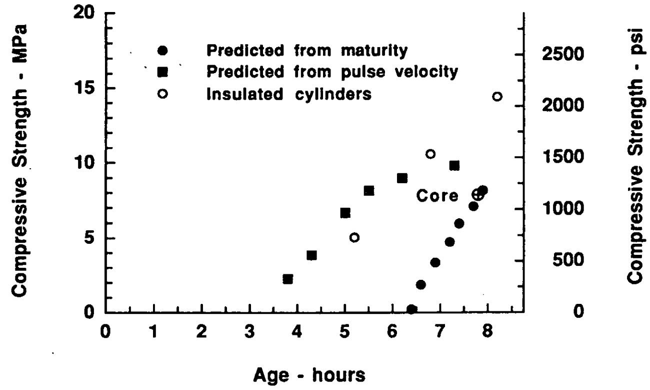

FIGURE 5 **Compressive strength predictions for fast track mix.**

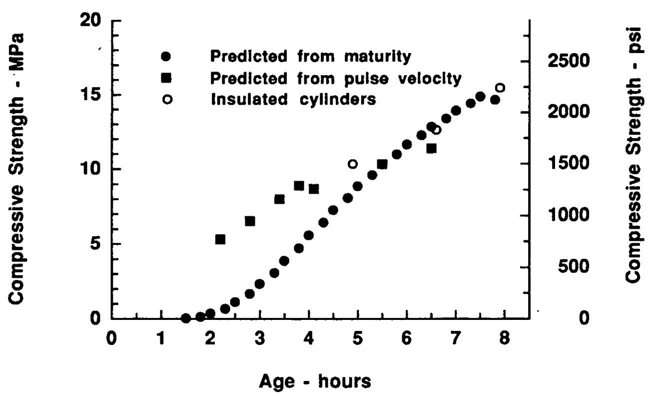

FIGURE 6 **Compressive strength predictions for GADOT mix.**

CONCLUSIONS

Based on the results of the study described in this paper the following conclusions may be drawn:

- NDT readings must be calibrated to strength before construction. Strength as a function of NDT reading must be established using job materials and proposed mix designs. Changes in mix design or materials during construction can lead to significant predictive errors.
- Both maturity and pulse velocity techniques can be used to monitor early strength gain during the curing period in pavement repair slabs. Results obtained using these techniques agree favorably with strengths of cores extracted from repair sections before opening to traffic.
- The maturity approach offers a more exact prediction of strengths close to time of opening. At earlier ages, however, the maturity approach appears to significantly underestimate strength in some instances.
- Both techniques employed in this study are practical and well suited to field operations. However, significant amounts of calibration must be done in the laboratory before either method is used on a particular job. It is likely then, that the methods will have their greatest application on larger and longer-term projects for which the same mix is repeated many times and rate of strength gain must be verified in the field.

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