Nondestructive Testing of Concrete Pavements

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One of the principal factors considered in the determination of allowable wheel loads for existing rigid pavements by Corps of Engineers procedure is the flexural strength of the concrete. Since speed is of vital importance in the success of a military mission, and because use of available cutting and testing equipment is slow and laborious, an investigation was conducted to determine the suitability of an instrument, the electronic interval timer, for use as an expedient nondestructive means of flexural strength determination.

Longitudinal wave velocities through a selected group of concrete test beams and through a slab in situ were determined with the interval timer, and flexural strength values were predicted by application of appropriate formulas. Actual flexural strengths of the test beams and of beams cut from the slab were determined by conventional technique, and these results are compared statistically and practically with the predicted values.

The validity of a general correlation between dynamic modulus of elasticity and flexural stength of concrete is briefly reviewed. Additional related information pertinent to the use of the interval timer is discussed.

It was concluded that: (1) the electronic interval timer is capable of providing results of practical utility for expedient rigid pavement evaluation as recommended by the Corps of Engineers; (2) accuracy of flexural strength determinations of unreinforced concrete with the electronic interval timer is well within the accuracy of a suggested correlation between dynamic modulus and flexural strength; and (3) further investigation of the utility of nondestructive testing techniques for pavement evaluation is warranted before its full potential or specific limitations can be established.

● THE study of the properties of concrete by sonic or dynamic testing has, in the past few years, attracted the interest of many investigators. Similarly, the development of several instruments capable of measuring dynamic properties has vastly broadened the scope of nondestructive testing of concrete. One such instrument, the electronic interval timer, developed by Henry J. Kurtz has been found suitable for determining the traveling time of a longitudinal or compressional wave between two given points. Thus, the pulse velocity through an assumed isotropic and elastic medium such as concrete may be determined, and by means of appropriate formulas a value called the "dynamic modulus of elasticity" may be obtained.

Further, Jones (*4*), Munger (*6*), Anderson and Nerenst (*1*), Long, Kurtz, and Sandenaw (*5*), and other investigators have attempted to correlate dynamic *E* with modulus of rupture or flexural strength of concrete. Results of these studies indicate a rather general and broad relationship between the two values, especially when properties of aggregates, mix proportion, and curing conditions are unknown. Thus, it is generally agreed that no precise prediction may be made concerning flexural strength of an "unknown" concrete specimen by dynamic means.

Evaluation of concrete pavements (allowable wheel load determination) for an existing rigid pavement by use of Corps of Engineers' evaluation curves (*2*) is based on consideration of three factors: (a) concrete slab thickness, (b) subgrade or base course modulus, and (c) flexural strength of the concrete. Current procedures for measuring flexural strengths involve sampling and cutting beams from representative slabs and conducting conventional destructive tests. Available sampling and testing machines are extremely bulky and evaluation by such means is slow and laborious, and not to be desired in military application where speed and ease of operation are essential requirements. A method for evaluation of concrete pavements in situ by measuring the velocity of a sonic impulse through the material has been under study by the Ohio River Division Laboratories, CE, for several years. The purpose of the investigation reported here was to study the effectiveness of the electronic interval timer for flexural strength determination, suitable for expedient pavement evaluation as recommended by the Corps of Engineers.

DESCRIPTION OF APPARATUS

The timer consists primarily of, (a) two similar crystal cartridge pickups and amplifiers, (b) two similar thyratron tube circuits, (c) condenser and vacuum tube voltmeter circuit, and (d) batteries (see Figure 1). The complete unit is assembled in a 17- by 19- by 18-in. carrying case and weighs about 50 lb., thus affording excellent portability characteristics.

Briefly, the instrument operates as follows: Pickups 1 and 2 are actuated in turn by a wave impulse initiated by striking the concrete with a hammer in line with the two pickups. A voltage generated in the first pickup is amplified and "fires" a thyratron tube which starts a flow of constant current into a condenser. When the same wave impulse passes the second pickup, the current passing through the condenser is reduced to zero. The amount of residual charge on the condenser is then directly proportional to the time required for the wave to travel the distance between the two pickups. The time interval, expressed in micro-seconds, is obtained by reference to a calibration curve accompanying the instrument. A more detailed discussion of the fundamental principles of the interval timer has been presented by Kurtz (*5*) and needs no further explanation here. Although several modifications and improvements have since been incorporated in later model Interval Timers, the basic instrumentation has not been changed.

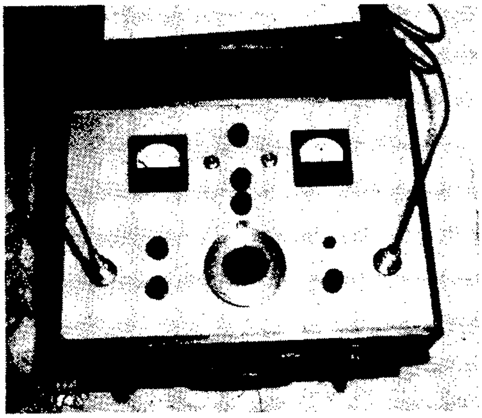

Figure 1. Electronic interval timer.

DETERMINATION OF FLEXURAL STRENGTH

Using the values of wave transmission times obtained with the electronic interval timer, the longitudinal wave velocity through the concrete may be determined. In this investigation, the wave velocities were determined graphically in all instances. By this method corresponding values of pickup spacing (in feet) and transmission time (in micro-sec.) are plotted, and a straight-line curve drawn through the points, such that the vertical distances from the points to the line are as small as possible. The slope of this line represents the average longitudinal wave velocity in feet per second.

The dynamic modulus of elasticity was computed on the basis of longitudinal wave velocity by the following expressions:

$$E_d = V^2\rho \qquad \text{(for beams)}$$

and

$$E_d = V^2\rho(1 - \mu^2) \qquad \text{(for pavements)}$$

where E_d = dynamic modulus of elasticity (lb. ft./sec.^{2} ft.^{2})

V = longitudinal wave velocity (ft./sec.)

ρ = density (lb./ft.^{3})

μ = Poisson's ratio, assumed to be 0.20 in accordance with Corps of Engineers design recommendation (*3*).

The value of E_d may be expressed in psi by multiplying by a conversion factor of 2.16×10^{-4}.

Flexural strength values corresponding to

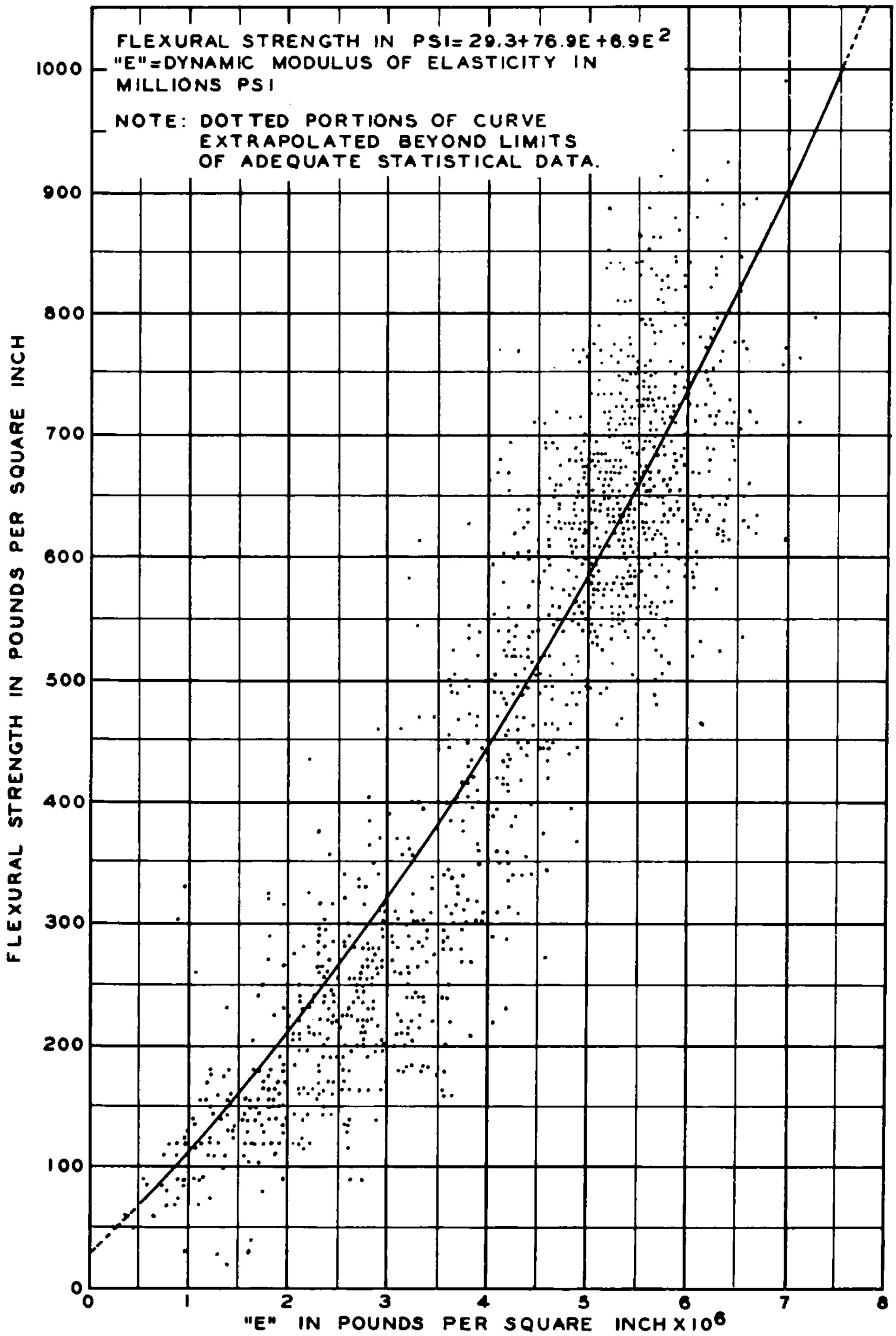

Figure 2. Relationship between dynamic modulus of elasticity (*E*) and flexural strength of concrete beams.

E_d were obtained from the relationship shown in Fig. 2. The curve corresponds to the formula:

$$R = 29.3 + 76.9\,E_d + 6.9\,E_d^2$$

where R = flexural strength (psi)

E_d = dynamic modulus of elasticity in millions psi

This relationship was obtained from a statistical analysis of 1400 concrete beam specimens by Kurtz (*5*), relating E_d values determined by flexural resonance with corresponding flexural strength values determined by third-point loading. It is noted that a large spread of strength values exists for a given E_d, represented statistically by a probable error of 70 psi.

INVESTIGATION

Three phases of tests were conducted during the course of the investigation. The first tests were basically for familiarization, conducted to develop a testing technique, as well as to establish a procedure for field utilization of the Interval Timer. In order to determine a technique would would afford reliable wave velocity determinations, the effects of several variable factors were investigated and the following results noted:

Direction of impact

The propagation of the required longitudinal wave is dependent on the direction toward which the impact is delivered. With the pickups in position on a concrete slab, the direction of impact was varied from a blow parallel to the top of the slab (in line with the pickups) to a vertical blow applied on the slab surface. Readings did not vary more than 5 micro-sec. at a given pickup spacing with a parallel blow, but became extremely erratic, varying as much as 100 micro-sec. as the direction of blow was varied toward the vertical. This may be explained by the fact that transverse wave forms, or complex combinations of transverse and longitudinal waves, are introduced as the direction of impact changes, and it is these wave fronts which activate the timer pickups.

Force of impact required

By varying the impact force from a light tap to a heavy blow, the effects of this variable were determined. Since the shape of the wave front depends on the force of impact, decreasing impact energy causes a decrease in amplitude, with noticeably increased time readings. This was evident when readings were attempted with very light blows. As the force of blow was increased, readings became more consistent, until a point was reached where further increase did not affect successive readings. Extremely heavy blows caused crumbling of the concrete, which also increased time readings. Thus, it is necessary to determine the force required by trial for a given type of concrete.

Additional information useful in determining a useable technique such as other methods to create wave front, and orientation and spacing of pickups was obtained but will not be elaborated on in this presentation.

The second series of tests was conducted with the electronic interval timer on three groups of concrete test beams to compare values of flexural strengths predicted with the interval timer with results obtained by conventional test methods. All beams were cast in wooden molds, 6- by 6- by 72-in., and were prepared in accordance with ASTM designation C31-49. The specimens were removed from the molds after three days and buried in wet sawdust for an additional 25 days prior to testing. Table 1 shows the design mix

TABLE 1
CONCRETE MIX PROPERTIES

Test Group	Mix by Weight			W/C Ratio by Weight	Slump (inches)	Description of Materials
	Cement	Sand	Gravel			
I	1.00	3.08	4.43	0.71	2	Normal Portland Cement; Poorly graded Belvoir sand and gravel (rounded) with excess fines present; 1 in. maximum size aggregate.
II	1.00	2.13	3.07	0.53	1	Same as Test Group I.
III	1.00	1.62	2.27	0.40	1	Normal Portland Cement; Well-graded Warrenton crushed stone (angular), ¾″ maximum size aggregate; Medium-graded Belvoir sand with excess fines removed.

and type of materials used in preparing the beam specimens for each group.

Tests on beams of Groups I and II were conducted as follows: (1) Beams were placed on a level section of soil subgrade. (2) Pickups were placed on the beam, with the first pickup 1 ft. from the point of impact, and the second pickup varied from 1 to 5 ft. from the first pickup. (3) Interval timer readings were taken with an impact produced by placing a ¾-in.-diameter rounded bar against the end of the beam and striking the bar with a hammer. (4) Interval timer readings were taken with a pendulum device designed to afford repetitive impact forces. (5) The beam was placed on a layer of thick sponge rubber

TABLE 2

COMPARATIVE TEST RESULTS OF PLAIN CONCRETE BEAMS

Beam No.	Side	Density (lb/ft^3)	Flexural Str (psi) 3rd-Pt. Load	Electronic Interval Timer Results								
				Impact with Hammer and Punch (Beam on Soil Base)			Reproducible Impact (Beam on Soil Base)			Reproducible Impact (Beam on Sponge Rubber)		
				Vel. (ft/sec)	Dyn. E ($\times 10^6$ psi)	Flex Str (psi)	Vel. (ft/sec)	Dyn. E ($\times 10^6$ psi)	Flex Str (psi)	Vel. ft/sec)	Dyn. E ($\times 10^6$ psi)	Flex Str (psi)
I-1	A	145.0	428	11,330	4.02	450	11,270	3.98	444	11,200	3.94	440
	B		398	10,940	3.75	414	11,330	4.02	450	11,270	3.98	444
	C		415	11,270	3.98	444	11,200	3.94	440	11,430	4.09	458
I-2	A	145.0	407	11,110	3.86	428	11,090	3.85	426	11,010	3.80	420
	B		397	11,200	3.94	440	11,130	3.88	432	11,230	3.95	440
	C		362	11,010	3.80	420	11,110	3.86	428	11,050	3.82	421
I-3	A	143.0	495	11,950	4.41	500	11,600	4.16	467	11,660	4.20	472
	B		434	11,370	4.00	446	11,430	4.04	452	11,600	4.16	467
	C		421	11,200	3.94	440	11,140	3.84	425	11,010	3.75	413
I-4	A	145.0	456	11,400	4.07	456	11,430	4.09	458	11,400	4.07	456
	B		444	11,230	3.96	441	11,210	3.94	439	11,370	4.04	452
	C		439	11,050	3.82	422	11,050	3.82	422	11,170	3.90	433
I-5	A	145.5	488	11,700	4.28	484	11,460	4.11	460	11,500	4.14	464
	B		486	11,430	4.10	459	11,500	4.15	466	11,300	4.00	446
	C		456	11,030	3.81	421	11,140	3.89	432	11,300	4.00	446
II-1	A	147.5	506	12,100	4.66	536	12,400	4.88	568	12,400	4.87	568
	B		542	11,950	4.55	522	11,500	4.20	472	11,700	4.36	496
	C		568	11,950	4.55	522	12,400	4.88	568	12,500	4.96	580
II-2	A	145.5	504	12,160	4.63	533	12,200	4.65	535	11,950	4.47	510
	B		475	11,830	4.40	500	12,200	4.65	535	11,950	4.47	510
	C		451	11,900	4.45	507	12,200	4.65	535	11,700	4.30	486
II-3	A	146.0	468	11,900	4.45	507	12,200	4.67	536	12,000	4.53	520
	B		489	12,150	4.65	535	12,050	4.57	524	11,900	4.45	506
	C		440	11,850	4.43	504	12,000	4.53	520	11,900	4.45	506
II-4	A	146.0	460	11,550	4.20	472	11,700	4.31	488	11,730	4.34	492
	B		458	11,900	4.46	508	11,700	4.31	488	11,860	4.44	506
	C		470	11,600	4.24	478	11,620	4.26	481	11,700	4.31	488
III-1	A	153.5	675	13,460	6.02	740	—	—	—	—	—	—
	B		685	13,460	6.02	740	—	—	—	—	—	—
	C		703	13,460	6.02	740	—	—	—	—	—	—
III-2	A	153.0	687	13,150	5.71	690	—	—	—	—	—	—
	B		758	13,110	5.68	685	—	—	—	—	—	—
	C		736	13,110	5.68	685	—	—	—	—	—	—
III-3	A	154.0	708	13,120	5.71	693	—	—	—	—	—	—
	B		693	13,370	5.95	730	—	—	—	—	—	—
	C		697	13,240	5.82	710	—	—	—	—	—	—
III-4	A	153.0	698	13,060	5.60	676	—	—	—	—	—	—
	B		719	13,420	5.91	724	—	—	—	—	—	—
	C		702	13,330	5.83	712	—	—	—	—	—	—
III-5	A	155.0	711	13,250	5.86	717	—	—	—	—	—	—
	B		755	13,560	6.15	762	—	—	—	—	—	—
	C		758	13,450	6.06	748	—	—	—	—	—	—

and readings taken using the pendulum device to create the pulse. (6) The above procedures were repeated on two other sides of the beam, affording results on the top, side, and bottom of each beam with respect to its position as molded. (7) The beams were sawed to 6- by 6- by 24-in. specimens and flexural strengths determined by the third-point loading technique in accordance with ASTM designation C78–49.

The procedure used to test beams of Group III was the same as described above, except that the method of creating the pulse was restricted to the use of the hammer and punch, and testing was accomplished on a soil base only. This was done because it soon became evident that no significant differences were created by use of the pendulum device or with the beam resting on a different base. A subsequent statistical comparison of the data verified this observation.

Comparative test results obtained from the plain concrete beam specimens are given in Table 2. Density determinations of each beam were obtained by comparison of normal and submerged weights of at least three samples obtained from each beam. The column of Table 2 headed "Side" distinguishes that area of the beam upon which the pickups were placed, with A, B, and C referring to the top, side, and bottom, respectively, of the beam with respect to its molded position.

Although not tabulated herein, two beams containing single ½-in.-diameter reinforcing rods were tested. An average increase of velocity of 4 to 6 percent over the average values obtained from beams of the same group without reinforcing was evident.

The third test phase was conducted on a concrete pavement slab to determine the ability of the interval timer to perform under field conditions, and to investigate its applicability for evaluation of pavement in situ. A concrete slab, 10 ft. by 13.5 ft. by 10 in. thick with no visible evidence of cracks, was used in the test, and three sets of Interval Timer readings were taken, with the pulse originating from each of three exposed sides of the slab. The average of five individual time readings at each pickup spacing was used in the velocity determination. Results of this test are shown in Table 3, along with comparative flexural strength values obtained from two beam specimens cut from the slab.

TABLE 3

RESULTS OF TEST CONDUCTED ON CONCRETE PAVEMENT SLAB*

Test Designation	Interval Timer Results			Flexural Strength (psi) (3rd-Point Loading)
	Vel. (ft/sec)	Dyn E ($\times 10^5$ psi)	Flex Str (psi)	
A	11,410	4.04	452	
B	11,580	4.17	468	
C	11,600	4.18	469	
Average values	11,530	4.13	463	487†

* Density determined as 150 lb per cu ft.

† Average of two beams with flexural strengths of 482 and 492 psi, respectively.

ANALYSIS AND DISCUSSION

To provide sufficient data for analysis, individual results obtained from testing each side of each beam were used, thus avoiding average beam values, which may differ appreciably from individual determinations. Any strength differences existing in a given beam with respect to its test position should be apparent in the results of both test methods used. Further, only the results obtained using the hammer method to create the pulse were used for comparative analysis, since the effects due to using the pendulum device and different base support were determined to be insignificant.

Inspection of the data shown in Table 2 indicates relatively good agreement between predicted values of flexural strength obtained from E_d and results of the third-point load test for the beam specimens. A graphical comparison of values obtained by the two methods is shown in Figure 3. The greatest individual difference between any predicted and beam break value is 16 percent.

A method of statistics is suggested to determine the extent of significant difference between the two test methods. Assuming a normal distribution of flexural strength differences between the two methods, a test of significance called the "t-test" may be used. Here the assumption is made that corresponding observations have the same value, apart from random variations, and that the differences between corresponding values (d_i) are assumed to be normally distributed with estimated variance S_d^2. The mean difference may be expressed as

$$\bar{d} = \frac{1}{n} \sum_{i=1}^{n} d_i$$

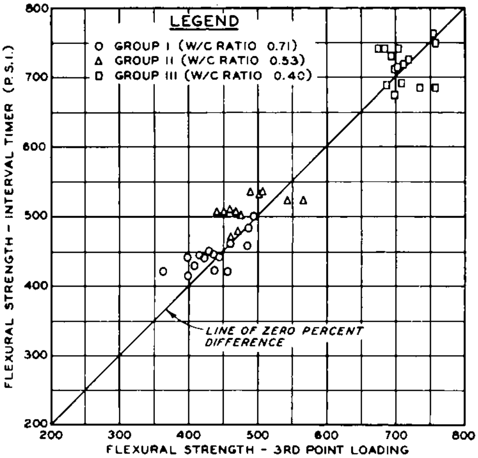

Figure 3. Comparison of predicted vs. actual flexural values of beam specimens.

where n = number of observations. The estimated variance then is

$$S_d{}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(d_i - \bar{d})^2$$

The form

$$t = \frac{\bar{d}}{S_d/\sqrt{n}}$$

has a t-distribution with $n - 1$ degrees of freedom. If the computed value of t is significant (level established as a probability of 5 percent with $n - 1$ degrees of freedom), then the assumption of equal corresponding values is rejected and a statistically significant difference exists between the two methods of observation. Applying this to the data:

$$\bar{d} = 12.0 \text{ psi (mean difference)}$$

$$S_d{}^2 = 1016.56 \text{ (estimated variance)}$$

whence

$$t = 2.44 \text{ (standard error units).}$$

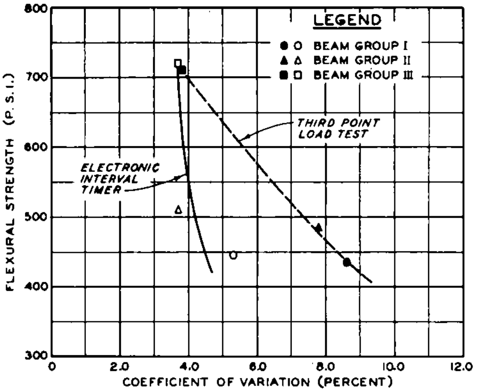

Figure 4. Coefficients of variation vs. average flexural strength values of beam groups I, II and III.

From a table of t-distribution values with 41 degrees of freedom, the probability of exceeding a deviation of 2.44 standard error units due to chance alone is only about 2 percent. Since this value is less than the critical probability of 5 percent, a statistically significant difference is suggested between results obtained by the interval timer and by the third-point loading method.

The probable error which can be expected is approximately 22 psi, which is a relatively small amount in comparison with the magnitude of flexural strengths existing in most airfield pavements. This value is well within the probable error of 70 psi indicated by Kurtz, and suggests validity of the general relationship of E_d and flexural strength to a degree useful for expedient pavement evaluation purposes.

To determine a measure of consistency of results, the coefficient of variation (ratio of the measure of variability to the arithmetical mean about which the variation occurs) was calculated for each of the three groups of beams, using predicted values of flexural strength obtained with the Interval Timer. Similarly, for comparison, the coefficients of variation were determined using values of flexural strength by the third-point loading test. These values are plotted against average beam group flexural strengths for both methods of test in Fig. 4. Although the curves shown are purely hypothetical they do indicate the general trend of reproducibility for each test method. It is of interest to note that, as the quality of the concrete becomes poorer, strengths obtained by the third-point load test show an increasingly greater variation from the mean than do results predicted with the interval timer. This might well be expected, however, since the strengths predicted on the basis of wave velocity are representative of average values over a given span of concrete, whereas the third-point load test will indicate the fiber stress at the weakest point of a much smaller portion of a span.

Since the field data were limited to a single slab, evaluation of the interval timer based on consideration of these data would not be justified. It originally was expected that the flexural strength of the concrete in the slab would be in the order of 600 psi or more. Repeated tests with the electronic interval timer indicated a much lower strength, and it was believed that the instrument was not affording correct wave traveling times. Upon removing and breaking two beam specimens, however, the actual strengths were found to average only 487 psi, a difference of 24 psi from the predicted strength of 463 psi. This represents an error of approximately 5 percent, which compares favorably with the previous results obtained from the laboratory beam specimens.

During the course of the investigation the interval timer was found to be effective in determining the presence of cracks in a section of pavement, including those not readily indicated by visual inspection. This knowledge is particularly useful as an indication of pavement condition based on consideration of slab defects. The effect of these cracks on interval timer readings is obvious. Any interruption of the impact-created longitudinal wave, such as that created by the presence of a crack, is reflected by an increased wave traveling time. Furthermore, a deep or wide crack may be differentiated from a shallow or narrow crack by a very great increase in traveling time, in most instances outside of the range of the interval timer, as compared to a considerably smaller increase in the case of a finer crack. Thus, an added utility of the interval timer for pavement evaluation may be realized.

CONCLUSIONS

It would be misleading to state that the electronic interval timer is capable of accurately determining the flexural strength of concrete about which there is little information. The fact that a statistically determined difference did exist between the predicted and actual measurements of strength for the beam specimens cannot be entirely neglected, the assumption being that the third-point loading test provides a satisfactory criterion. Similarly, the conclusion that the instrument is completely unsatisfactory for evaluation would be erroneous, since sufficient evidence was presented to indicate a good practical agreement between the two test methods. It therefore is concluded that, (a) the timer is capable of providing results of practical utility for expedient rigid pavement evaluation as recommended by the Corps of Engineers and (b) the accuracy of flexural strength determinations of unreinforced concrete with the interval timer is well within the accuracy of the suggested correlation between dynamic modulus of elasticity and flexural strength.

Further, the results obtained, although limited in scope, are believed to be indicative of the performance of the electronic interval timer. The results of this investigation have also indicated the highly controversial position currently existing in the field of nondestructive testing. It is therefore evident that further investigation of the utility of nondestructive tests and techniques must be made before its full potential or specific limitations can be established.

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DISCUSSION

C. A. **Anderson**, *Engineer, Ohio River Division Laboratories, Corps of Engineers, U. S. Army*—The paper describes excellent and very worthwhile laboratory work in evaluation of the electronic interval timer. There is considerable incentive for continuing this work and the practical field evaluation of the instrument, which is the subject matter of this discussion. The prime incentive for continuing is that comparative costs indicate that flexural strength determinations measured by the electronic interval timer at a field location, are about $\frac{1}{100}$ of the cost of the same information obtained by sawing beams from the pavement and testing them in flexure.

In practical field use of the timer, correlation tests have been made, (1) to test the accuracy of the instrument in measuring sonic velocities in concrete pavements, and (2) to directly compare pavement flexural strengths computed from timer measurements, with pavement flexural strengths measured by actual tests. This work permits an appraisal of the advantages and limitations of this instrument for use in the field.

Tests of the first type, for accuracy of sonic velocity measurements by this instrument, were initially made in the laboratory, and then attention was turned to field tests of this accuracy.

Another instrument for measuring sonic velocities in concrete (the soniscope) had been developed by others, and a test to compare these two independently developed instruments was arranged. The soniscope normally measures velocities between two parallel faces of concrete, such as is encountered in mass concrete structures, whereas the electronic interval timer was designed primarily for use on concrete pavements. Personnel of the Portland Cement Association Laboratory at Skokie, Illinois, have used their soniscope for pavement concrete, and furnished their soniscope and operators for comparative tests. For the time measurement of a horizontally traveling wave as is normal with the interval timer, it was necessary in a similar application of the soniscope to "Pick out" the small horizontal component of a vertically propagated wave. The soniscope transducers occupy two or three square inches of surface of the pavement, so for this test it was assumed that the impulse and reception of the wave fronts occurred at the center of the area of these transducers.

Table 1 shows a sample of the comparative velocities measured in the tests with the two instruments. Readings were taken on concrete pavements at an airfield, alternately with each instrument, on precisely the same spots on the pavement at intervals between pickups of 2, 4, 6, 8, and 10 feet. It may be noted that some discrepancies occur at short measured intervals and again at the longer intervals. A possible explanation of these differences is that the soniscope transducers may have been operating other than in the center of the contact areas they cover, introducing a relatively large error for the short interval; and at the greatest intervals the extremely high amplification necessary for the soniscope to discern the tiny horizontal component of the vertical wave,

TABLE 1
RESULTS OF COMPARISON TESTS WITH INTERVAL TIMER AND SONISCOPE

Test No.	Velocities, ft/sec. at Spacings of:									
	2′–4′		2′–6′		2′–8′		2′–10′		2′–12′	
	Soniscope	Interval timer	Soniscope	Interval timer	Soniscope	Interval timer	Soniscope	Interval timer	Soniscope	Interval timer
1	15,750	—	15,750	—	16,000	—	16,100	—	16,100	—
2	15,750	19,400	16,050	16,100	16,150	15,500	16,250	14,400	16,250	14,000
3	16,000	17,200*	16,200	16,700*	16,100	16,200*	16,200	15,900*	16,100	15,000*
4	15,050	15,500*	15,300	15,400*	15,400	15,100*	15,550	15,000*	15,350	13,9 0*
5	16,000	16,200*	16,000	15,450*	16,100	15,390*	16,300	15,500*	16,300	14,500*
6	14,300	17,100*	14,600	15,800†	14,900	15,100†	15,200	14,200†	15,200	13,600†

* Readings taken with the AMINCO Timer.
† Readings taken with ORDL Timer with AMINCO needles in pickps.

may have caused slight distortion in that instrument's circuit. Velocities at the intermediate intervals of 4 feet and 6 feet compare favorably. These are the intervals commonly used in practice.

A program of testing was begun about a year ago to make comparisons of timer-measured flexural strengths, with flexural strengths measured by actual tests, on beams sawed from the same pavement. Timer-measured flexural strengths are derived by computation from velocity readings, through application of the relation curve of dynamic modulus of elasticity vs. flexural strengths described in the paper just presented. Field cut beams and slabs are used for correlation measurement of flexural strengths by actual tests, in order to eliminate as many variables as possible. The data from field cut beams and slabs are difficult to obtain; however, due to the high cost of sawing and transporting the concrete, and patching of the pavements. As a result the data are not too plentiful for this correlation work. The current practice is to find locations where beams are to be sawed out of field concrete, and record timer readings before the sawing occurs. The data to date, although sketchy, are encouraging.

Table 2 shows a few of the velocity measurements made by the interval timer during the soniscope comparison tests, converted to flexural strengths. These quantities are compared with flexural strengths measured conventionally at the same location a few years before. This correlation is considered exceptionally good.

TABLE 2

COMPARISON OF CONCRETE STRENGTHS AS OBTAINED WITH INTERVAL TIMER AND MEASURED, CHANUTE AFB, ILLINOIS

Test No.	Velocity ft/sec. I.T. 2′–6′ Spacing	Dynamic Modulus I.T. Correlation, psi 10^{-6}	Flexural Strength I.T. Correlation, psi	Flexural Strength 1944 Airfield Evaluation, psi
1	—	—	—	1,035
2	16,100	8.1	1,110	—
3	16,700	8.3	1,150	1,154
4	15,400	7.4	960	970
5	15,500	7.5	995	—
6	15,800	7.7	1,040	960

TABLE 3

COMPARISON OF CONCRETE STRENGTHS AS OBTAINED WITH INTERVAL TIMER AND BEAM BREAK METHOD, SIX AIRFIELDS

Field No.	Location	Flexural Strength Interval Timer, psi	Flexural Strength Beam Break Method, psi	Remarks
1	A	744	512	Coated aggregate, very weak bond
2	A	685	690	Coated aggregate, somewhat weak bond
	B	580	515	Coated aggregate, somewhat weak bond
3	A	680	765	
4	A	815	435	Bottom badly honeycombed
5	A	785	655	
	B	655	640	
	C	640	500	
	D	650	640	
6	A	905	925	

Table 3 shows a sample of similar comparative data taken recently from six different airfield pavements. In this case the sawed beams were broken in flexure immediately after interval-timer readings were taken on the pavement in place. Notes in the "Remarks" column are information taken from airfield records and observed from beam-break operations. At Fields 1 and 2, peculiar emergency conditions during construction of the pavements justified the use of aggregates loosely coated with substantial thicknesses of soft lime. Discrepancies between the figures at Field 3 and at Locations A and C of Field 5 are unexplainable at present. The figures at Field 4 are indicative of the effect of bottom honeycomb in a pavement. Table 3 is typical of comparative data of this type. It may be seen that about one-third of the comparisons are very close, a second third are explainable differences and the other third unexplainable differences (at least at the present time).

There are a few limitations and precautions to be borne in mind when using the electronic interval timer.

The longitudinal wave fronts must travel in a horizontal direction through a pavement. Otherwise the transverse wave (slower but of greater magnitude) will trip the pickup circuits and give a reading of no value. The wave fronts are created by hammer blows in a horizontal direction against the edge face of pavements. The wave travel is interrupted by a construction joint in the pavement; therefore, in military airfield pavements we cannot as yet measure velocities, dynamic modulae of elasticity or flexural strengths beyond the first construction joint from the edge of the pavement. For highway application this would not be a limitation.

If pavement is honeycombed near the bottom, sawed beams will show a lower flexural strength by beam break methods than by sonic wave measurements made on the pavement. This is because the beam is weaker in its area of greatest tensile strain, whereas the sonic wave will be carried by the more dense concrete higher in the pavement's cross section. It also appears that the type of break in flexure (whether through the aggregate or around it), and whether the aggregate is round or elongated, makes some difference in flexural strengths; these differences are not discernible when flexural strengths are measured using sonic wave instruments. Thus it is necessary where quantitative data are desired, to know something about the concrete characteristics. This can often be obtained from job records. This is a limitation of the application, rather than of this instrument.

Field readings with sonic wave measuring equipment are not as consistent through a presumably uniform area of field pavement as they are throughout the area of cast beams or slabs made in a laboratory. This can be caused by a lesser degree of uniformity control in placing field concrete, or may be due to the beginning of internal cracking from traffic loads on the field pavement.

CONCLUSION

The electronic interval timer is found to measure sonic velocities nondestructively, cheaply, and with good accuracy when used with proper techniques.

Computations of dynamic modulae of elasticity from these velocities are found to compare favorably with laboratory determination made on beams.

Computations of flexural strengths from timer measurements compare sufficiently well with actual measurements to warrant continued correlation studies.

Due to a few characteristics of sonic methods and to some variables of pavement concrete, field testing with the timer cannot at present give conclusive data in every individual test measurement. However, its ability to produce a great number of measurements in a small amount of time at very low cost, makes it a valuable tool to obtain an overall evaluation of the strength of pavements. It is particularly valuable when such overall evaluation is coordinated with a few selected specimens taken from the pavement for determination of concrete characteristics, including flexural strengths. Subgrade evaluation requires some opening of the slab, which can be the source of beams for flexural strength correlation.