Detection of Concrete Deterioration Under Asphalt Overlays by Microseismic Refraction

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Nondestructive testing of structural materials, particularly concrete, has received increasing attention from highway engineers and other members of the civil engineering profession during the last decade. Application of nondestructive test methods to existing, and aging, highways and structures offers apparent economic advantages over methods that require defacement and repair, or interruption of normal service. A special problem in the monitoring of concrete deterioration is presented by concrete slabs overlain by asphaltic surface courses. Such concrete is not visible for inspection. On bridge decks and in similar exposed locations, considerable slab deterioration can occur without producing visible evidence at the asphalt surface. Until recently, test procedures have been limited to core sampling, or removal of asphalt for inspection. Both are costly. A method is presented for determination of asphalt thickness and estimation of concrete structural soundness by measurement of the direct and refracted microseismic wave velocities produced by low-energy hammer impacts on the surface of the material. Thickness is determined by solution of the classical seismic refraction formula. Concrete condition is estimated by comparison of the measured velocity in the concrete with standard velocity of concrete having known properties. Laboratory-type instrumentation used in evaluation of the test method and field-type instruments developed for general application are described. The theoretical basis for the method and the detailed procedure for field tests are given in the Appendix.

•HISTORICALLY, test methods for the determination of concrete quality have been destructive when carried out on specimens. The disadvantages of destructive methods for the investigation of in-service structures are obvious. Considerable time and expensive facilities are required for obtaining core samples and testing of specimens in the laboratory. Interruption of service on the structure and repair of defacement caused by specimen procurement also add to costs. Furthermore, only a single test result is yielded by destructive methods for each specimen, so that a large number of specimens are necessary to give statistically representative data over large structural areas.

These factors have spurred intensive study and increasing application of nondestructive methods for testing of concrete. One example is the resonant frequency method developed for the determination of dynamic modulus of elasticity. This has contributed greatly to the study of deterioration of concrete during freezing and thawing cycles.

Other nondestructive methods are based on the measurement of elastic (seismic) wave velocity in concrete. Wave velocity methods have wide applicability because they

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may be applied to in-service structures without damage or defacement and with little interruption of service. A number of test procedures, using a variety of measuring apparatus, have been developed in the United States (1), Canada (2), England (3), France (4), and Denmark (5). Work is continuing, in these countries and others, on studies of wave velocity in concrete and similar materials and on the correlation of wave velocity with the physical properties of the material homogeneity, such as compressive strength, dynamic elastic moduli, aging processes, and degree of deterioration with age in various environments.

As the store of empirical correlative data increases, the application of wave velocity measurements to increasingly varied field testing problems will become both possible and economically rewarding.

One such problem, of special interest to highway and bridge maintenance engineers, is the monitoring of the structural condition of concrete pavements and deck slabs supporting overlays of asphaltic material. Because of its asphalt cover, the surface of such concrete is not visible for routine inspection. It has been found that considerable, even dangerous, deterioration of the concrete can occur beneath the asphalt in structures exposed to severe environmental conditions before evidence of the damage becomes visible on the asphalt surface. Asphalt is a relatively plastic material, particularly when warm, and it can undergo a certain amount of deformation in compliance with loss of underlying support without exhibiting surface cracking or weathering. Thus it masks the unsatisfactory condition of the underlying concrete. Even with the asphalt-concrete interface bond broken and the concrete surface pitted, the asphalt can span the damaged area for some time when it is of the thickness normally used for heavy-traffic surface courses. In many cases, the asphalt thickness is not accurately known because of heavy wear over protracted periods or absence of original construction information.

A method for the rapid and economical determination of asphalt thickness and estimation of the structural condition of the underlying concrete over large areas therefore has obvious value. In the summer of 1964, the Port of New York Authority retained the consulting engineering firm of Joseph M. Phelps & Associates to develop the basis for such a method, and to assist the Port Authority's Engineer of Materials Research in evaluation of the method's feasibility on an existing structure. Laboratory-type equipment suitable for the evaluation program was developed in the laboratories of DynaMetric, Inc., Pasadena, Calif.

Engineers from the three organizations then conducted tests on portions of the asphalt-surface concrete deck of the Outerbridge Crossing, a large steel cantilever-truss bridge spanning Arthur Kill, between Perth Amboy, N.J., and Staten Island, N.Y. This structure was chosen for evaluation purposes because it was undergoing extensive repairs to and widening of the concrete deck system, both on the main span and on the two girder approaches. Tests were conducted at locations ahead of the field work, so that visual examination could later be made at the same spots. Tests were also made on new concrete decks with freshly laid asphalt surfacing. In addition, core samples of the old materials were taken at the test locations and evaluated in the strength of materials laboratory of the Port Authority.

This paper presents a brief discussion of the basis for the test method; a description of the laboratory-type equipment used in evaluation; an outline of the test procedure; a discussion of the correlative examinations used in evaluation of the method; and a brief description of new portable, self-powered instruments and accessories being developed for general application of the test method. The Appendix gives the theoretical basis for microseismic refraction and a selected list of references.

BASIS FOR TEST METHOD

Refraction seismology has been used by exploration geophysicists for many years. Its principal purpose is the detection of subsurface materials, such as rock or shale strata, and the determination of their depths below ground surface. For deep exploration such as that for potential sources of petroleum, seismic waves are created in the earth by high-explosive detonation, and their arrivals at a series of geophones at or

near the surface are electrically recorded. Travel times of the waves and the velocities indicated thereby are determined by examination of the records. More recently, seismic refraction has been employed for the shallower depths of interest to engineering geologists and foundation engineers. For this application, elaborate recording equipment has been replaced by portable timers reading directly in milliseconds (msec), and the seismic waves are created by striking the ground (or a steel plate or ball resting on the ground) with a sledge hammer, which is wired to start the timer counting operation. Survey lines for shallow exploration of this type are usually 100 to 200 ft long. A geophone array is not used—only a single geophone. The hammer makes a series of impacts at successive stations along the line to produce a series of travel times needed to plot the travel-time graph from which depth to subsurface materials and velocities in those materials can be calculated.

Microseismic refraction essentially takes the process of miniaturization one step lower. As applied to the determination of asphalt thickness and concrete investigation, the survey line becomes only some 3 ft long. Blows from a small hammer are used, at impact stations only some 3 in. apart. Because of the very short distances involved, and the high seismic velocities in asphalt and concrete, the travel times must be measured in microseconds (μsec). And because of the small amplitudes and much higher frequencies of the arriving waves, the detection geophone must be replaced by a transducer of higher capability. Basic principles of the method, however, remain the same. They are covered in all standard texts on exploration seismology and are briefly discussed in the Appendix. The necessary formula for depth calculation is given, and determination of the quantities used in the formula is explained.

Two of the quantities used in the dpeth formula are the velocities of the seismic wave in the asphalt and in the concrete. Velocity in the concrete is of special interest in the present application because it serves as a basis for estimation of the structural condition of the concrete. Strong, homogeneous concrete will exhibit a seismic velocity much higher than that shown by the asphalt. As representative values, velocity in good quality concrete will range from 11,000 to 14,000 ft/sec; whereas velocities in good quality, unfractured asphalt will be in the 8,000- to 10,000-ft/sec range. Velocities in damaged or weathered concrete will rarely be as high as those in good asphalt and may be much lower, depending on degree of deterioration.

The velocity characteristics of the two materials thus make it possible to detect areas where concrete deterioration has occurred and to gain a fairly accurate determination of the depth of weathering or other damage. For example, on a slab covered by a nominal 3-in. thickness of asphalt surfacing, areas may be found where the calculated depth to concrete is, for example, 6 in., indicating that the concrete has so deteriorated that its velocity is as low as, or lower than, that of asphalt for a 3-in. depth in the concrete slab. This would be enough to render top reinforcement, if any, ineffective due to loss of bond strength.

In other cases, where concrete deterioration is just beginning or has not deeply penetrated the slab, the surface concrete may exhibit a velocity higher than that of the asphalt, but not as high as the strong concrete deeper in the slab. In such cases, the asphalt/concrete interface may appear as a first horizon (see Appendix) and the surface of the strong concrete as a second horizon. Any material at depth, having a seismic velocity higher than the velocities in materials above it, will appear in the refraction survey. Materials having velocity lower than the velocities of overlying materials will not appear on the travel-time graph, but may affect the so-called breaks in the graph.

LABORATORY-TYPE EQUIPMENT FOR TEST EVALUATION

Initial analysis of the problems involved in the miniaturization of the seismic refraction method for application to high-velocity materials such as asphalt and concrete, showed that it would be necessary to measure travel times in the range from 25 to 500 μsec with an accuracy of ± 5 μsec over the shortest base lines. Because of the very short time differentials involved, the rise time of the arriving seismic signal must be steep, corresponding to frequencies in the 2-kc range, in order to get repeatable time detection. The conclusion that ordinary geophones, which rapidly lose sensitivity at frequencies above 500 cps, could not be used, was confirmed in the laboratory. Studies

also showed that use of an impact type shock switch to start time measurement would be unreliable due to unacceptable nonuniform time delay in the triggering circuit.

Since the frequency of the elastic wave generated by an impact is a function of the resonant frequency of the spring-mass system formed by interaction of the impacting device with the elastic boundary of the deformed surface material at the impact point, it was felt that design of the impacting system should incorporate a coupler mass of the proper size and shape to generate an efficient, high-frequency shock effect.

Impacting Device

Mereu, Uffen and Beck (6) have shown that conversion of impact energy into seismic energy can be effected by proper selection of coupler mass and shape. Calculations based on coupler theory indicated that use of a small hardened-steel sphere as a coupler, struck sharply by a light steel hammer, would produce sufficient energy of the required frequency range. The mass of the coupler must be such that the product of its mass and coefficient of restitution are of the same order of magnitude as the mass of the falling weight, in order to minimize production of complex wave forms. A number of couplers (rods, cones, flat plates) were evaluated in the laboratory. Results showed the sphere most efficient, as theory indicated.

Triggering Device

The impact device, coupler and hammer, was used as a simple contact to trigger the operation of the timing instrument. This was accomplished by the design of the coupler. A brass rod was inserted through diamond-drilled holes in two ¾-in. diameter steel ball bearings. One ball was secured to each end of the rod by end nuts and lock nuts. One end of the rod was connected electrically to the timing trigger circuit. The hammer was also wired to the trigger circuit; thus contact between hammer and either of the balls on impact closed the circuit at the instant of impact and initiated the timing sweep. The ball not in use served as a handle. The device is shown in operation in Figure 1.

Transducer

A review of several available types of high frequency-response accelerometers indicated that one suitable for the work would be a Model 2217 accelerometer manufactured by Endevco Corp. This transducer has a resonant core frequency of 30 kc, a flat frequency response of 2 cps to 6 kc when driving into 1000-megohm impedance, and a flat frequency response from 20 cps to 6 kc when driving into 100 megohm. Its use at 100

Figure 1. Evaluation of microseismic refraction method: (a) observing travel times on portable oscilloscope triggered by impacts; (b) refraction survey line, impact device and accelerometer.

megohm requires an amplifier and a power supply, also manufactured by Endevco. These instruments were procured for the investigation and used in laboratory development and field evaluation.

Timing Instrument

Because of the time and cost involved in the design and production of any direct-reading digital counter, it was decided not to engage in such development before evaluation of the test method. Laboratory work confirmed that the arriving seismic wave generated a signal that could be seen and measured on a cathode-ray tube oscilloscope with sufficient accuracy, although use of an oscilloscope is not satisfactory for regular field testing because of operator fatigue. A Tektronix, Type 321, self-powered portable oscilloscope was used for both laboratory studies and field tests. This is a small but precise oscilloscope that can be operated from an a-c line, from an external d-c supply, or from its own self-contained and rechargeable batteries. It weighs 16 pounds. It provides Miller-integrator sweeps from 0.5 μsec per division to 0.5 sec per division in 19 calibrated steps. It can be externally triggered by from 2 to 50 volts with an input impedance of 10 pf, paralleled by 100 K, plus or minus trigger slope, a-c or d-c coupled. The scope display area is marked in 6 vertical and 10 horizontal divisions, each $1/4$ in. wide. The sweep rate found most useful in the microseismic measurements was 50 μsec per division. The cathode-ray tube of this oscilloscope has a long retention time that

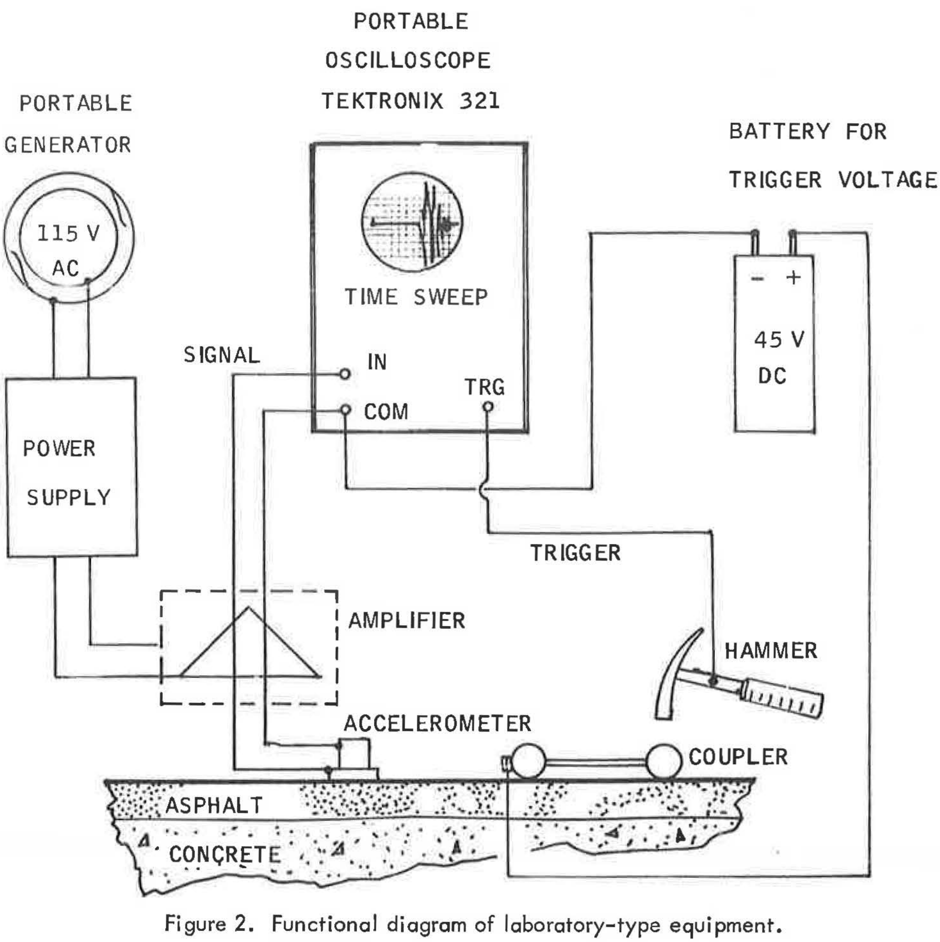

Figure 2. Functional diagram of laboratory-type equipment.

permits visual retention of the extremely fast trace and greatly assists in reading of time intervals.

During part of the field work, a large laboratory oscilloscope, powered by a portable generator was used. The large scope gave equally good results, but was more difficult to read. There may be some question as to the stability of its time base when powered by a portable generator, whereas the bistable Schmitt trigger multivibrator of the portable oscilloscope is independent of any a-c supply or line fluctuations. A block diagram of the system components is shown in Figure 2.

TEST PROCEDURE

The microseismic refraction method for determination of depth to sound concrete comprises four distinct steps:

1. Lay out a refraction survey line on the surface of the pavement. The line, as used in the evaluation of the method, was normally 3 ft long. (It was laid out at a 45-deg angle with the centerline of roadways, since steel reinforcement existed in the slabs in the normal and transverse directions. Steel carries sound waves at velocities of 16,000 to 17,000 ft/sec and so would mask the effect of the concrete refraction wave if the survey line paralleled the steel. By running at 45 deg, the sound in the steel must travel a longer path by the factor of $\sqrt{2}$, hence does not short-cut the concrete refracted wave.) Generate seismic waves in the pavement by hammer blows on a small steel sphere, at impact stations spaced at equal intervals (usually 3 in. apart) successively farther from a detector at the zero end of the line. Measure the travel time (in µsec) of the seismic wave from each impact station to the detector. Use repeated hammer blows at each station to get repeatable confirmation of the time reading, and record the lowest repeatable travel time.

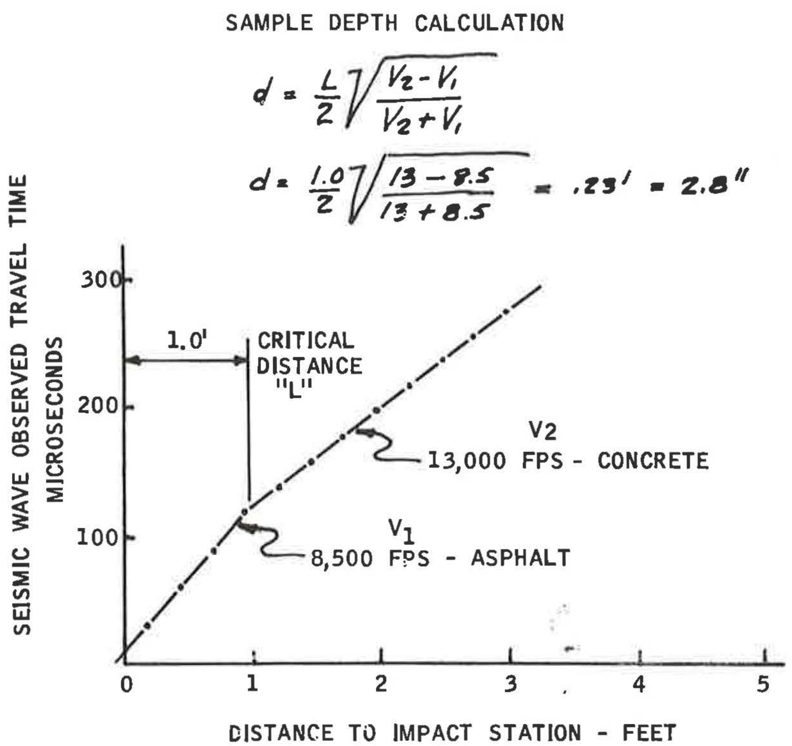

Figure 3. Typical travel-time graph.

2. Using the observed travel times and the known distances to successive impact stations, plot a travel-time graph, with time as the ordinate and distance as the abscissa (Fig. 3).

3. Observe the point on the travel-time graph at which the line changes slope. From all stations more distant than this point, the observed arriving waves have traveled through the concrete by refraction, rather than directly through the asphalt. Obtain the seismic velocity in the asphalt from the slope of the first portion of the graph, and the seismic velocity in the concrete from the slope of the second portion of the graph. Calculate the depth to sound concrete (asphalt thickness, or asphalt plus bad concrete thickness) using the measured velocities and the distance to the point at which the graph changes slope (critical distance—see Appendix).

4. Estimate the structural condition of the concrete by comparing the measured seismic velocity in the concrete with velocities known to be exhibited by good quality concrete of that type. For correlation purposes, tests can be run on known good concrete of the same type in the same structure at locations not covered by asphalt. Additional information about the nature of the surface of the concrete and the asphalt/concrete interface may also be obtained by special interpretation of aberrations in the travel-time graph.

The refraction method is not necessarily limited to cases of concrete covered by asphalt overlays. The velocity determination works equally well on exposed concrete. If surface deterioration of the concrete is visible, the depth of such damage can be determined by refraction. Recently placed concrete can also be checked for velocity increase correlative with increase of compressive strength and homogeneity during curing. One powerful advantage of the refraction method is the determination of velocity from the slope of a graph plotted through several stations, which eliminates the effect of any system delay in the timing devices and gives true velocity both in surface materials and in the underlying materials if such exist.

FIELD EVALUATION OF THE TEST METHOD

In May 1964, field tests of the microseismic refraction method were conducted, using the laboratory-type equipment, on the concrete deck system of the Outerbridge Crossing. Preliminary observations were made at a location on the New Jersey approach span where removal of old asphalt and concrete was in progress and structural conditions could be inspected visually. Velocity was measured on the surface of exposed, old concrete which appeared to be in good condition, and was found to be 11,500 ft/sec. Velocity was measured on the surface of pieces of old asphalt which had been removed from the deck, but did not appear to be cracked. The asphalt was isolated from the concrete deck by a cloth pad to avoid refracted concrete transmission. Asphalt average thickness was 2.5 in. The asphalt velocities obtained were from 6,500 to 7,000 ft/sec. These velocities are lower than those later found for undisturbed traffic-compacted asphalt well bonded to good concrete.

A refraction survey was then made on the surface of old asphalt in an area where considerable concrete slab deterioration was evident from chip tests and visual inspection. No velocity break was obtained in the travel-time graph, indicating that the concrete velocity was no higher than that in asphalt, in this case 8,500 ft/sec.

The test location was then moved to an area where a new portion of the deck had been constructed and asphalt-surfaced about one month previously, and not yet subjected to traffic loads. Three separate refraction surveys at this location indicated an asphalt velocity of about 9,500 ft/sec, an asphalt thickness of 2 to 2¼ in. (which accorded with the known construction), and concrete velocities of about 13,000 ft/sec.

Since the results of the preliminary tests were favorable and correlated with available visual information (indicating the feasibility of the method), a systematic survey of a large portion of the main span deck system was conducted. The survey included refraction determinations at a total of 65 points on the westbound lanes over the entire suspended span and portions of the east and west cantilever spans. The outer westbound lane in this section was scheduled for partial removal and widening. It was desired to check on the condition of the center westbound lane so that any necessary repairs could be accomplished at the same time.

The 65 point determinations, using laboratory-type equipment, required the equivalent of two working days for two men. Of the total number of determinations, 45 were made in the center traffic lane, and of these, severe concrete deterioration was evidenced at 7 points, and slight surface weathering was indicated at 3 points. The remaining 35 points gave data indicative of good or excellent concrete.

Twenty determinations were made at points in the outside lane (which was scheduled for partial removal) adjacent to the main steel trusses. Of these, 12 points gave indication of severe deterioration of concrete, in three cases for the full depth of the slab. In 9 of these cases, the overlying asphalt appeared in satisfactory condition to visual inspection. Five other points indicated moderate or slight weathering to partial slab depth, and only 3 points indicated sound concrete for the full depth of the slab. Of the 20 points, asphalt appeared good at 13 locations, fair at 6 locations, and poor at only 1 location. The inferior condition of the outer lane concrete compared to that of the center lane is assumed to result from the proximity of the outer lane slab joints to the curb, the sidewalk, and the constantly moving steel trusses. The most severe deterioration was observed at points closely adjacent to heavy supporting steel members.

CORRELATIVE EXAMINATIONS

Shortly after completion of the field evaluation studies, the asphalt surfacing and portions of the concrete slabs were removed from the outer portion of the westbound lane to permit construction of a new and wider roadway. Visual inspection at the locations of the 20 refraction test points in this lane gave good correlation with predicted conditions. At points where the refraction method predicted severe deterioration of the concrete, the slab was found to be essentially destroyed. At points where surface weathering was predicted, the slab was found to be pitted, with cement bond broken between aggregate particles, and the asphalt/cement interface broken and containing voids and loose aggregate. At points where good concrete was predicted, the weathering process had not occurred.

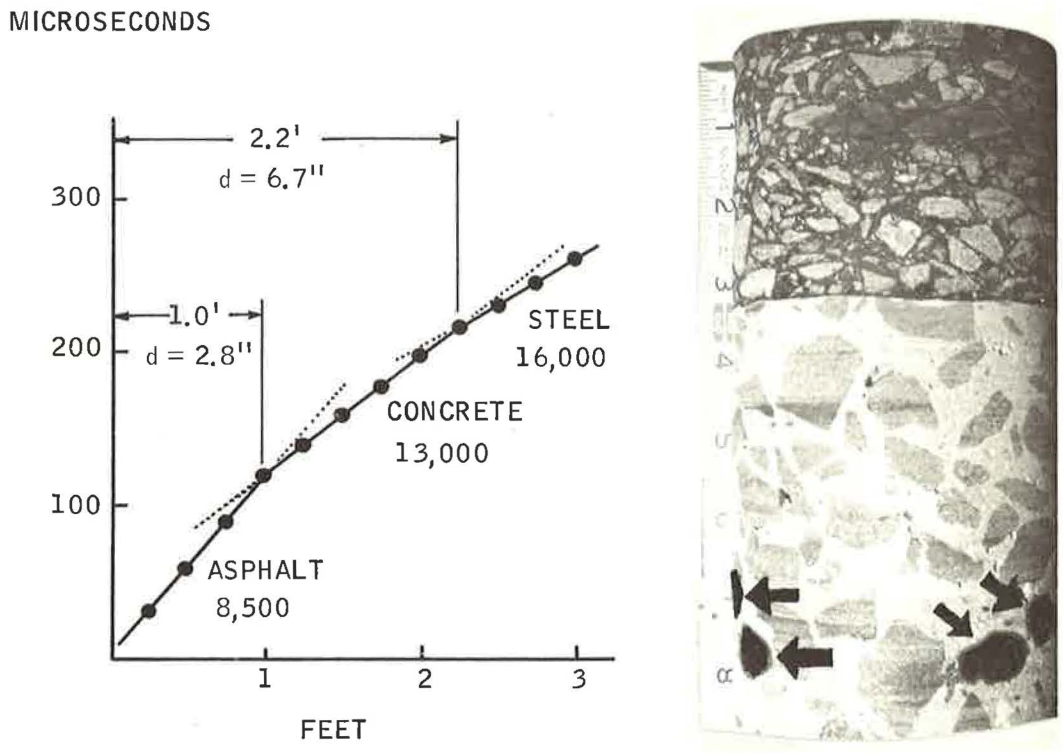

Figure 4. Good asphalt over good concrete.

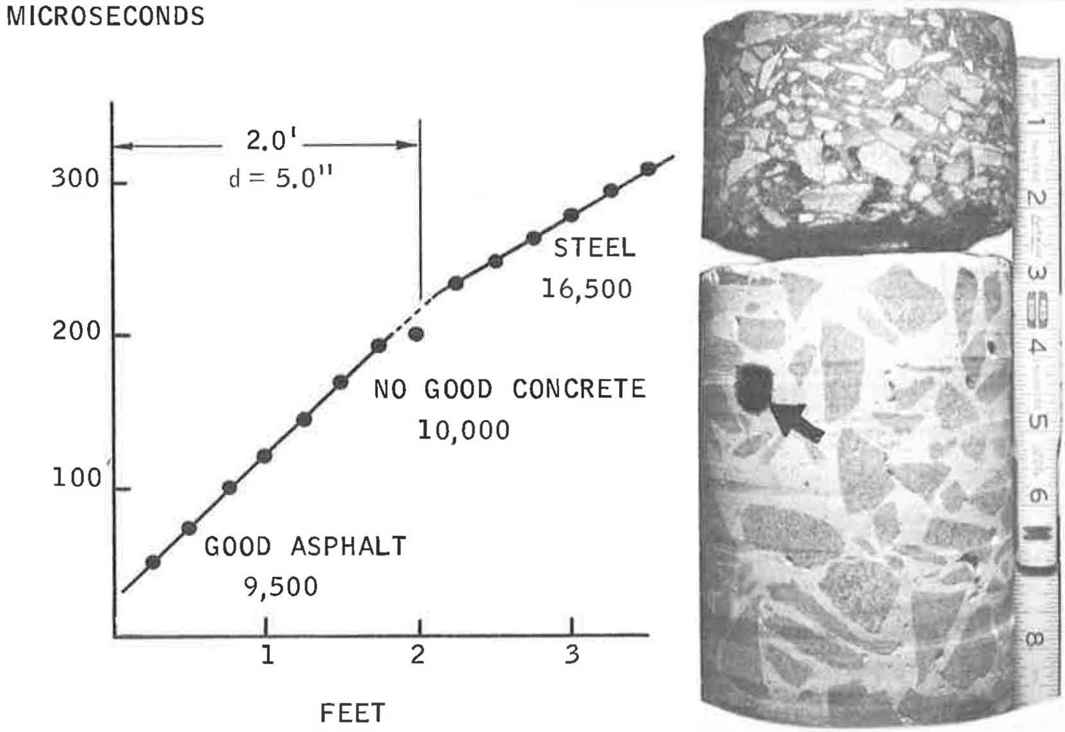

Figure 5. Some concrete deterioration beginning.

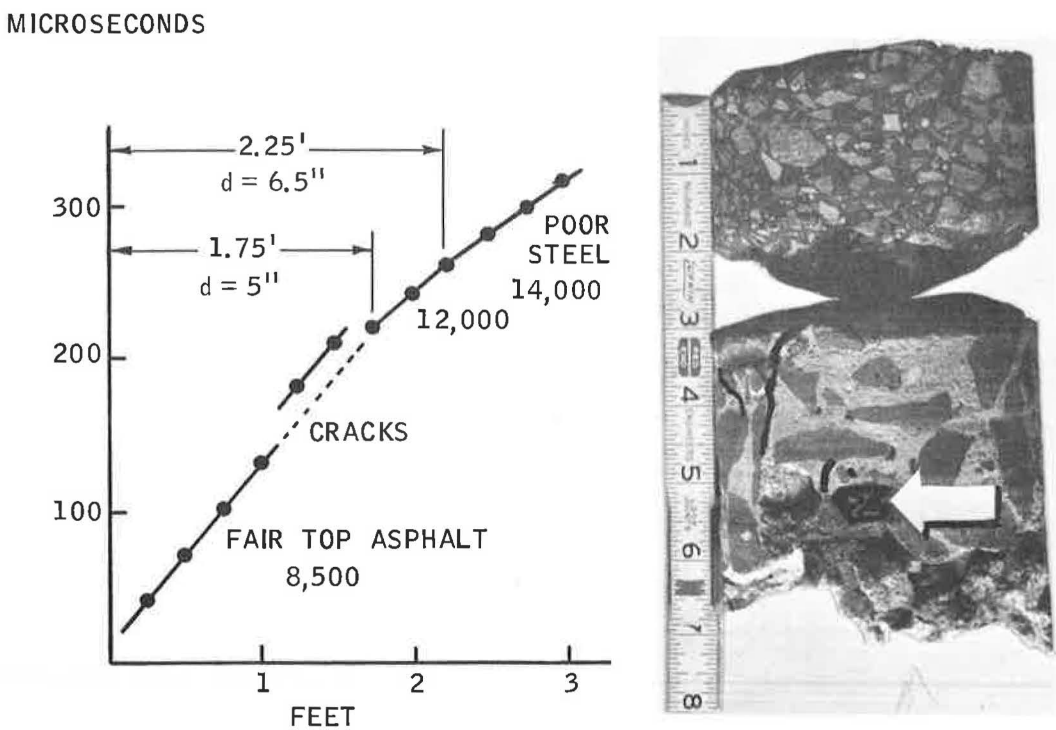

Figure 6. Concrete badly deteriorated.

A number of core samples were taken in the center westbound lane, at the location of some of the 45 refraction test points made in that lane. These core samples were photographed and examined in the laboratory. Again, the results gave good correlation with the predictions of the refraction tests. Typical core samples are shown in Figures 4, 5 and 6, together with their corresponding travel-time graphs and the predictions based thereon.

In summary, evaluation of the test method and correlative examinations indicate that the microseismic refraction method is suitable for the routine monitoring of concrete base-slab conditions over large portions of asphalt-overlaid structures and for determining asphalt thickness without disturbance of the material. Economical use of the method for routine testing presupposes the existence of suitable high-speed, direct-reading timing instruments that permit rapid procurement of field data.

FIELD EQUIPMENT FOR MICROSEISMIC REFRACTION TESTING

After successful demonstration of the feasibility of the microseismic refraction method for asphalt and concrete testing, development work began on compact, self-

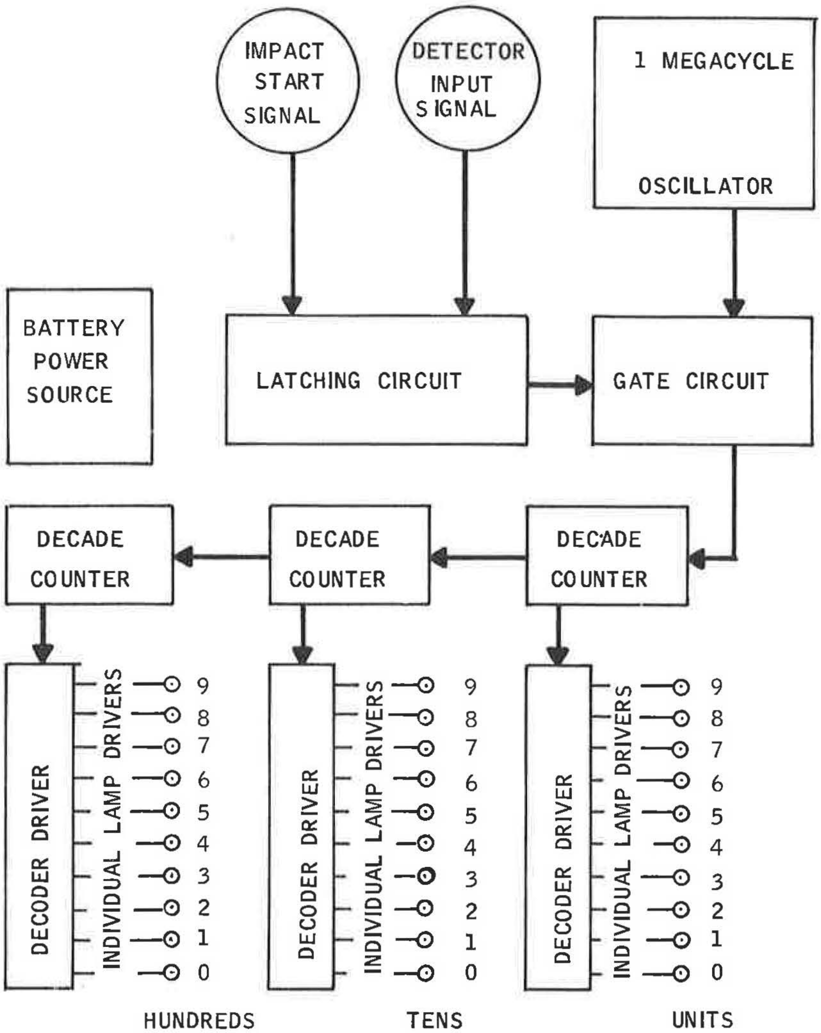

Figure 7. Functional components of direct-reading portable microsecond timer.

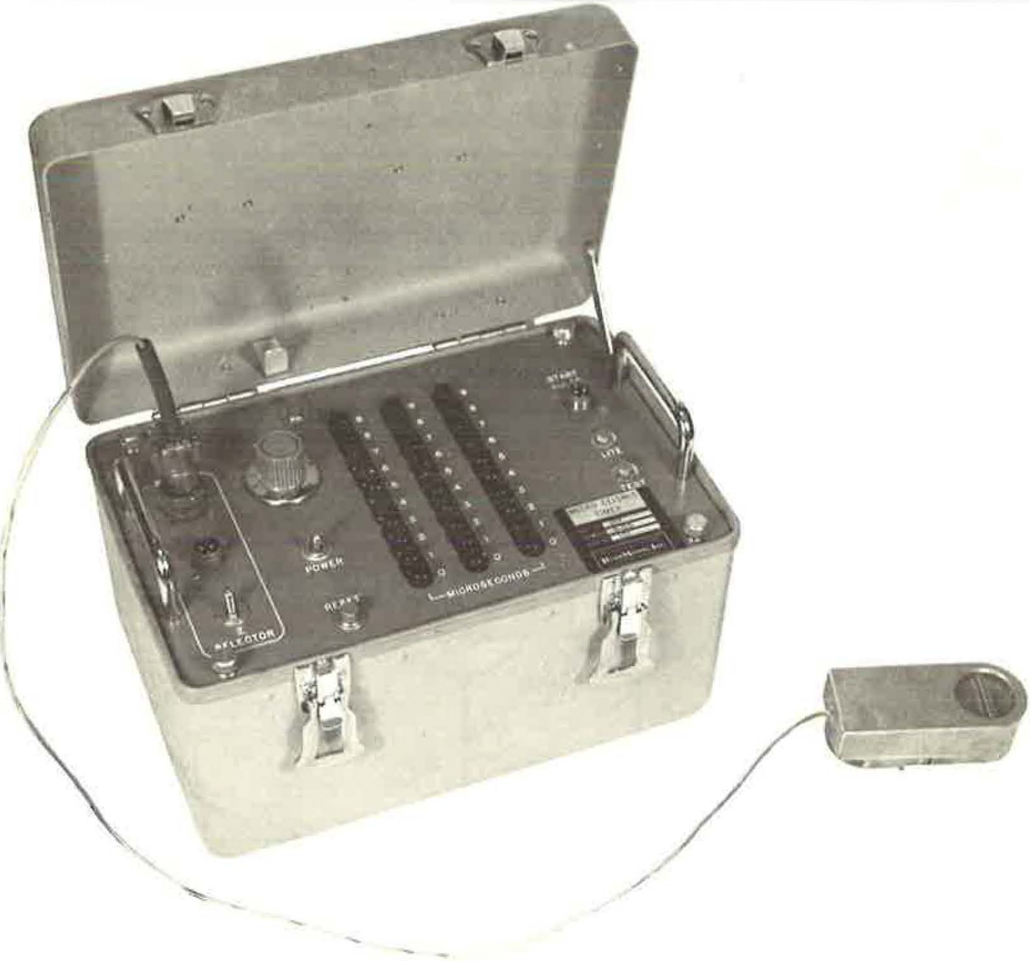

Figure 8. Microseismic timer and pickup.

powered, direct-reading instruments and accessories suitable for regular use by engineering department and maintenance department inspectors. A microsecond seismic timer and the necessary accessories have been developed, and field application studies are in progress.

The timer replacing the portable oscilloscope for use in direct measurement of travel times is a self-powered, direct digital reading instrument similar to the millisecond and tenth-millisecond timers used in shallow seismic exploration. Its time-counting operation is initiated by receipt of a start signal from the hammer impact. The counter is controlled by a stable oscillator. Time is measured by a series of three decade counters with microsecond switching capability displayed on appropriate decades of incandescent lights. A suitable amplifier and gate circuit receive the wave-arrival signal from the transducer and operate to stop the time count. The elapsed time in microseconds is displayed by the lamps that remain lit on the instrument panel, from 0 to 999 μsec. The timer can be reset instantly to 0, ready for a repeat reading. For elapsed times greater than 999 μsec, the count recycles. A simplified block diagram of the instrument's functional components is shown in Figure 7. The instrument is shown in Figures 8 and 9.

The transducer is a modified crystal-type pickup, having the required frequency response characteristics. The impact and triggering device is an improved version of

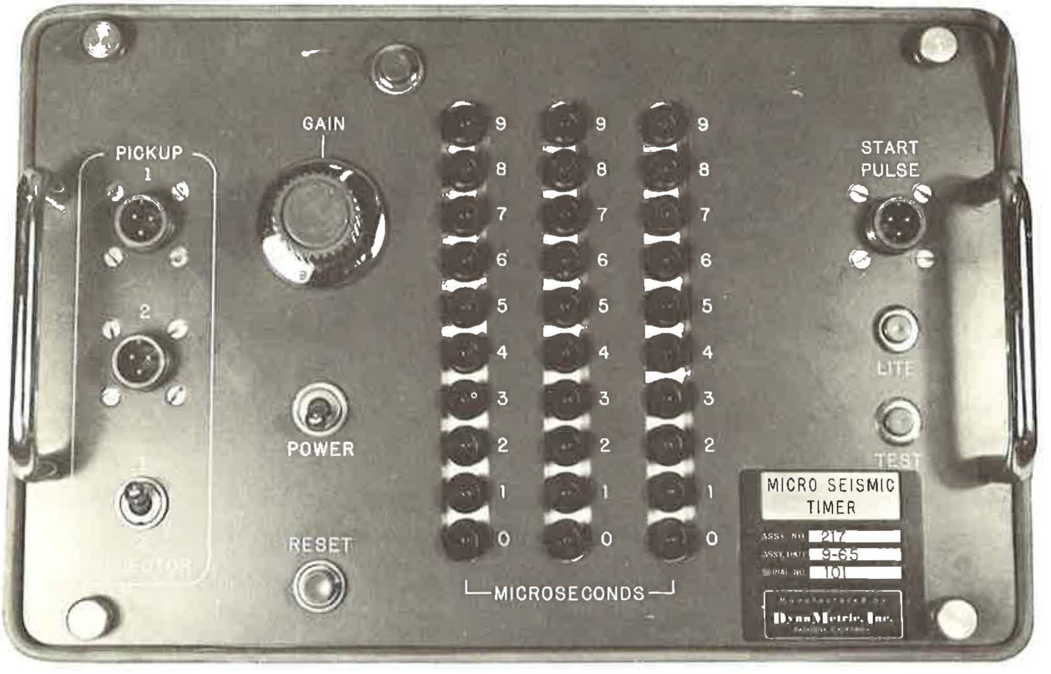

Figure 9. Microseismic timer control panel.

the hammer-coupler contactor used in evaluation tests, designed to withstand continuous hard field use. An accessory has also been developed for rapid layout of the survey lines. The instrument is powered by rechargeable batteries, and the total equipment kit is suitable either for hand-carrying or for transportation and operation from a small trailer with operator's seat mounted close to the pavement surface, for rapid coverage of long stretches of roadway.

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REFERENCES

1. Long, Bartlett G., Kurtz, Henry J., and Sandenaw, Thomas A. An Instrument and a Technique for Field Determination of the Modulus of Elasticity and Flexural Strength of Concrete (Pavements). ACI Jour., Proc., Vol. 41, pp. 217-231, Jan. 1945.

2. Leslie, J. R., and Cheesman, W. J. An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures. ACI Jour., Proc., Vol. 46, pp. 17-33, Sept. 1949.
3. Jones, R. The Non-Destructive Testing of Concrete. Mag. of Concrete Res., No. 2, pp. 67-76, June 1949.
4. Chefdeville, J., and Dawance, G. L'Auscultation Dynamique du Beton. Annales de l'Institute Technique du Batiment et des Travaux Publics, Nouvelle Série No. 16, Aug. 1950.
5. Andersen, Johannes, and Poul, Nerenst. Wave Velocity in Concrete. ACI Jour., pp. 613-635, April 1952.
6. Mereu, R. F., Uffen, R.J., and Beck, A.E. The Use of a Coupler in the Conversion of Impact Energy into Seismic Energy. Geophysics, Vol. 28, No. 4, Aug. 1963.

Appendix

THEORY OF MICROSEISMIC REFRACTION

This brief discussion of the refraction method is presented for those not familiar with seismic techniques, and will aid in understanding the method described in this paper.

Consider the surface of a broad expanse of material such as asphalt or concrete, as shown in Figure 10. If, at point A, a shock is imparted to the material, by hammer impact or other means, an elastic wave will travel out through the material in all di-

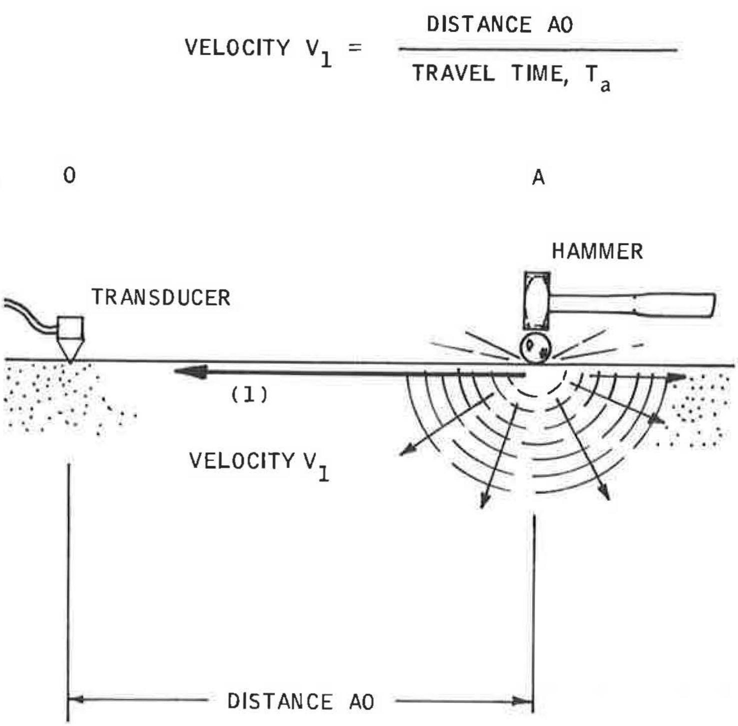

Figure 10. Measurement of velocity in surface material.

rections. If the material is homogeneous and free from boundary conditions, the wave front will be of spherical shape.

Elastic energy travels through elastic materials in a number of modes. The most important modes are the compressional mode (P-wave), in which elastic deformations take place in a direction parallel to the line of propagation; and the transverse, or shear, mode (S-wave), in which elastic deformations occur in directions normal to the line of propagation. Of these two modes, the compressional mode energy travels at the higher velocity, and so represents the leading surface of the expanding spherical wave front with which the refraction method is concerned.

It is helpful to visualize the expanding wave front as composed of an infinite number of rays, similar to the light rays emitted by a point source.

If there is placed at point O (Fig. 10) a transducer capable of detecting the arrival of the disturbance, it is possible to measure the time required for the wave front to move from point A to point O, along the path of ray (1). If the distance, AO, is known, the velocity, V_1 of the compression wave in the material can thus be determined.

Next, consider the condition encountered in a refraction survey (Fig. 11) in which the surface material is underlain at some depth, d, by another material capable of transmitting the compression wave at a velocity, V_2, higher than that of the surface material. Note that this condition is essential to the refraction method—underlying materials with velocity lower than that of surface materials cannot be detected.

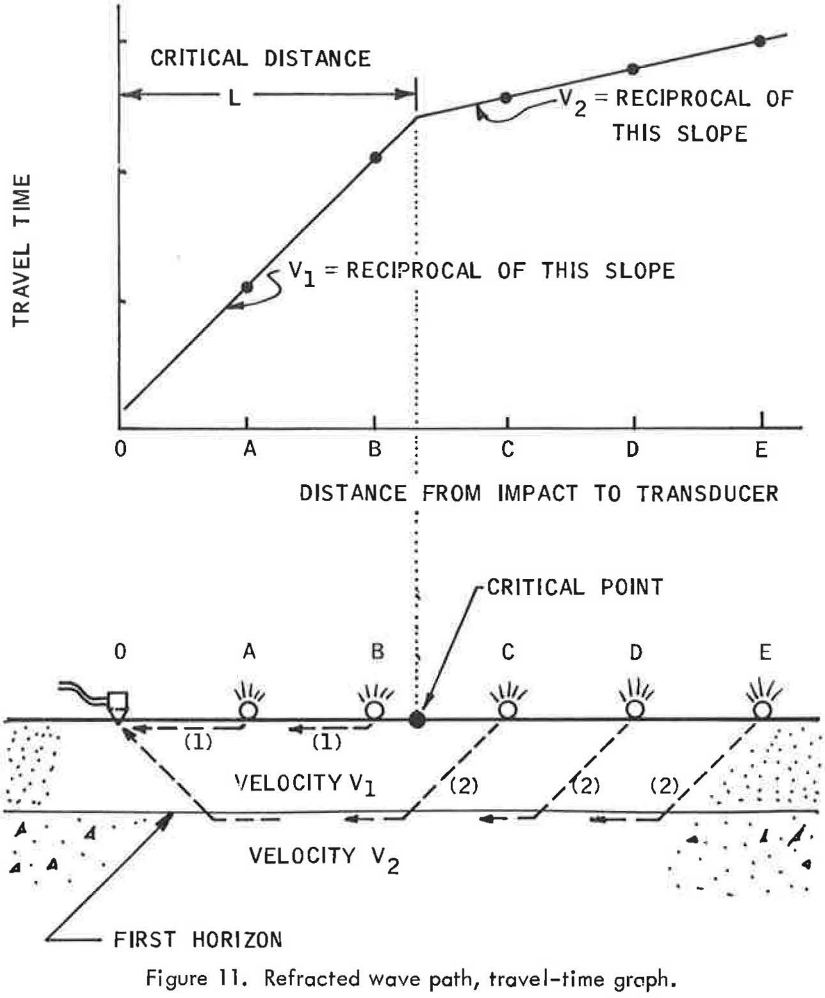

Figure 11. Refracted wave path, travel-time graph.

Assume that an impact is first produced at point A, close to the transducer, O, and that impacts are then produced at points B, C, D, and so on, each successively more distant from O. The travel time from each impact station is measured and plotted on a graph similar to the one in Figure 11. The measured travel times are based on the first arrival of disturbing energy at the transducer. Energy from any impact station can now reach the transducer over more than one ray path. Since time measurements are based on first arrival, it is a permissible simplification to state that there are now two available paths. One is the direct path (1) of Figure 10, at velocity V_1. The other is the refracted path (2) of Figure 11, along which energy travels down to the underlying material at velocity V_1, through the underlying material at velocity V_2, and back to the surface at velocity V_1.

Obviously, if the impact point is close to the transducer, the direct path offers the shortest travel time. As impact distance increases, and if V_2 is appreciably higher than V_1, a point will be reached at which the refracted path (2) offers a travel time as short as the direct path (1). This point is called the critical point, and its distance from the transducer is called the critical distance. From all impact points beyond the critical point, the first energy to reach the transducer will have traveled over the refracted path (2), i.e., travel times measured from impact points at greater than critical distance will be less than those which would be observed were there no underlying material, hence no refracted path available.

A distinct change in the slope of the travel-time graph thus indicates the presence of underlying material (in this case, concrete) capable of transmitting elastic energy at a velocity higher than that of the surface material. The velocity, V_1, in the surface material is represented by the reciprocal of the slope of the first portion of the graph. The velocity, V_2, in the underlying material is represented by the reciprocal of the slope of the second portion of the graph.

The physics governing the refracted path follows the laws of optics in refractive media. The various rays entering the underlying material are refracted by varying amounts according to Snell's law, i.e., the relation of the sine of the angle of incidence to the sine of the angle of refraction is proportional to the ratio of the velocities in the two materials. One of these rays will therefore be refracted at the correct angle to travel along the surface of the underlying material. This ray, in turn, will continue to emit elastic energy, some of which will eventually be refracted at the correct angle to return to the surface at the transducer.

Calling the depth to the underlying material (first horizon) d, and using the previously given nomenclature, the formula for depth to first horizon can be derived by writing expressions for the travel time from the critical point in terms of the two available paths, and equating these two expressions (since travel times are equal from the critical point), then solving for d. The expressions are derived in all standard tests on exploration geophysics. The resulting depth formula is

$$d = \frac{L}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

where L is the critical distance as observed on the travel-time graph, and V_1 and V_2 are the velocities in the surface and underlying materials, taken from the slopes of the respective portions of the travel-time graph.

Similar expressions can be derived for depths to second, third, and successively deeper horizons, the mathematics in each case becoming somewhat more complicated. For concrete testing, it is doubtful that more than a second horizon (three materials) would ever be encountered. The second horizon (surface of a third material) would appear on the travel-time graph as a second critical point, or change in slope. This might be caused, for example, by medium quality concrete on the surface of a slab, underlain by high quality concrete, both being covered by asphalt. The expression for depth to a second horizon is

$$d_2 = d_1(1 - R) - \frac{L_2}{2}\sqrt{\frac{V_3 - V_2}{V_3 + V_2}}$$

where d_2 is the depth from surface to the second horizon, d_1 is the depth to the first horizon computed by the simpler formula, L_2 is the second critical distance from the transducer to the second change in slope of the travel-time graph, V_3 is the velocity in the third material, and as before, V_2 is the velocity in the second material. R is an algebraic simplification factor related to the ratios of V_3/V_2, and V_2/V_1, having the following values:

Values of V_3/V_2 \ Values of V_2/V_1	1.1	1.5	2	3	5	10
1.1	.39	.17	.12	.06	.03	.02
1.5	.56	.31	.21	.12	.07	.03
2	.60	.34	.24	.15	.08	.04
3	.63	.36	.26	.16	.09	.04
5	.64	.37	.26	.16	.09	.05
10	.64	.38	.27	.17	.11	.05

Values of R