Designation: C1740 – 16

Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method[1]

This standard is issued under the fixed designation C1740; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This practice provides the procedure for using the impulse-response method to evaluate rapidly the condition of concrete slabs, pavements, bridge decks, walls, or other plate-like structures.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.4 The text of this standard references notes and footnotes that provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C125 Terminology Relating to Concrete and Concrete Aggregates

C1383 Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method

D5882 Test Method for Low Strain Impact Integrity Testing of Deep Foundations

E1316 Terminology for Nondestructive Examinations

3. Terminology

3.1 *Definitions:*

3.1.1 Refer to Terminology C125 for general terms related to concrete. Refer to Terminology E1316 for terms related to nondestructive ultrasonic examination that are applicable to this practice.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *impulse-response method, n*—a nondestructive test method based on the use of mechanical impact to cause transient vibration of a concrete test element, the use of a broadband velocity transducer placed on the test element adjacent to the impact point to measure the response, and the use of signal processing to obtain the mobility spectrum of the test element.

3.2.1.1 *Discussion*—Fig. 1 shows the testing configuration for the impulse-response method. The hammer contains a load cell to measure the transient impact force and a velocity transducer is used to measure the resulting motion of the test object (see top plots in Fig. 2). In plate-like structures, the impact results predominantly in flexural vibration of the tested element, although other modes can be excited. Waveforms from the load cell and velocity transducer are converted to the frequency domain and used to calculate the mobility spectrum, which is analyzed to obtain parameters representing the element's response to the impact. These parameters are used to identify anomalous regions within the tested element.

3.2.2 *mobility, n*—ratio of the velocity amplitude at the test point to the force amplitude at a given frequency, expressed in units of (m/s)/N.

3.2.2.1 *Discussion*—For a plate-like structure, mobility is an indicator of the relative flexibility of the tested element, which is a function of plate thickness, concrete elastic modulus, support conditions, and presence of internal defects. A higher mobility indicates that the element is relatively more flexible at that test point (**1,2**).[3]

3.2.3 *mobility ratio, peak-mean, n*—the ratio of the peak mobility value between 0 to 100 Hz to the average mobility between 100 to 800 Hz

3.2.3.1 *Discussion*—A high ratio of the peak mobility to the average mobility has been found to correlate with poor support

[1] This practice is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.64 on Nondestructive and In-Place Testing.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

*A Summary of Changes section appears at the end of this standard

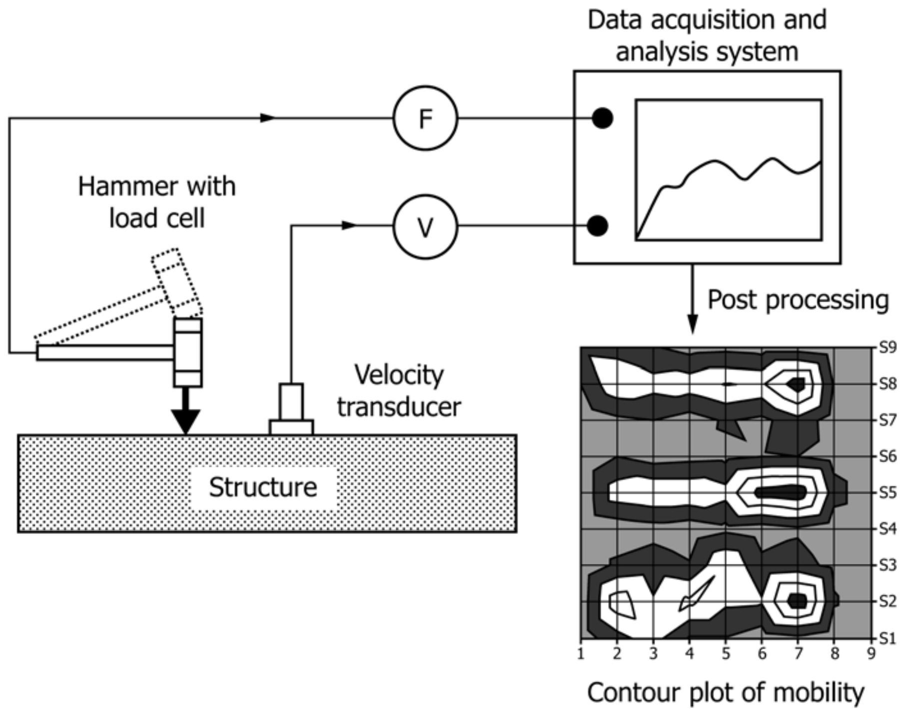

FIG. 1 Schematic of the Test Set-Up and Apparatus for Impulse-Response Test

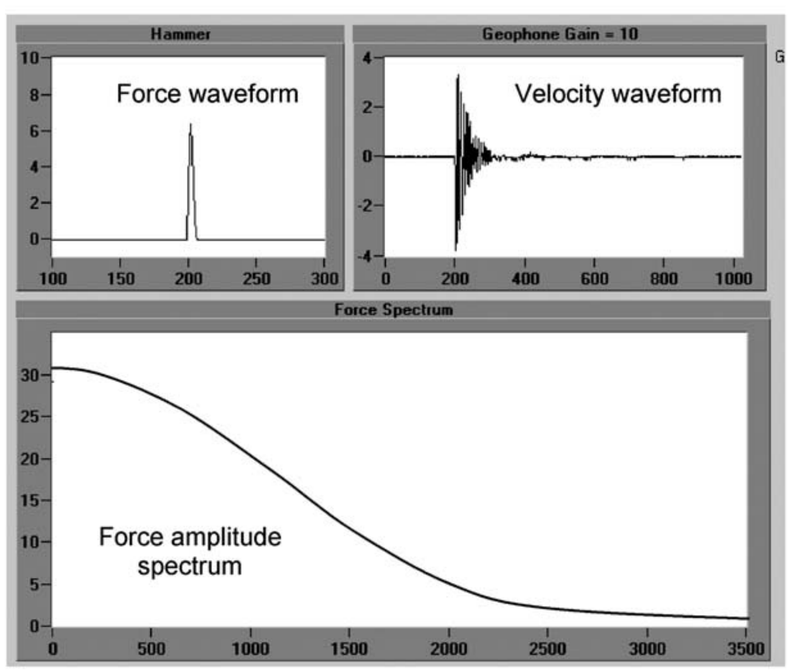

FIG. 2 Typical Force-Time Waveform and Amplitude Spectrum Plots for Hammer with a Hard Rubber Tip

conditions or voids that may exist beneath concrete slabs bearing on ground (**1**,**2**).

3.2.4 *mobility, average, n*—average of the mobility values from the mobility spectrum between 100 and 800 Hz, expressed in units of (m/s)/N.

3.2.4.1 *Discussion*—This parameter is used to compare differences in overall mobility among test points in the tested element (**1**,**2**).

3.2.5 *slope, mobility, n*—the slope of the mobility spectrum obtained from the best-fit line to mobility values between 100 Hz and 800 Hz.

3.2.5.1 *Discussion*—A high mobility slope has been found to correlate with locations of poorly consolidated (or honeycombed) concrete in plate-like structures (**1**,**2**).

3.2.6 *spectrum, mobility, n*—the value of mobility as a function of frequency obtained from an impulse-response test at one point on the surface of the tested element.

3.2.6.1 *Discussion*—The mobility spectrum, also referred to as the *transfer function*, is obtained by converting the recorded waveforms of the hammer impact force and velocity response into the frequency domain (**3**,**4**). The resulting spectra are used to compute the mobility spectrum as follows:

$$M(f) = \frac{V(f) \times F^*(f)}{F(f) \times F^*(f)} \tag{1}$$

where:

$M(f)$ = mobility spectrum,
$V(f)$ = velocity spectrum,
$F(f)$ = impact force spectrum, and
$F^*(f)$ = complex conjugate of force spectrum.

The numerator is the cross power spectrum of the force and velocity and the denominator is the power spectrum of the force. Matrix multiplication by the complex conjugate of the force spectrum is required because the velocity and impact force spectra are matrices of complex numbers. By the rule for division of complex numbers, the numerator and denominator have to be multiplied by the complex conjugate of the denominator, that is, the force spectrum. Fig. 3 is an example of a mobility spectrum. The vertical axis represents response velocity amplitude per unit of force and the horizontal axis is frequency.

3.2.7 *stiffness, dynamic*—inverse of the initial slope of the mobility spectrum from 0 to 40 Hz, expressed in units of N/m (See Fig. 3).

3.2.7.1 *Discussion*—The initial slope of the mobility spectrum defines the dynamic compliance (or flexibility) at the test point. The inverse of the initial slope is the dynamic stiffness, which is an indicator of the relative quality of the concrete, of the relative thickness of the member, of the relative quality of the subgrade support for slabs-on-ground, and of the support conditions for suspended structural slabs and walls (**1**,**2**).

4. Summary of Practice

4.1 A grid is laid out on the surface of the concrete element to be tested. Grid spacing normally ranges between 500 mm and 2000 mm and is selected on the basis of the size and shape of the element to be tested. A closer spacing is used for smaller elements and to locate smaller anomalous regions.

4.2 A hand-held hammer with a force measuring load cell is used to impact the concrete surface and generate transient stress waves in the concrete test element. These waves set up flexural and other vibrational modes of the element in the vicinity of the test point.

4.3 The impact point is within 100 ± 25 mm of the velocity transducer used to measure the response due to the hammer blow.

4.4 The force and velocity waveforms are recorded and subjected to digital signal processing to obtain the mobility spectrum at each test point. Key parameters are computed from the mobility spectra at the test points and displayed in the form of contour plots from which the likely locations of anomalous regions can be identified.

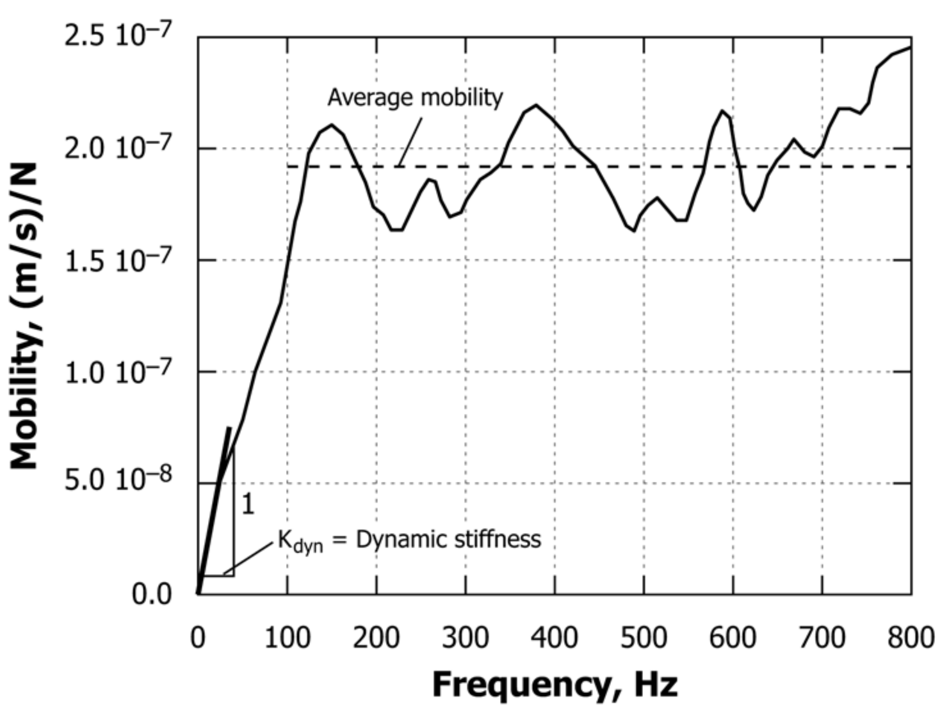

FIG. 3 Example of a Mobility Spectrum Obtained from an Impulse Response Test of a Plate-Like Concrete Element

5. Significance and Use

5.1 The impulse-response method is used to evaluate the condition of concrete slabs, pavements, bridge decks, walls, or other concrete plate structures. The method is also applicable to plate structures with overlays, such as concrete bridge decks with asphalt or portland cement concrete overlays. The impulse-response method is intended for rapid screening of structures to identify potential locations of anomalous conditions that require more detailed investigation.

5.2 This practice is not intended for integrity testing of piles. For such applications refer to Test Method D5882.

5.3 This practice can be used to locate delaminated or poorly consolidated concrete. It can also be used to locate regions of poor support or voids beneath slabs bearing on ground.

5.4 Results are used on a comparative basis for comparing concrete quality or support conditions at one point in the tested structural element with conditions at other points in the same element, or for comparing a structural element with another element of the same geometry. Invasive probing (drilling holes or chipping away concrete) or drilling of cores is used to confirm interpretations of impulse-response results.

5.5 Because concrete properties can vary from point to point in the structure due to differences in concrete age, batch-to-batch variability, or placement and consolidation practices, the measured mobility and dynamic stiffness can vary from point to point in a plate element of constant thickness.

NOTE 1—The flexural stiffness of a plate is directly proportional to the elastic modulus of the material and directly proportional to the thickness raised to the third power (**5**). As a result, variations in thickness will have a greater effect on variations in mobility than variations in elastic modulus.

5.6 The effective radius of influence of the hammer blow limits the maximum concrete element thickness that can be tested. The apparatus defined in this practice is intended for thicknesses less than 1 m.

5.7 For highway applications, results may be influenced by traffic noise or low frequency structural vibrations set up by normal movement of traffic across a structure. The intermittent nature of these noises, however, may allow testing during traffic flow on adjacent portions of the structure. Engineering judgment is required to determine whether the response has been influenced by traffic-induced vibrations.

5.8 Heavy loads on suspended slabs may affect test results by altering the frequencies and shapes of different modes of vibration. Debris on the test surface may interfere with obtaining a sharp impact and with measuring the response.

5.9 The practice is not applicable in the presence of vibrations created by mechanical equipment (jack hammers, sounding with a hammer, mechanical sweepers, and the like) impacting the structure.

5.10 Tests conducted next to or directly over structural elements that stiffen the plate will result in reduced mobility and not be representative of the internal conditions of the plate.

5.11 The practice is not applicable in the presence of electrical noise, such as that produced by a generator or other electrical sources, that is captured by the data-acquisition system.

6. Apparatus[4]

6.1 Fig. 1 is a schematic of the basic components of a suitable test system.

6.2 *Hammer*—A nominal 1-kg hammer with a 50-mm diameter cylindrical rubber tip of sufficient hardness to produce an impact force amplitude spectrum spanning at least 2 kHz. The hammer shall have a built-in load cell, capable of measuring dynamic forces up to 20 kN. The resonant frequency of the load cell shall exceed 10 kHz.

NOTE 2—Commercially available hammers equipped with load cells have been found to produce the required force amplitude spectrum. Fig. 2 shows a typical force-time waveform and force amplitude spectrum for a hammer with a hard rubber tip. The maximum frequency in the amplitude spectrum of the waves generated by hammer impact is related inversely to the duration of the impact.

6.3 *Transducer*—A broadband, induction coil, velocity transducer (geophone) that responds to normal surface motion. The transducer shall have a natural frequency less than 15 Hz and a constant sensitivity over the range 15 to 1000 Hz.

NOTE 3—Commercially available induction coil velocity transducers with a base diameter of 50 mm have been found suitable. Such a transducer is housed in a case with three protruding screws or spikes around its perimeter forming a tripod for stability during testing. No coupling material such as gel or grease is needed to couple the transducer to the concrete.

6.4 *Data-Acquisition and Analysis System*—Hardware and software for acquiring, recording, and processing the outputs of the hammer load cell and velocity transducer. The system shall be capable of displaying test results immediately after impact and storing test results.

NOTE 4—A portable computer with a two-channel data-acquisition card or a portable two-channel waveform analyzer is acceptable. A computer data-acquisition card with a voltage range of $\pm$ 5 V and 8-bit resolution has been found to be suitable for the transducer described. Higher voltage ranges and resolutions are also suitable.

6.4.1 The sampling rate for each channel shall be 10 kHz or higher (sampling interval of 100 µs or less). The recorded waveforms from the load cell and velocity transducer shall contain at least 1024 points each (see Note 5). The system shall be capable of triggering on the signal from the hammer channel.

NOTE 5—The sampling frequency should be about 10 times the maximum frequency of interest. For typical concrete structural elements, the maximum frequency of interest is about 1 kHz. For a sampling rate of 10 kHz and 1024 points, the frequency resolution is about 10 Hz. For faster sampling rates, the number of points in the waveforms should be increased to maintain a similar frequency resolution. Typical signal processing software that is used to compute the velocity and force spectra requires that the number of points in the waveforms be a power of 2 (for example, 512, 1024, 2048 and so forth).

6.4.2 The voltage range of the data-acquisition system shall be matched with the sensitivity of the transducers so that the

[4] Suitable apparatus is available commercially.

peak hammer force and response velocity are measured without clipping of the signals.

6.4.3 Software shall be provided for acquiring, recording, displaying, analyzing, and storing data. The display shall include voltage versus time waveforms for both the impact force and velocity measurements for each test. The software shall compute the mobility spectrum from the recorded waveforms. The mobility spectrum shall be displayed immediately after the waveforms have been captured.

NOTE 6—Fig. 4 is an example of a computer display showing the time domain waveforms in the upper plots and the mobility spectrum in the lower plot.

6.4.4 The data-acquisition system shall be operated by a power source that does not produce electrical noise detectable by the transducers and data-acquisition system when the system is set at the voltage sensitivity required for the particular structural element under test.

NOTE 7—Battery-powered data-acquisition systems have been found suitable.

6.5 *Cables and Connectors*—Use shielded cables to connect the force and velocity transducers to the data-acquisition system. Connectors shall be high quality and attached tightly to the cables.

6.6 *Calibration of Hammer Load Cell*—The hammer load cell shall be calibrated by the hammer manufacturer, and a certificate shall give the sensitivity factor in mV/N. Load cell calibration shall be renewed at least every 12 months or sooner if there is an indication of improper performance.

6.7 *Calibration of Velocity Transducer*—The velocity transducer shall be calibrated by the manufacturer, and a certificate shall give the sensitivity in mV/(m/s). Transducer calibration shall be renewed at least every 12 months or sooner if there is an indication of improper performance.

7. Preparation of Test Surface

7.1 The test surface can be dry, moist or wet, but not inundated. Remove any debris from the immediate vicinity of each test point.

7.2 If the test surface is extremely rough so that it is difficult to achieve good contact between the transducer base and the concrete or obtain the correct impact duration, grind the surface so that good contact and proper impact are achieved. Remove loose material before placing the transducer on the surface.

NOTE 8—Surface roughness may be a problem when testing weathered or deteriorated concrete surfaces, but is not normally a problem when testing highway pavements with roughly textured or grooved surfaces. If the hammer impact fractures the surface or dislodges particles, grinding may be needed to obtain an impact of sufficiently short duration, that is, less than about 0.5 ms.

7.3 Tests are not to be performed within 300 mm of the edge, a continuous crack, or a joint of a plate-like structure because of the effect of a plate boundary on test results.

8. Procedure

8.1 Connect the load cell and velocity transducer to the data acquisition system. Verify that the test system is functioning properly in accordance with the manufacturer's instructions.

8.2 Ready the data-acquisition system with appropriate data-acquisition parameters (sampling rate, voltage range, triggering level, and transducer amplification).

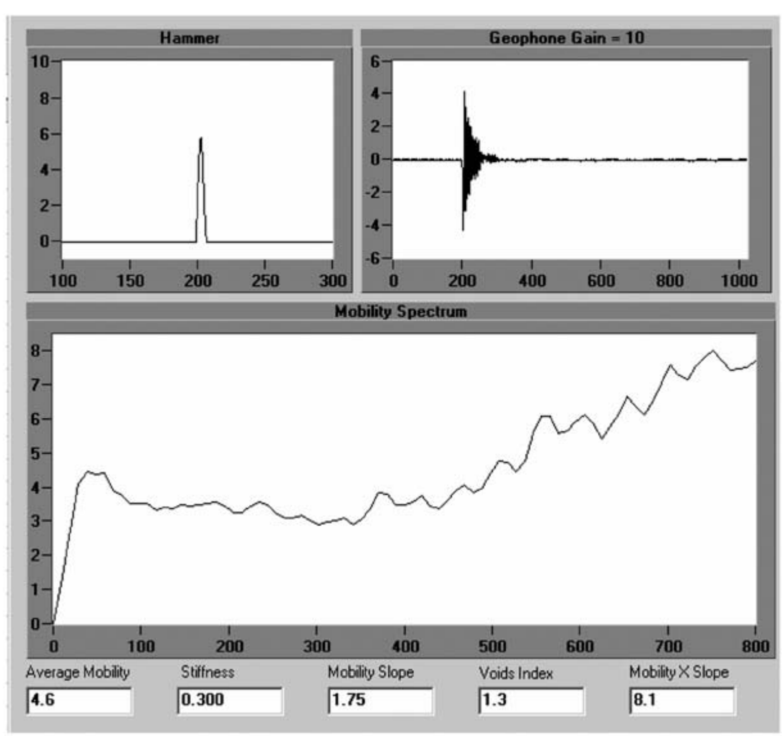

FIG. 4 Valid Set of Waveforms for Hammer Voltage Versus Time and Velocity Transducer Voltage Versus Time (Mobility Spectrum is at Bottom)

8.3 Position the transducer at the intended test point so that it measures velocity perpendicular to the surface. Position the hammer to strike at a distance of 100 ± 25 mm from the transducer. If testing on a roughened or grooved surface, position the transducer on its tripod support so that no rocking of the transducer base occurs.

8.4 Perform the impact. Examine the acquired waveforms. If the waveforms from both the hammer and transducer are valid (See Note 9), compute the mobility spectrum and display the calculated average mobility from 0 to 800 Hz. Store the data for subsequent analysis.

8.5 Repeat the test at the same impact point. If the second average mobility value is within ± 5% of the first value, proceed to the next point on the test grid, and repeat 8.3 and 8.4. If the second average mobility value is not within ± 5% of the first value, move the transducer location or impact point to within 50 to 75 mm from the original test point and repeat 8.3 and 8.4. If the new test point does not result in a repeatable value, move to the next grid point and indicate in the report that a repeatable test was not obtainable at that grid point.

NOTE 9—Fig. 4 is an example to illustrate a valid set of waveforms and mobility plot. A valid force-time waveform has a half-cycle, sine-curve shape with a constant base voltage. A valid velocity transducer waveform has a constant base voltage, with the response signal oscillating 10 to 15 times about the base value with continuously decreasing amplitude. This indicates that the velocity transducer is stable during data acquisition and no extraneous vibration affected the test. Fig. 5 is an example of an invalid velocity transducer waveform, as a result of movement of the transducer base during the test. This is evidenced by a varying base voltage on the waveform and a large amplitude peak at a low frequency on the mobility spectrum.

9. Calculations and Presentation of Results

9.1 For each test point, use the values in the mobility spectrum to calculate the following parameters as defined in Section 3:

9.1.1 average mobility;
9.1.2 dynamic stiffness;
9.1.3 mobility slope; and
9.1.4 peak-mean mobility ratio.

9.2 Use the values of these parameters at each grid point to construct contour plots of each parameter. Select contour intervals that are consistent with the ranges of values of the parameters obtained at the grid points.

NOTE 10—Fig. 6 illustrates a contour plot of average mobility. Appendix X1 provides guidance on interpreting results.

10. Report

10.1 Report the test grid parameters. These include the test spacing, number of test rows and columns in the grid, and reference points for grid location.

10.2 Provide description of the condition of the test surface.

10.3 For concrete slabs-on-ground, report the design slab thickness, the type of material supporting the slab, if known, and the locations of joints, cracks, or edges.

10.4 For suspended slabs and walls, report the design slab thickness, the support conditions, such as beam and column locations, and locations of cracks or joints.

10.5 For each test point, report average mobility, dynamic stiffness, mobility slope and peak-mean mobility ratio, in accordance with the definitions in Section 3.

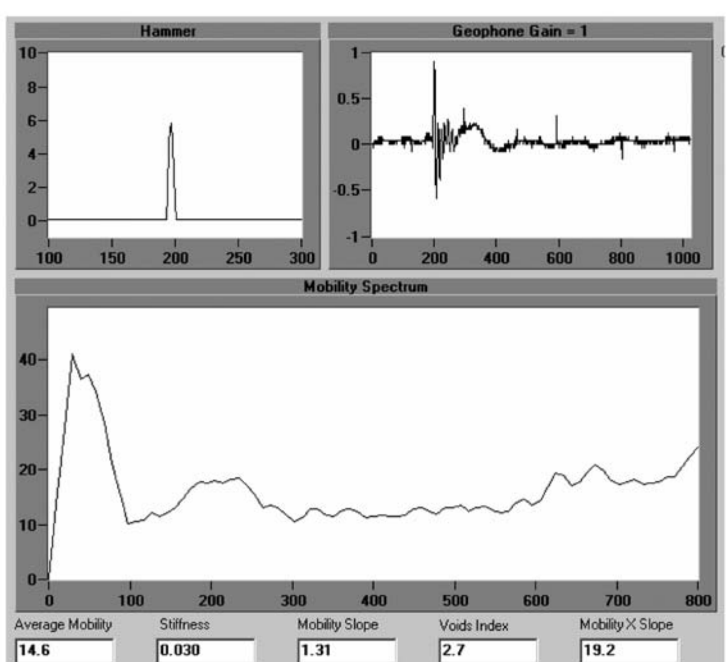

FIG. 5 Invalid Waveform (Upper Right Plot) Caused by Movement of the Velocity Transducer Base

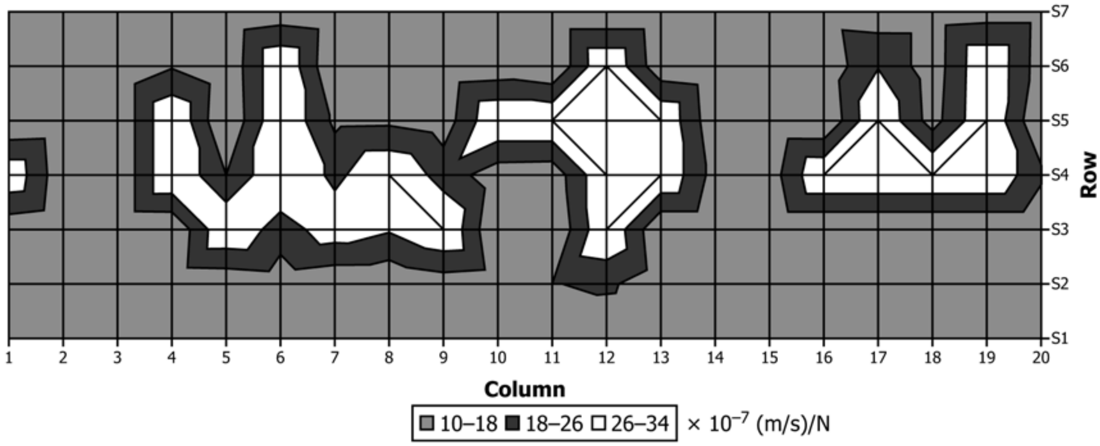

FIG. 6 Typical Contour Plot of Average Mobility (White Regions Indicate Higher Mobility)

10.6 Provide contour plots for each parameter.

11. Keywords

11.1 concrete plate; dynamic mobility; dynamic stiffness; impulse response; nondestructive testing

APPENDIX

(Nonmandatory Information)

X1. INTERPRETATION OF RESULTS

X1.1 Impact Response

X1.1.1 The impact response of a structural element is complex and depends on the geometry and boundary conditions of the element, the material properties, and the location and duration of the impact. Because of these complexities, it is not practical to use absolute values of measured impact responses to infer the internal conditions of a test element. The practical approach is to evaluate the response at different test points on a comparative basis. Those regions of the structure with unusually higher measures of mobility (velocity per unit of force) can be selected for further examination, either by other test methods or by invasive probing. This appendix provides basic information about the parameters measured by impulse-response testing according to this practice. Interpretation of results should be done only by trained personnel.

X1.2 Mobility Spectrum

X1.2.1 The output of the impulse-response method described in this practice is the mobility spectrum, which summarizes the response of the member as a function of frequency. Mobility represents the maximum velocity at a given frequency at the test point per unit of applied impact force. A high mobility means that the unit force results in a relatively high velocity. Thus mobility is related to the flexibility of the structural element at the test point. For plate-like structures, the mobility is related to the plate thickness, support conditions, the density and elastic modulus of the concrete, and the presence of defects. A series of regularly-spaced, high peaks in the mobility spectrum usually indicate resonant frequencies.

X1.3 Average Mobility

X1.3.1 The test element's vibrational response to the impact-generated elastic wave will be moderated by the element's intrinsic rigidity. For a plate, the average mobility value over the 100 to 800 Hz frequency range is related directly to the density, elastic modulus, thickness, and whether there are defects in the plate (**1**,**2**). Fig. X1.1 is a schematic of a concrete slab-on-ground with a sub-grade void and a region of honeycombed concrete. As will de discussed, the response of the slab to impact will be affected by conditions in the vicinity of the impact.

A reduction in plate thickness corresponds to a large increase in mean mobility, because flexural rigidity is proportional to the thicknesses raised to the third power (**5**). As an example, when total delamination of an upper layer occurs in a plate, the mobility at that test point will be much higher than for a test over a sound portion of the element. Cracking or honeycombing in the concrete will reduce rigidity, and experience has shown that mobility plots show a characteristic increase in mobility with frequency (**6**). Variations in average mobility recorded across a tested element that is known to have a consistent thickness can indicate anomalous regions that may require further investigation. Additional testing, such as by the impact-echo method (Test Method C1383) or invasive probing

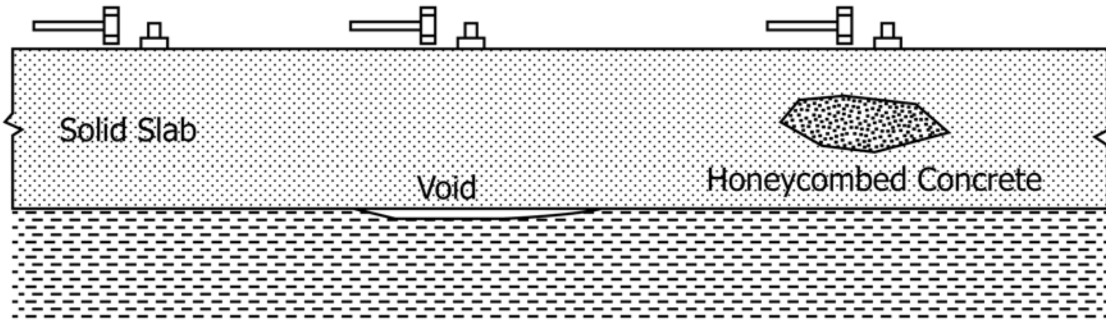

FIG. X1.1 Example of Slab-on-Ground with Different Types of Defects

should be performed in areas of higher average mobility to confirm possible variations in concrete quality. Variations in average mobility recorded across a test area with only one side visible (such as slabs-on-ground or retaining walls) can be due to changes in element thickness, material properties, or support conditions. Impact-echo testing may be used to verify whether there is a change in thickness.

X1.4 Dynamic Stiffness

X1.4.1 The slope of the portion of the mobility spectrum up to about 40 Hz defines the dynamic compliance or dynamic flexibility of the area around the test point (**1**,**2**). The inverse of the dynamic compliance is the dynamic stiffness of the structural element at the test point in units of N/m. The dynamic stiffness is a function of the elastic modulus of the concrete, the element thickness, element support conditions, and presence of internal defects.

X1.5 Mobility Slope

X1.5.1 It has been found that when the mobility plot from a test on sound concrete is compared with the plot from a test on concrete with honeycomb inclusions, the honeycombed zone shows increasing mobility with increasing frequency over the frequency range 100-800 Hz, whereas the solid concrete maintains a relatively constant average mobility over the same frequency range (Fig. X1.2) (**2**,**7**). The rising mobility with frequency is a direct function of reduction in mass damping of the velocity response over this frequency range. The mobility slope is determined from the best linear fit to the mobility spectrum between 100 and 800 Hz. A contour plot of mobility slope can be used to indicate regions where there is high likelihood of poorly consolidated (honeycombed) concrete. Because honeycombed concrete often occurs in small pockets, closer grid spacing may be required to locate such regions. The

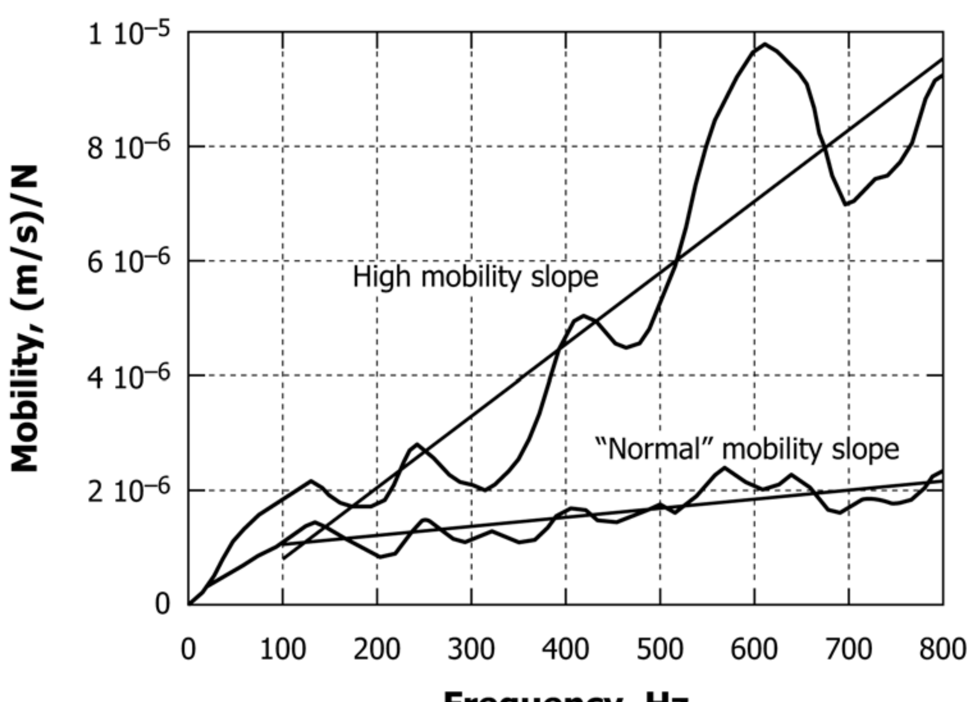

FIG. X1.2 Example of Steep Mobility Spectrum at a Test Point with Poor Consolidation Compared with Spectrum at Point with Sound Concrete

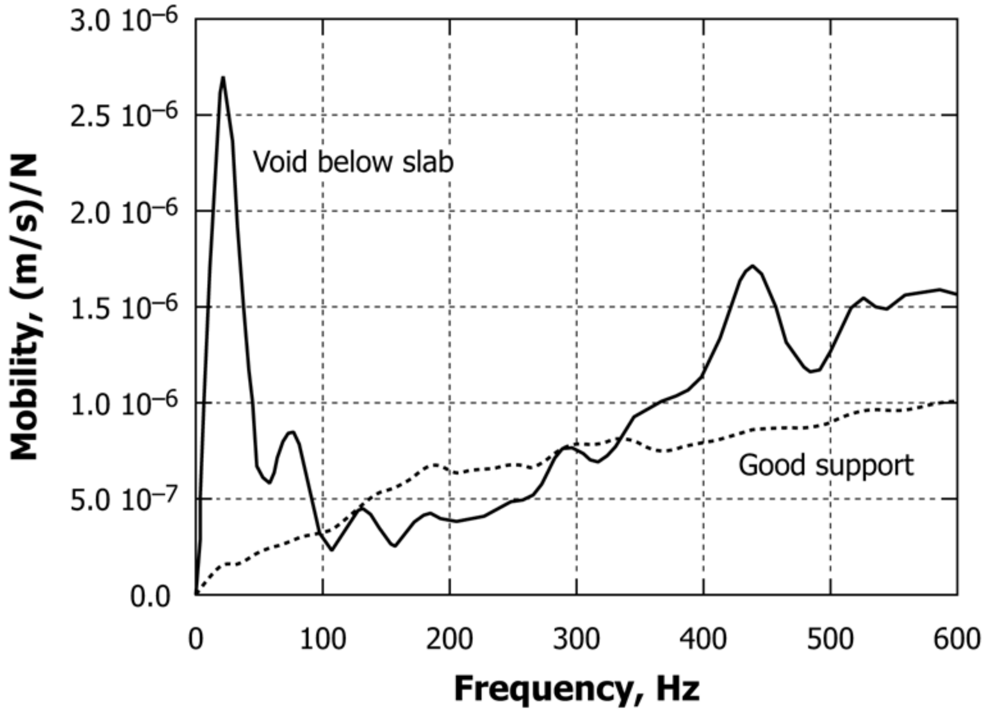

FIG. X1.3 Example of Mobility Spectrum for Test on Slab-on-Ground with Void Below Slab Compared with Test at Point Without Void

existence of honeycombing should be confirmed by invasive probing or by impact-echo testing in combination with invasive probing.

X1.6 Peak-Mean Mobility Ratio

X1.6.1 When debonding or delamination is present within a structural element, or when there is loss of support beneath a concrete slab supported on ground, the response behavior of the uppermost layer dominates the response. In addition to the increase in average mobility between 100 and 800 Hz, the dynamic stiffness decreases greatly. The peak mobility below 100 Hz becomes appreciably higher than the average mobility between 100 and 800 Hz (see Fig. X1.3). The ratio of this peak to average mobility is an indicator of the presence of either debonding within the element or loss of support beneath a slab-on-ground (**6**). Based on experience, when the peak-mean mobility ratio exceeds 2.5, loss of support beneath slabs-on-ground is likely (**6**). Loss of support may be confirmed by drilling holes and inspecting the conditions at the bottom of the slab.

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SUMMARY OF CHANGES

Committee C09 has identified the location of selected changes to this standard since the last issue (C1740–10) that may impact the use of this standard. (Approved Dec. 15, 2016.)

(1) Removed reference to Test Method C1383 in 3.1.1 and 3.2.1.1.