# INDUSTRIAL FLOORS ON GROUND

## 1. Introduction

Industrial floors on ground are engineered structures with significant demands placed on them, such as high-density storage with heavy rack loads and very flat and smooth surfaces for smooth operation of lift trucks. As a result, floors account for more complaints than any other part of industrial facilities. The Portland Cement Association (PCA) publication EB075, *Concrete Floors on Ground* [11] lists the factors influencing floor performance, including:

- Uniformity and bearing capacity of the subgrade support
- Concrete quality (density, uniformity, finishing and curing)
- Structural capacity (thickness)
- Load transfer at joints

These particular factors are highlighted because it is possible to examine their significance at any particular site using nondestructive testing (NDT) techniques. The NDT approach becomes valuable when large floor areas have to be checked. The methods described here have been developed to test large areas rapidly, with storage of data for the record on computers. The three most useful NDT methods are:

- Impulse Response (s'MASH)
- Impact-Echo (Docter)
- Impulse Radar

The first two tests use *stress waves* generated by impact on the slab surface, and Impulse Radar uses high frequency *radar pulses* generated by an antenna placed on the surface of the slab. These methods are described in Reference 10, and their operating principles are given in the Appendix to this document. In essence, the Impulse Radar test allows a very rapid measurement of slab thickness, easily correlated with concrete core values [12]. Radar also can be used to examine for the presence, depth and alignment of dowel bars at slab joints and the location of steel reinforcing. The s'MASH test can quickly map slab curl and support conditions, concrete quality such as poor consolidation, delamination and cracking, as well as provide information on variations in concrete thickness. S'MASH also can give information on load transfer across slab joints. Docter testing is used to pinpoint the location and extent of defects in the concrete, including the depth to cracking, delamination and honeycombing, as well as slab thickness..

Applying the NDT test approach can create very large savings in time and cost, together with increased confidence in the evaluation conclusions because of the greater percentage of tested slab area.

## 2. Typical Testing Approach

This depends on the problem(s) existing in the slab:

a. Slab support and slab curl: s'MASH
b. Delamination and spalling due to rebar corrosion: s'MASH
c. Load transfer across slab joints: s'MASH
d. Slab cracking: s'MASH and Docter
e. Variations in thickness: Impulse Radar and Docter
f. Dowel bar alignment: Impulse Radar

The two stress wave tests require a grid to be laid out on the slab. Typical grid spacing for Impulse Response is 1 to 1.5 m, and Impact-Echo grid spacing would depend on the area to be examined. Impulse Radar uses linear traversing; with preliminary traverse spacing at 1.5 m. Coring at selected areas after testing is advised in cases a, b, d and e to correlate the findings of the NDT program.

## g. s'MASH - Floor Slab/Pavement Support Conditions

Impulse Response was first applied to slab support evaluation following Paquet's experiments with the Djakarta airport slabs at CEBTP, Paris France in 1981[2]. This was the first departure from traditional pile testing using Impulse Response. Trials in 1983 on the perimeter road for an old Royal Air Force airfield in Abingdon, England showed that poor support beneath concrete pavement could be detected. The first indicator that poor slab support was characterized by a reduction in s'MASH dynamic stiffness accompanied by an early mobility peak below 100 Hz with a mobility value greater than that expected for the slab thickness. When these test locations were excavated, the observations did confirm voiding beneath the slab joints. It must be stated that any interpretation of the response curves to indicate voiding was purely empirical at that stage.

Testconsult (United Kingdom) demonstrated this test approach in 1985 in the USA to both Arkansas and Oklahoma State Departments of Transportation on a section of jointed concrete pavement on Interstate Highway 40, just to the west of Little Rock. The demonstration convinced Oklahoma DOT to conduct further trials on US 69 near Muskogee on 15 ft long by 12 ft wide jointed slabs founded on "hot sands" (sand asphalt) as base. Initially, a one-mile section was tested with a 3 x 3 test point grid per slab using manual sounding with a single hammer/geophone system. After interpretation of the data, Oklahoma selected two full slabs for careful removal to examine the degree of success in identifying voiding. The results proved conclusive, and a further ten miles of US 69 were tested by the single manual method [1, 2]. The test helped to quantify the amount of grout required for injection to stabilize the pavement slab. At the same time, Impulse Response testing detected the effect of slab curl provoked by diurnal temperature change. Testing had to be performed at night, because maximum upward curl at slab corners and edges occurred when top-of-slab temperature is at its lowest, and vice versa. Industrial floors in buildings can be tested at any time to examine slab curl.

The success of the Impulse Response test in void detection led to a research initiative at UTEP to examine the theory behind testing of slab-like structures founded on grade [5, 6, 7]. This application has seen continued growth in the 1990s, and has been extended to large concrete slab-on-ground structures such as industrial factory and warehouse floors, parking areas and airport runways [2, 4, 9]. Probably the greatest advance to help this test approach has been the development of fast data acquisition systems on laptop PCs, with the possibility to analyze test data on site and to display Impulse Response parameters in spreadsheet contour plots immediately testing is completed. The following paragraphs describe case histories of this application.

### h. s'MASH - Slab Concrete Consolidation and Honeycombing

The trials run by Paquet at CEBTP in 1981 on slabs with built-in defects showed that intentional honeycombing in the slabs was detected by comparing the s'MASH mobility spectra for sound and honeycombed concrete. When the mobility of a sound slab was compared with that of concrete with honeycomb inclusions, it was noted that the latter showed increasing mobility with increasing frequency over the frequency range 100-800 Hz, whereas the former maintained a relatively constant average mobility over the same frequency range. Typical test responses showing this comparison are given in Figures ** in the following case histories.

At that time, the reason for the shift in mobility was not understood, and the observation and its application to studies of real structures were purely empirical. Subsequent studies at University of Texas El Paso [5,6,7,8] have allowed the separation of the Impulse Response spectrum stiffness function from the damping function, and have been useful in understanding the difference in response between sound and poorly consolidated concrete.

It now appears that the rising mobility with frequency is a direct function of change in damping of the velocity response over this frequency range. This was suggested by Reddy [6] and has been confirmed by experimental work.. Figure 1 shows constant mobility for a sound test point compared with that of a point with poor consolidation with rising mobility taken from tests on a reinforced concrete water tank wall 300 mm thick.
This mobility slope is measured by calculating the linear best fit of the $|V_0/F_0|$-frequency spectrum between 100-800 Hz, then dividing the 800-Hz mobility by the 100-Hz mobility values on this linear best fit. Typical values of this parameter for sound concrete vary between 1 and 3. When mobility slope values rise significantly above 3, poor consolidation and honeycombing have been confirmed in many documented cases, up to depths of 450-500 mm from the structure surface.

### Industrial Floor Slab - Case History

The s'MASH test evaluated a 9600 sq m industrial reinforced concrete floor slab for the presence of poorly consolidated areas, as well as voiding in the slab base. The slab design thickness for the entire area tested was 200 mm. Average mobility and stiffness contour plots indicated areas with probable slab thickness less than 200 mm. Coring of select locations and impulse radar traverses correlated overall floor slab thickness with core thickness. The Voiding Index when >2 showed voided/poor support areas beneath the slab (Figure 2). s'MASH also identified an area of potentially honeycombed or voided concrete. This was confirmed by coring at selected locations. In addition, areas of lower stiffness were located along construction joints, which is typical of jointed slabs on grade (Figure 3). Fieldwork was completed in 3 days!

### References


1. Pederson, C.M. and L.J. Senkowski, 1986. *"Slab Stabilization of PCC Pavements"*, Paper presented at TRB Annual Conference, Washington, D.C. Jan. 1986.
2. Davis, A.G. and B.H. Hertlein, 1987. *"Nondestructive Testing of Concrete Pavement Slabs and Floors with the Transient Dynamic Response Method"*, Proc. Int. Conf. Structural Faults & Repair, London, July 1987, Vol. 2, 429–433.
3. Davis, A.G., *"CEBTP and the English Channel Tunnel"*, TRB Annual Conf., Washington, D.C., Jan. 1990, 11 pp.
4. Scull, T.P. and A.G. Davis, 1990. *"Experiences in Nondestructive Testing by Impulse Radar and Impedance Methods in the Evaluation of Concrete Highways"*, 6$^{th}$ Int Symp. on Concrete Roads, Madrid, Oct. 1990, 103–112.
5. Nazarian, S., M. Baker and R. Smith, 1991. *"Measurement Concepts and Technical Specifications of Seismic Pavement Analyzer"*. Strategic Highway Research Program, Washington, D.C.
6. Reddy, S. 1992, *"Improved Impulse Response Testing: Theoretical and Practical Validations"*, Master of Science Thesis, University of Texas at El Paso (Director, S. Nazarian), 219 pp.
7. Nazarian, S and M. Baker, 1992 *"A New Nondestructive Testing Device for Comprehensive Pavement Evaluation"*. Proc. Conf. Nondestructive Evaluation of Civil Structures and Materials, University of Colorado at Boulder, May 1992 (Ed. Suprenant, Noland & Schuller), 437-452.
8. Nazarian, S, M.R. Baker and K. Crain, 1993. *"Development and Testing of a Seismic Pavement Analyzer"*. Research Report H-375, Strategic Highway Research Program, Washington, D.C., 165 pp.
9. Hertlein, B.H. and A.G. Davis, 1996. *"Performance-based and Condition-based NDT for Predicting Maintenance Needs of Concrete Highways and Airport Pavements"*. Conf. Nondestructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware, R.D. Rempt and A.L. Broz, Ed., Proc SPIE 2945, 273-281, Scottsdale, AZ, December 1996.
10. American Concrete Institute Report ACI 228.2R-98, *"Nondestructive Test Methods for Evaluation of Concrete in Structures"*. ACI, Farmington Hills, Michigan, 1998, 62 pp.
11. Farny, J.A., 2001. *"Concrete Floors on Ground"*, EB075, Portland Cement Association, Skokie, Illinois, USA, 136 pp.
12. Lim, M.K., 2001. *"Publication in CI"*.

# APPENDIX

## THE IMPULSE RESPONSE TEST

The Impulse Response (IR) test method is a nondestructive, stress wave test, used extensively in the evaluation of machined metallic components in the aircraft industry. Its application to concrete structures in Civil Engineering is less well known, and the method has received far less publicity than the recently developed Impact-Echo (I-E) test (Sansalone & Streett, 1997). Both methods are described in the American Concrete Institute Report ACI 228.2R-98, "*Nondestructive Test Methods for Evaluation of Concrete in Structures*".

The IR method (also referred to in earlier literature as the Transient Dynamic Response or Sonic Mobility method) is a direct descendant of the Forced Vibration method for evaluating the integrity of concrete drilled shafts, developed in France in the 1960's (Davis & Dunn, 1974). The basic theory of dynamic mobility developed at that time has not changed; however, its range of applications to different structural elements has increased to incorporate the following problems:

- voiding beneath concrete highway, spillway and floor slabs (Davis & Hertlein, 1987),
- delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimney stacks and silos (Davis & Hertlein, 1995),
- low density concrete (honeycombing) and cracking in concrete elements (Davis & Hertlein, 1995; Davis *et al,* 1997),
- the depth of ASR attack in drilled shafts used as pylon foundations (Davis & Kennedy, 1998),
- debonding of asphalt and concrete overlays to concrete substrates (Davis *et al*, 1996),
- the degree of stress transfer through load transfer systems across joints in concrete slabs (Davis & Hertlein, 1987).

### IR Testing Equipment

The IR method uses a low strain impact to send a stress wave through the tested element. The impactor is usually a 1-kg sledgehammer with a built-in load cell in the hammerhead. The maximum compressive stress at the impact point in concrete is directly related to the elastic properties of the hammer tip. Typical stress levels range from 5 MPa for hard rubber tips to more than 50 MPa for aluminum tips. Response to the input stress is normally measured using a velocity transducer (geophone). This receiver is preferred because of its stability at low frequencies and its robust performance in practice. Both the hammer and the geophone are linked to a portable field computer for data acquisition and storage.

### Method Description

When testing plate-like structures, the Impact-Echo method uses the reflected stress wave from the base of the concrete element or from some anomaly within that element (requiring a frequency range normally between 10 and 50 kHz). The IR test uses a compressive stress impact approximately 100 times that of the I-E test. This greater stress input means that the plate responds to the IR hammer impact in a bending mode over a very much lower frequency range (0-1 kHz for plate structures), as opposed to the reflective mode of the I-E test.

Both the time records for the hammer force and the geophone velocity response are processed in the field computer using the Fast Fourier Transform (FFT) algorithm. The resulting velocity spectrum is divided by the force spectrum to obtain a transfer function, referred to as the *Mobility* of the element under test. The test graph of Mobility plotted against frequency over the 0-1kHz range contains information on the condition and the integrity of the concrete in the tested elements, obtained from the following measured parameters:

- *Dynamic Stiffness:* The slope of the portion of the Mobility plot below 0.1 kHz defines the compliance or flexibility of the area around the test point for a normalized force input. The inverse of the compliance is the dynamic stiffness of the structural element at the test point. This can be expressed as:

  Stiffness *f [concrete quality, element thickness, element support condition]*

- *Mobility and Damping:* The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). The mean mobility value over the 0.1-1 kHz range is directly related to the density and the thickness of a plate element, for example. A reduction in plate thickness corresponds to an increase in mean mobility. As an example, when total debonding of an upper layer is present, the mean mobility reflects the thickness of the upper, debonded layer (in other words, the slab becomes more mobile). Also, any cracking or honeycombing in the concrete will reduce the damping and hence the stability of the mobility plots over the tested frequency range.
- *Peak/Mean Mobility Ratio:* When debonding or delamination is present within a structural element, or when there is loss of support beneath a concrete slab on grade, the response behavior of the uppermost layer controls the IR result. In addition to the increase in mean mobility between 0.1 and 1 kHz, the dynamic stiffness decreases greatly. The peak mobility below 0.1 kHz becomes appreciably higher than the mean mobility from 0.1-1 kHz. The ratio of this peak to mean mobility is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

## THE IMPACT-ECHO TEST

Like the Impulse Response test, the Impact-Echo (IE) test uses stress waves to detect flaws within concrete structures. However, the frequency range used is considerably higher in the I-E test, since much shorter wavelengths are required to detect smaller anomalies. Surface displacements caused by reflecting stress waves can be viewed versus time as a displacement waveform. The amplitude spectrum of this waveform is computed by FFT, as for the Impulse Response. This spectrum has a periodic nature, which is a function of the depth to the reflective boundary (either the back of the element, or some anomaly such as a crack in the element under test. The depth of a concrete/air interface (internal void or external boundary) is determined by:

$$d = v_c \, / \, 2f \qquad (1)$$

$d$ is the interface depth, $v_c$ is the primary stress wave velocity and f is the frequency due to reflection of the P wave from the interface.

If the material beyond the reflective interface is acoustically stiffer than concrete (e.g. concrete/steel interface), then the following equation applies:

$$d = v_c \, / \, 4f \qquad (2)$$

The difference in the acoustic impedance of the two materials at an interface determines whether the presence of an interface will be detected by an I-E test. For example, a concrete/grout interface gives no reflection of the stress wave because the acoustic impedance of concrete and grout are nearly equal. In contrast, at a concrete/air interface, nearly all the energy is reflected, since the acoustic impedance of air is very much less than concrete.

## THE IMPULSE RADAR TEST

The impulse radar technique employs high-frequency electromagnetic energy waves for rapidly and continuously assessing a variety of characteristics of concrete structures. The principle of operation is based on reflection of electromagnetic waves from varying dielectric constant boundaries in the material being probed. The impulse radar equipment is self-contained, compact, and portable. The system consists of the main radar unit, antenna and transducer cable. All data is stored in the main radar unit, by means of a computer hard drive.

A single or double contacting transducer (antenna) transmits and receives radar signals. High frequency, short pulse electromagnetic energy is transmitted into the element (concrete, sub-base etc.). Each transmitted pulse travels through the material, and is partially reflected when it encounters a change in dielectric constant. The receiving section of the transducer detects reflected pulses. The location and depth of the dielectric constant boundary is evaluated by noting the transit time from start of pulse to reception of reflected pulse. Boundary depth is proportional to transit time. Since concrete to air, water, and/or backfill interfaces are electronically detected by the instrument as dielectric constant boundaries, the impulse radar method is capable of assessing a variety of reinforced concrete, masonry and environmental characteristics.

Impulse radar has been successfully used to evaluate the thickness of concrete slabs in industrial floors, locations of embedded reinforcing, to distinguish between grouted and ungrouted cells in masonry block walls, to locate high chloride concentration in bridge decks, embedded foreign objects (clay balls) in concrete pavement, and alignment of dowel bars and the consolidation of the concrete around dowel bars in concrete pavement.

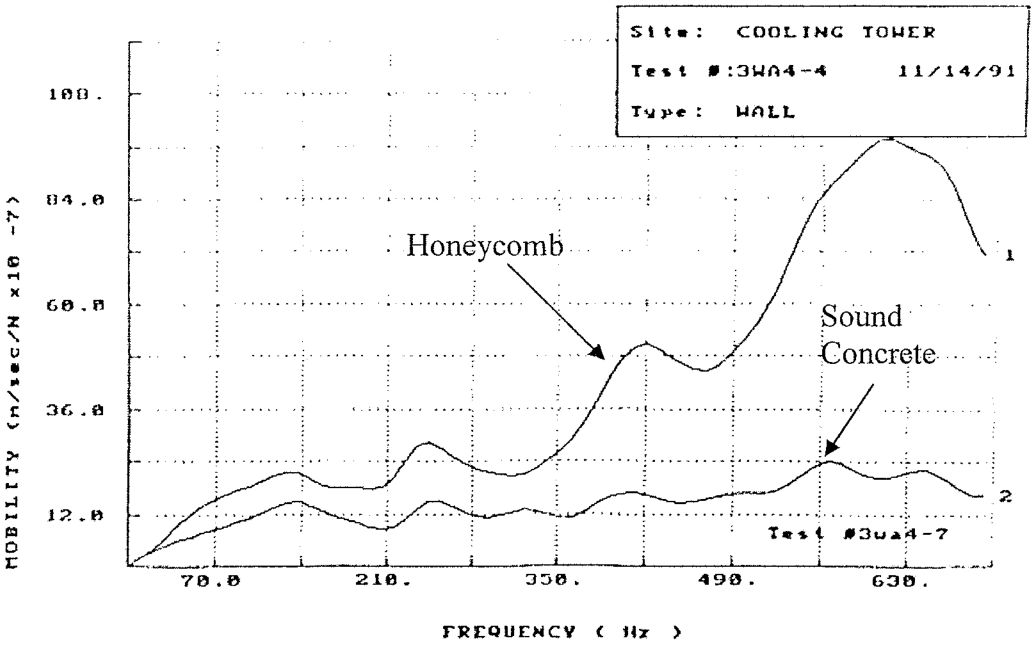
### Consolidation of Concrete Around Dowel Bars

Dowel bars are used to assist in load transfer between concrete slabs. The dowels are usually placed at mid-depth to reduce joint deflection due to heavy loads. Dowels are usually placed in baskets or pushed directly into the plastic concrete with an automatic dowel bar inserter. Both horizontal and vertical alignment is important for dowels to function appropriately. Any misalignment in the dowels can cause the concrete pavement joints to lock up, not allowing the slab to move freely and causing cracks. One of the key problems with a dowel bar inserter is voiding of the concrete above the dowel bars, resulting in a weak plane and not allowing full load transfer.

Impulse radar surveys to evaluate for the consolidation of the concrete around dowel bars are performed in conjunction with surveys to evaluate any misaligned dowel bars. For misalignment surveys, a twin radar antenna setup is used, spaced 300 mm apart. The apparatus is then rolled along the slab joint with one antenna on either side of the joint. Post processing is performed on the data, noting the depth and the position of the reflection of the dowel bar on either side of the joint to evaluate for any misaligned bars. Voiding above the bar is noted usually as a change in the reflected signal. Poor consolidation (voiding) above the dowel bars can affect the load transfer capabilities of the bar and render the bar ineffective.

### References


1. Davis, A.G. and C.S. Dunn, 1974, "From theory to field experience with the nondestructive vibration testing of piles," *Proc. Inst. Civ. Engrs.* Part 2, 59, Dec., pp. 867-875.
2. Davis A.G. and B.H. Hertlein 1987, "Nondestructive testing of concrete pavement slabs and floors with the transient dynamic response method," *Proc. Int. Conf. Structural Faults and Repair,* London, July 1987, Vol. 2, pp. 429-433.
3. Davis, A.G. and B.H. Hertlein, 1995, "Nondestructive testing of concrete chimneys and other structures," *Conf. Nondestructive Evaluation of Aging Structures and Dams,* Proc. SPIE 2457, 129-136, Oakland CA, June 1995.
4. Davis, A.G., J. G. Evans and B.H. Hertlein, 1997, "Nondestructive evaluation of concrete radioactive waste tanks," *Journal of Performance of Constructed Facilities,* ASCE, Vol. 11, No. 4, November 1997, pp. 161-167.
5. Davis, A.G., B.H. Hertlein, M. Lim and K. Michols, 1996, "Impact-Echo and Impulse Response stress wave methods: advantages and limitations for the evaluation of highway pavement concrete overlays," *Conf. Nondestructive Evaluation of Bridges and Highways,* Proc. SPIE 2946, 88-96, Scottsdale AZ, December 1996.
6. Davis, A.G. and J. Kennedy, 1998, "Impulse Response testing to evaluate the degree of alkali-aggregate reaction in concrete drilled-shaft foundations for electricity transmission towers", *Conf. Nondestructive Evaluation of Utilities and Pipelines II,* Proc. SPIE 3398, 178-185, San Antonio, TX, April 1998.
7. Sansalone, M. and W.B. Streett, 1997, "Impact-Echo: nondestructive evaluation of concrete and masonry," Bullbrier Press, Ithaca, NY.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36.0
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MOBILITY (m/sec/N x10 -7)
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Sound Concrete
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2
Test #3wa4-7
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490.
630.
FREQUENCY ( Hz )

Figure 1

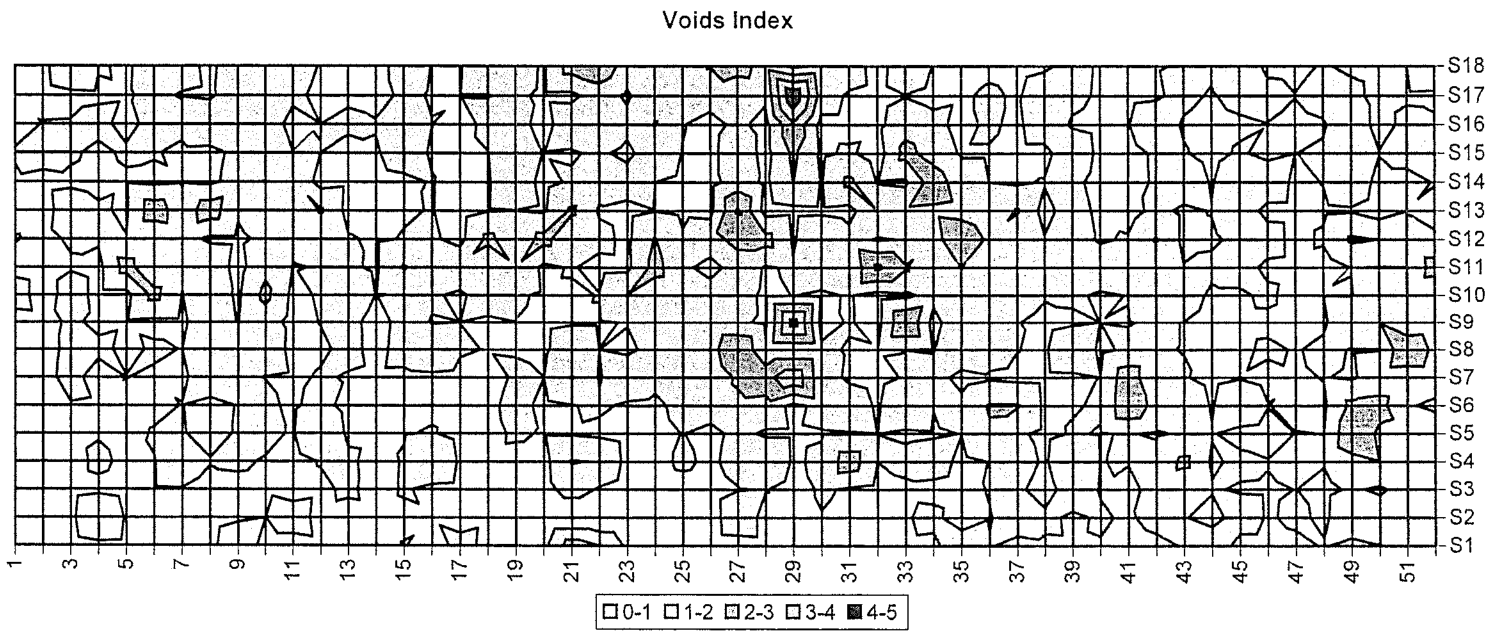
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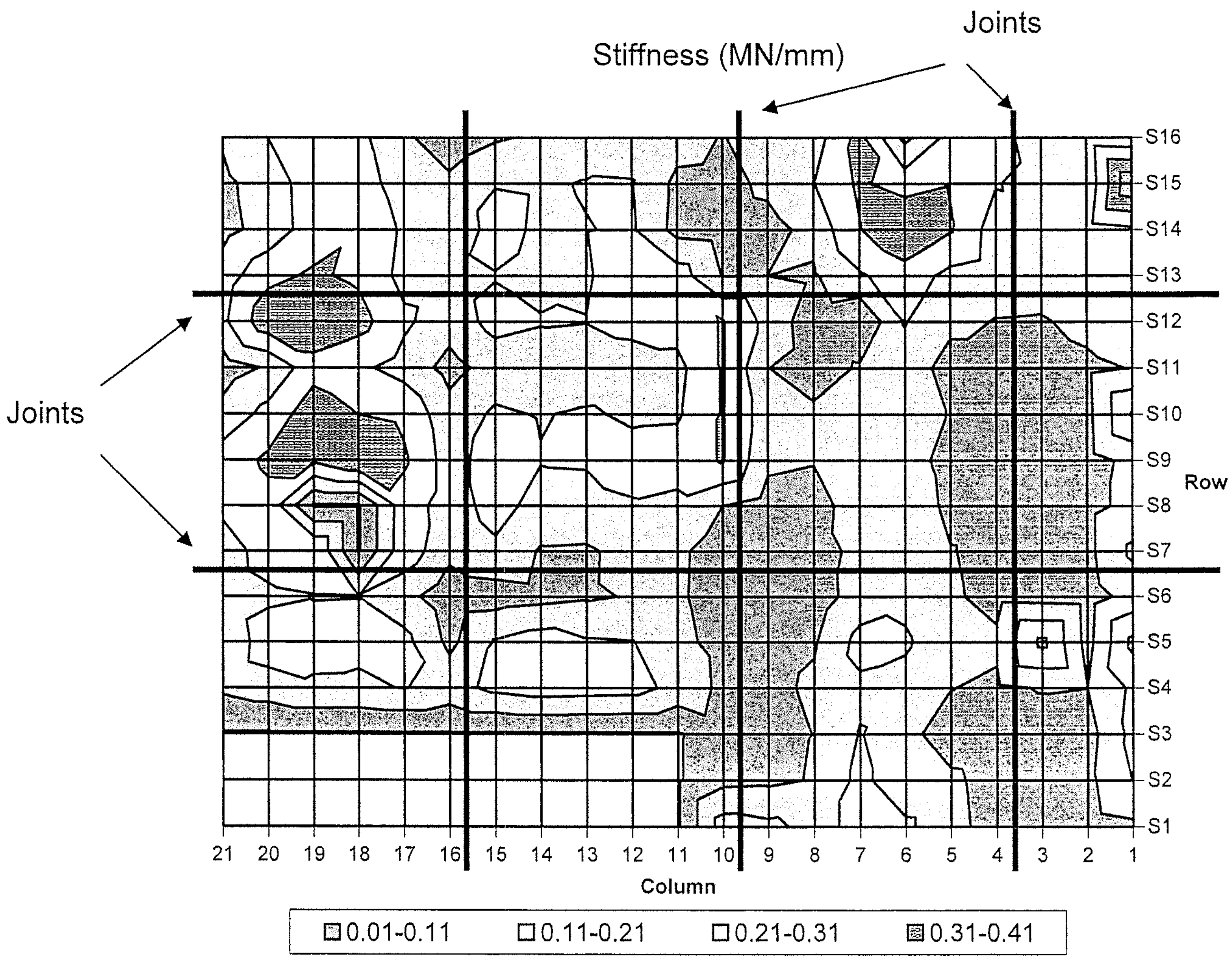
Figure 2


Stiffness (MN/mm)
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Joints
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S14
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
S3
S2
S1
Row
21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
Column
0.01-0.11
0.11-0.21
0.21-0.31
0.31-0.41

Figure 3