The Effectiveness of Non-Destructive Testing for Decision Making in Structural Assessments – A Case Study using Impulse Response Method

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ABSTRACT: Infrastructures around the world are aging. To ensure continued safe use of the aging infrastructures, there is an on-going need to actively manage the structural condition, undertake repairs, and/or strengthening. As part of these processes, Engineers are required to carry-out inspections, structural testing and investigations, and structural assessments. The use of Non-Destructive Techniques (NDTs) along with minimal destructive testing can enable efficient evaluation of the structural condition, and target deteriorated areas for repairs, rehabilitation, and strengthening. There are many types of NDT systems available within the Civil Engineering industry, from simple devices to highly advanced systems. The selection of the right system leads to a better match between the information needed by the Engineers for their assessments and the information collected on-site. The collection of appropriate data when testing leads to more effective decision-making in structural assessments. This paper presents a brief overview of certain NDTs. A case study is presented where the impulse response method was successfully used in assessing multiple composite slabs in a larger floor. Based on the comparative analysis of the NDT results, a limited number of slabs (poorest performing slabs in terms of certain NDT parameters) were further evaluated by static load testing. The case study shows that the use of a NDT technique led to a cost-effective evaluation of the in-situ slabs. This paper thus provides an example of the use of NDT methods for better decision-making in structural assessments for the practicing engineers and relevant personnel.

KEY WORDS: Existing building, structural assessment, cost-effective evaluation, non-destructive testing, impulse response method.

1 INTRODUCTION

Civil engineering infrastructures around the world are aging. To ensure continued safe use, there is an on-going need to actively manage these old infrastructures. Moreover, with high environmental and economic impact of new construction, the choice to reuse and extend the life service has become more desirable and efficient. In fact, more than half of the all construction activities in recent years relate to the existing buildings, bridges, and other civil engineering works [1]. Assessment of structural condition is important before carrying out any repair or maintenance work. If the defects or damage in a structure can be identified properly, an efficient repair strategy can be applied and hence, the cost of repair will be reduced. Non-destructive testing (NDT) can greatly help assessing the performance of the structures or identifying the damage within the structures [2]. NDTs are usually non-invasive indirect techniques that provide information on the physical or other mechanical properties of the structural elements. During NDT assessment, the condition of the concrete is inferred from the measured response to some stimulus, such as impact or electromagnetic radiation. The use of NDT helps reduce the extent of destructive or invasive investigation of the structure. Once the reliability of the NDT method is established, the assessment of the structure can be done economically [3].

NDT technologies are improving and with the advancement of technological aspects and quick data processing capability allows for investigating larger areas of a structure at a faster rate. There are several NDT methods available for investigation different types of defects or damage within the structures. A comprehensive review of the NDT methods with their principles and field of applications is documented in the literature [2,4,5].

NDT methods can offer the advantages by providing information related to the in-situ properties of hardened concrete, such as, elastic properties, density, resistivity, moisture content, penetrability characteristics, etc. Also, NDTs offer information regarding the in-situ quality of concrete i.e., delamination, presence of voiding, honeycombing. Location and size of reinforcement, corrosion activity of reinforcement can also be estimated using NDTs.

Selection of NDTs to be used for structural investigation is a choice by the Engineers. Proper choice of NDT will lead to a better match between the information needed and the information collected on-site. The appropriate selection of NDT, thus, will lead to more effective decision-making in structural assessments.

This paper presents such a practical application of NDTs where the performance of an existing structure was evaluated in a cost-effective way. The paper also provides a brief overview of commonly used NDT systems and their applications. The paper focuses on the application of Impulse Response (IR) test in a comparative evaluation of the structural performance of multiple slabs in an existing floor structure. The IR test was used as a fast-screening method where the anomalous areas of the floor were differentiated from relatively sound areas. The selected areas of the floor based on the IR test were further investigated to finally assess the overall capacity of the slabs. Since the invention, the IR test has been reported to be applied for locating voids, delamination, honeycombing, and/or poor supporting condition in concrete structures as well as for pile integrity assessment.

2 BRIEF OF OVERVIEW OF NDT METHODS

Different types of NDTs are used for different purposes during the condition evaluation of existing structures. Many of the methods are completely non-destructive, while certain methods require localised intrusion on the surface. NDTs can be grouped into few different categories depending on the purpose of use on-site. A brief overview on the possible applications of several methods is provided here.

2.1 NDTs for mechanical properties of concrete

For the assessment of in-situ compressive strength of concrete, NDTs such as rebound hammer, Ultrasonic Pulse Velocity (UPV) and Cut And Pull Out (CAPO), penetration resistance test are frequently used both in industry and research. Combination of two or more NDTs, especially rebound hammer and UPV (i.e., SonReb) are popular. ACI 228.1R [6], RILEM TC249-ISC [7] and EN 13791 [8] provide detailed guidelines on the use of the NDTs, interpretation of results in evaluating the in-situ compressive strength of concrete.

2.2 NDTs for relative quality assessment of concrete

NDTs used for assessing mechanical properties of concrete can provide useful information in evaluating variation in the apparent properties of concrete within the structure. Ultrasonic pulse echo is cable of locating delamination and voids in relatively thin elements [9,10]. Sounding technique is an efficient tool to locate delaminated areas. Infrared thermography is a newly adopted technology in the industry in evaluating delamination, cracked areas in concrete [11].

Impact echo can help locating defects within the concrete elements such as delamination, voids, honeycombing or measure element thickness [12]. Impulse response provides information regarding the relative quality of concrete in an area of a structure [13].

2.3 NDTs for structural make-up in concrete

Low frequency alternating magnetic field (commercially known as covermeter) can locate the embedded steel reinforcement, measure depth of cover, and estimate diameter of reinforcement [5]. Ground Penetrating Radar (GPR) is useful in locating metal embedment, pipes, voids, regions of high moisture and thickness of different layers (if present) and members [14]. Ultrasonic pulse echo can measure element thickness in relatively thin elements [9].

2.4 NDTs for durability related issues

Half-cell potential can identify the regions in a structure with high probability of corrosion [5]. Polarisation methods determine the instantaneous corrosion rate of the reinforcement located below the test point [5]. Electrical resistivity can be used for the performance-based evaluation of concrete as resistivity is directly linked to the chloride penetration into concrete [15]. Penetrability methods indicate penetrability characteristics of concrete which in turn can provide an indication of concrete resistance against aggressive ions [16].

3 IMPULSE RESPONSE (IR) TEST METHOD – A CASE STUDY

This paper presents a case study where the IR technique was applied to assess the performance of multiple composite metal deck slabs in an existing structure. The concrete slabs exhibited cracking at different locations. Previous investigations where cores were removed indicated low to moderate compressive strength. Out of 40no. slabs in the floor, 30no. slabs were determined to have compressive strength below 30 MPa. There was a concern that the slab would not be suitable for the design load of 3 kPa. To ensure the performance of the floor, full-scale static load testing was initially proposed. A full-scale load test would be a time-consuming operation involving higher costs and operational disruption in the building. Instead of full-scale load testing on all the suspected slabs, a cost-effective and rapid assessment using the IR technique was proposed. Thus, IR testing was performed on 31no. slabs including one reference slab in order to identify the poorest performing slabs in the floor. The reference slab was selected based on the in-situ compressive strength of concrete in the slab and design performance of the slab. Based on the data obtained by the IR testing, the 3no. poorest performing slabs were identified and assessed by static load testing for the selected design criteria.

3.1 Theoretical background of IR test method

The IR test was developed as a steady state vibration test for investigating pile shafts in the early 1970s [17]. In the 1980s, especially with the advancement of portable computers, data acquisition system, increased data storage facilities and data processing, the test has developed to investigate other concrete structures such as concrete slab on ground, pavements, bridge decks, walls, particularly plate-like structures, etc. ASTM C1740-10 "Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method" provides the procedure and technical aspects for using the IR test method to evaluate the condition of the concrete structures rapidly [13].

The test is a low strain, elastic stress wave propagation method. The test involves the use of mechanical impact to cause transient vibration of a concrete test element, the use of a 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 [13]. Figure 1 shows the schematic of the test set-up and apparatus of the IR test.

A load cell is incorporated within the hammer to measure the transient impact force and a velocity transducer is used to measure the resulting response of the test object. The impact mainly results in flexural vibration of the tested element. Force time history from the load cell and velocity time history from the velocity transducer are converted to the frequency domain and mobility spectrum, a basic output of the test, is computed using FFT (Fast Fourier Transformation) algorithm. This mobility plot is later used to analyse and obtain parameters representing the element's response to the impact. These parameters are then used to locate the areas of anomaly within the tested element [18]. Figure 2 shows an example of a mobility plot obtained from the IR test of a plate-like concrete element.

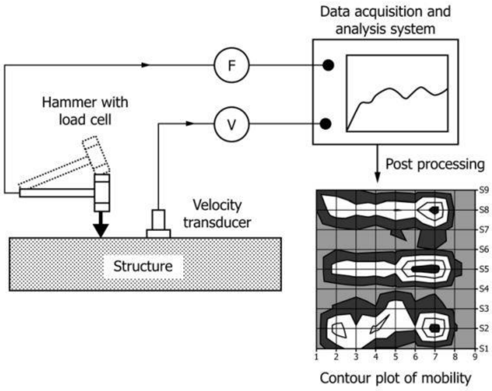

Figure 1: Schematic of the test set up and apparatus (taken from [13])

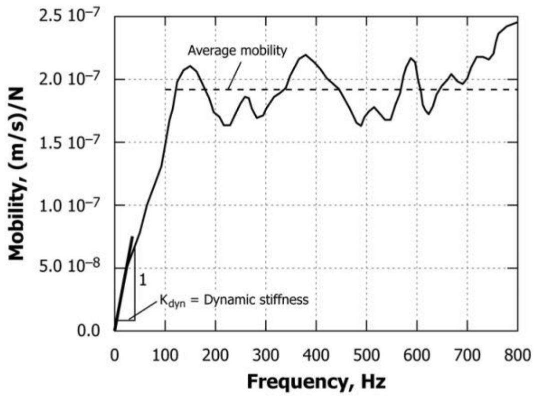

Figure 2: Typical Mobility (taken from [13])

3.2 Application of IR Test and Its Limitations

The IR test method is used for the condition assessment of concrete slabs, pavements, bridge decks, walls, or other plate like concrete structures. The method is also applicable to overlay structures such as asphalt or portland cement overlays on the bridge decks. Review of the application of the method suggests various successful application for identifying the potential poor areas within concrete [19,20]. A range of applications for the test method includes investigation on delamination/spalling/debonding [21,22], honeycombing and poorly consolidated concrete [23], cracking [24,25], assessing wall thickness variability [24], quality of support condition [18], etc.

The test can be used for rapid screening of the structures to identify potential locations of anomalous conditions that require more detailed investigation. Destructive or invasion testing such drilling holes or cores or chipping away concrete can be used to confirm the IR test results.

The following are parameters used for evaluation of concrete structures:

- **Average mobility:** It is defined as the ratio of the velocity amplitude at the test point to the force amplitude at a given frequency. The mean value of the mobility within the frequency range of 100-800 Hz is taken as the average mobility, see Figure 2. It is an indication of the relative flexibility and directly related to the density, support condition, and thickness of the structure as well as the concrete elastic modulus. A comparatively higher value in an apparently homogenous area may indicate reduced thickness, delamination, or voiding within the concrete.
- **Dynamic stiffness:** It is the inverse of the initial slope of the mobility plot from 0 to 40 Hz, see Figure 2, where the initial slope defines the dynamic compliance or flexibility at the test point. An indication of the stiffness of the structure at the test point and can be a function of relative quality of concrete, element thickness and support condition.
- **Mobility slope:** It is the slope of a best – fit line to fit the mobility curve between 100 and 800 Hz. This parameter is used to find poorly consolidated areas of concrete. A higher slope or non – stable mobility plot can be correlated with the areas of honeycombed or poorly consolidated concrete.
- **Peak-mean mobility ratio or void index:** It is the ratio of the peak mobility value between 0-800 Hz to the average mobility as defined above. This is an indication of the support condition or potential void within the concrete. A higher value indicates loss of support or voids beneath concrete slab bearing on ground.

The method is an empirical based method and uses a comparative assessment. The test does not provide any indication of the depth and size of the defects within the concrete. Lack of understanding of the response of the plate-like structures and no prior knowledge of the boundary conditions of the structure may lead to misinterpretation of the data. The results may be influenced by noise from traffic movement or low frequency structural movement. Heavy loads on suspended structures may alter the frequencies and shape of different modes of vibration and hence may affect the test results [13].

3.3 Proposed Methodology

As discussed, previous application of IR method successfully identified the problematic areas within concrete and later confirmed by other NDTs and/or invasive methods. Unlike other studies (where single area of concrete was the target for investigation), 31no. areas of slab were targeted to determine the poorest performing slabs on a comparative basis based on the results of the IR test. The structural system for all the slabs is similar; 160 mm concrete on the metal deck with 60 mm trapezoidal rib profile, primary beams between columns, columns being at 9m centres, and secondary beams at 3m centres along one direction. One of the 31no. slabs was taken to be the reference slab for comparative assessment of the other slabs. The locations of the slab area for the investigation are shown in Figure 3. It is to be noted that the floor surface had a polished finishing on top. Cracking was observed on the surface of the slab. In some slabs, there was evidence of repair works.

For the assessment of the slab, *s'MASH* Impulse Response system, a system developed by Germann Instruments, was used. Each slab was marked with a grid of 500 mm x 500 mm, thus providing 289no. of test points per slab area. In areas where the test slab had reduced accessibility, the number of test points varied. The evaluation of each test point on the top surface of the concrete surface was completed using the software provided by Germann Instruments. The data was

analysed, and the parameters associated with the test such as, the Average Mobility, Stiffness, Mobility Slope, Void Index, and the Mobility multiplied by Slope were calculated.
The test results were further analysed using statistical software to evaluate the condition of the slab with respect to the reference slab. The data obtained from individual slabs were analysed and compared with reference slab using first order statistics, pattern of distribution of the data, box-plot representations, tables, and graphs. In addition, Analysis of Variance (ANOVA), t-test and multiple comparison post-hoc tests were performed. Also, normalised contour plot data for all the slabs were visually assessed to evaluate the findings of the statistical analysis. This helped to identify the slab locations for further load testing for capacity evaluation. All mathematical computations were performed using Microsoft Excel Package and IBM SPSS Statistics (Version 27).

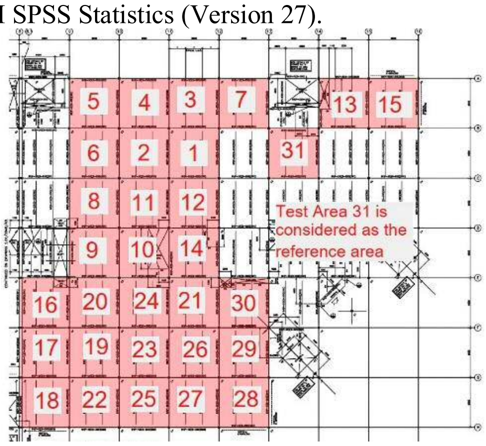

Figure 3: Individual slab locations in the floor during the assessment of composite metal deck slabs using the IR test.

3.4 Results of the IR test method

s'MASH Impulse Response testing provides four outputs (often referred to as parameters), namely the average mobility, dynamic stiffness, mobility slope, and void index. Each output is sensitive to different slab conditions and therefore indicating different properties associated with the slab. After the testing was done and data assembled and analysed on-site for each slab, a visual inspection of the slab was carried out to identify any anomaly present on the slab. As mentioned before, the slabs had severe cracking in certain areas and had repair patches in a few locations. Figure 4 shows the typical contour plots of different parameters, i.e., average mobility, dynamic stiffness, and void index. All the slabs had similar structural system. Hence, the parameters of the impulse response test would not be influenced by the structural system, rather depend on the inherent properties of the slab, such as, relative quality of concrete, elastic modulus, cracked and delamination areas, quality of concrete bond with the metal deck, etc. Assessment of average mobility parameter provided an indication of the poor, heavily cracks areas on the slab, see Figure 4(a). The locations of the secondary beams in the slab were clearly identified by assessing dynamic stiffness parameter, shown in Figure 4(b). Assessment of concrete based on the void index would indicate loss of support or voids beneath concrete slab bearing on ground. As all the slabs were supported on primary and secondary beams at fixed locations, the void index value confirmed the voiding under the slab and also the locations of the beams under the slab. Mobility slope is correlated with the areas of honeycombed or poorly consolidated concrete. Due to the thin section of the slab, no clear conclusion was made from the mobility slope data.

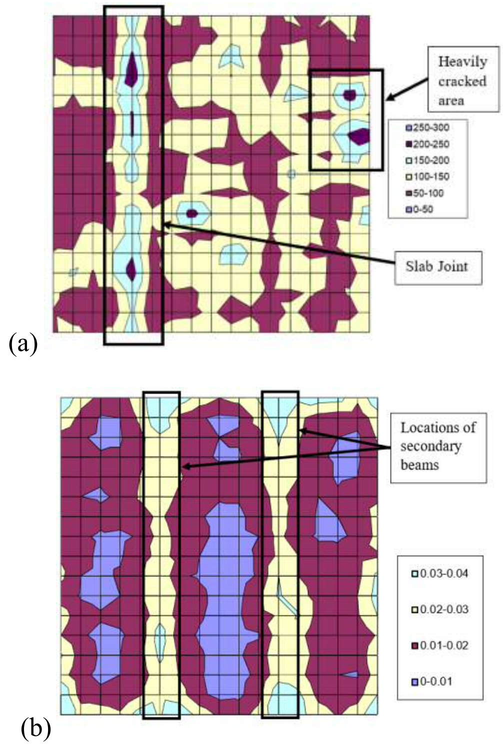

Figure 4: Contour plots of different parameters of the IR test; (a) average mobility for slab 31 (Reference Slab), and (b) dynamic stiffness for slab 6.

3.5 Analysis of the IR test results

Each parameter of the s'MASH Impulse Response test is sensitive to different slab conditions and therefore indicating different properties associated with the slab. Analysis of the output parameters will provide information on the changes of the properties within the slab and thus the poor/weak performing areas can be identified and assessed for further investigation. In order to identify the poorest performing slabs against the reference slab, a series of statistical analyses were performed, and the results were evaluated in a step-by-step procedure.
As indicated by Levene's Test for homogeneity of variance, null hypotheses of equal variance are rejected for all the datasets for a significance level of 95%. In this case, Welch's test (assuming normally distributed data with unequal variance) and Kruskall-Wallis H test (assuming equal variance and non-normally distributed data) were both performed. In both cases, p-value being less than 0.05 for a significance level of 95%, the analyses suggested that there are significant differences between the slabs for each type of datasets.

As in all cases, the null hypotheses of normally distributed data are rejected for a significance level of 95%. For this reason, both parametric and non-parametric tests were performed in the analysis. It is to be note that for sufficient number of data, ANOVA test can provide robust performance against non-normally distributed dataset. Mann-Whitney U test (with the assumption of normally distributed data is violated for t-test) was also performed to compare the performance of the slabs with the reference slab. Based on the p-value and other statistical parameters using appropriate post-hoc tests (such as highest absolute mean difference using ANOVA, highest absolute Z value using the Mann-Whitney test), the slabs were ranked and studied for the poorest possible performance as indicated by the test parameters.

Also, mean and median plots were studied to assess the performance of the slabs with respect to the reference slab. Mean plots with standard deviation as error bar are shown in Figure 5 for average mobility data. Based on the highest absolute difference from the mean value and associated standard deviation, the slabs were ranked and studied for the poorest possible performance as indicated by the test parameters relative to the reference slab. Similar studies were performed for other sets of data, such as, dynamic stiffness, mobility slope, void index, and mobility x slope. Due to limitation of space, the plots are not shown in the paper.

A summary of the statistical analysis of test data is provided in Table 1. Table 1 only provides information of the average mobility and stiffness parameters. The slabs indicating maximum deviation from reference slab in terms of average mobility and stiffness parameters are only shown in the table.

4 DISCUSSION

The structural system for all the slabs on each floor of the multistorey building were found to be identical in nature. Each of the IR test parameters is related to the properties of the slab. When all the slabs have a similar structural system, the mobility was highly influenced by the elastic modulus of the concrete and internal defects. A higher mobility indicates problematic areas within the concrete. Statistical analyses showed differences in the performance of the slabs in terms of average mobility as indicated in Table 1. When assessing the data, Slabs 6, 16, 19, 20, and 24 provided the poorest possible performance with respect to the other slabs and reference slab. Except Slab 6, the rest of the slabs are clustered together. Slab 7 also indicated a high deviation from the reference (see Table 1), the lower mobility in the slab compared to the reference slab indicated a better performance of the slab in terms of average mobility parameter.

Dynamic stiffness can be an indicator of relative quality of the concrete, thickness, and support conditions. Others being constant, a relative quality of concrete can be assessed using this parameter. As indicated by Table 1, Slabs 19, 20, and 24 showed the lowest dynamic stiffness. These locations are the same cluster of slabs having poor average mobility results. Slabs 7, 13, and 14 showed higher stiffness values than the reference slab. The higher stiffness indicated a better performance of these slabs in terms of dynamic stiffness parameter compared to reference slab.

Similar conclusions on the Slabs 6, 16, 19, 20, and 24 were made based on the analysis of the mobility slope data.

As all slabs are supported by the beams and columns at fixed locations, the area underneath the slabs can be regarded as void when testing with the IR test method. This was indicated by the statistical analyses as the performance of all the slabs in terms of void ratio were found to be similar with no significant difference.

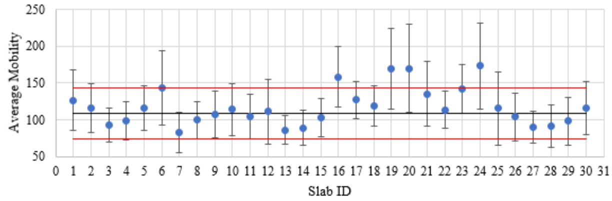

Figure 5: Mean plot representation with standard deviation as error bar. The black solid line represents the mean value obtained in the reference slab; and the upper and lower red solid line represents the mean plus standard deviation and mean minus standard deviation for the reference slab, respectively.

From the discussion of the results, it can be confirmed that Slabs 6, 16, 19, 20, and 24 provided the poorest performance compared to the reference slab and were selected for further investigation (e.g., static load testing). The tested Slabs 16, 19, 20, and 24 were noted to form a cluster within the same region indicating possible poor construction quality in the region during the concrete placement. The Slabs for static load testing were selected in such a way that they not only indicated the poor performance in terms of NDT parameter, but also, they represent different regions. Therefore, Slabs 6, 19 and 24 were selected for static load testing to establish the performance of the slabs under the proof load.

The design load of the composite slab was 3.0 kN/m^2. The slab was investigated for a proof load of 1.5 times the design load for a period of 24 hours. The maximum allowable deflection for the static load was set to 28mm. The Slabs 6 and 19 resulted in the similar performance providing maximum deflection of 14.5mm. The maximum deflection of 4.8mm was obtained in Slab 24. Further investigation revealed a load bearing wall hidden under the Slab 24, which restricted the movement of the wall during the static load testing. The crack width measurement at certain locations before and after the static load test indicated no change in width. Based on the acceptance criteria for maximum deflection and deflection recovery, the slabs were considered to be adequate for the design load.

5 CONCLUSION

Assessment of existing structure is of paramount importance to ensure the safe performance of structures. NDTs play an important role in condition and structural assessment of existing structures. The proper selection of NDT methods will influence the overall structural assessment and the quality of assessment with a cost-effective solution in the process.

In this regard, this paper presents a case study where a NDT method was used in the decision-making process for structural evaluation of composite slabs in an existing building. The impulse response test method was performed and based on the statistical analysis of the data; the poorly performing slabs of the floor were identified for further investigation. Though the method is empirical, uses comparative assessment and while the test does not provide any indication of the depth and size of the defects within the concrete, the method was successfully used to target the poor performing areas in the floor. Instead of carrying out a full-scale load testing on each slab at significant cost, the identified slabs were subjected to static load testing for capacity evaluation based on the design criteria and the overall structural capacity of the slabs was evaluated in a cost-effective way.

The paper intends to highlight the gap between the use of NDT methods and the need for information in the decision-making process during an industrial application. The purpose of testing is not the test itself, but to gather information that can be used as a decision-making tool in the efficient evaluation of the existing structures.

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Table 1. Summary of the statistical analysis of Impulse Response Test results

Parameters	Slab ID	Mean	Median	Std	CoV (%)	Comments	Statistical Evaluation+
Average Mobility	6	143.1746	135.0726	50.42834	35.2223	Higher mobility	Mean difference from ANOVA = -34.59651315; Z value =-10.011
	7	82.86924	77.37344	27.63006	33.34176	Lower Mobility**	Mean difference from ANOVA = 25.705874 Z value from t-test=-11.153
	16	158.5077	148.1644	41.55093	26.21382	Higher mobility	Mean difference from ANOVA=-49.42654657; Z value =-14.647
	19	169.2088	155.0531	55.41131	32.74729	Higher mobility	Mean difference from ANOVA=-60.63370123; Z value =-14.771
	20	169.4528	158.2815	59.95746	35.38298	Higher mobility	Mean difference from ANOVA=-60.87771802; Z value = -14.468
	24	173.3087	160.5005	58.74972	33.89889	Higher mobility	Mean difference from ANOVA=-64.73354800; Z value = -15.698
Stiffness	7	0.027007	0.025	0.009424	34.89353	Higher Stiffness**	Mean difference from ANOVA=-.00802422; Z value = -10.666
	13	0.024853	0.024	0.007662	30.82746	Higher Stiffness**	Mean difference from ANOVA=-.00587036; Z value = -9.094
	14	0.02586	0.023	0.011208	43.3411	Higher Stiffness**	Mean difference from ANOVA=-.00687766; Z value = -7.637
	19	0.013685	0.012	0.005948	43.46172	Lower Stiffness	Mean difference from ANOVA=.00529758; Z value = -9.619
	20	0.014377	0.012	0.007706	53.60163	Lower Stiffness	Mean difference from ANOVA=.00460554; Z value from t-test= -9.279
	24	0.014176	0.013	0.006263	44.18109	Lower Stiffness	Mean difference from ANOVA=.00480623; Z value from t-test= -8.925

*Based on Median, rest is based on both median and mean

**Better performance of the slab compared to Reference Slab

+Mean different calculated assuming unequal variance of the data, and Z-value based on Mann-Whitney test (non-parametric test) for comparing two sets of data.