DETERMINING THE THICKNESS OF CONCRETE PAVEMENTS USING THE IMPACT-ECHO TEST METHOD

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ABSTRACT

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Traditionally, destructive methods such as coring are used for the condition assessment of an existing concrete structure. Although these methods may yield valid data about the corresponding concrete section, they are quite expensive and time consuming. More important than these, destructive methods damage the structure being investigated and these points usually become focal points for further deterioration. For all these reasons, only a few samples can be collected from a structure and this results in a poor representation of the complete structure.

The impact-echo technique is one of the most suitable non-destructive test methods that may be used on concrete for thickness determination or for investigation of possible delaminations in the internal parts of a concrete structure without damaging the surface. It has been observed that reliable results can be obtained quickly. Unlike pulse-echo tests which are commonly used on steel, testing a heterogeneous material like concrete requires the use of low frequency sound waves as in impact-echo, in order to mitigate the effects of paste-aggregate interfaces or small air voids.

This method may be used to locate internal cracks or large air voids existing in concrete. It is known that impact-echo has been used successfully on structures with varying geometries and various purposes such as evaluation of concrete pavements, retaining walls and other reinforced concrete sections. Besides the investigation of the internal state, it may also be used when the other side of the section cannot be reached, as in the case of concrete pavements, in order to find the thickness of the section. This is especially important for quality control and for cost calculations.

Research conducted in this thesis study was concentrated on the thickness determination of existing concrete pavement sections, produced in the laboratory with dimensions of 1500 x 2000 mm four and varying thicknesses, and the accuracy associated with these results. In order to correctly determine the sensitivity, several other parameters were investigated and optimum ranges were determined for these to be used while on a field test. Among these factors were the steel impactor size, accuracy related to the data acquisition, distance between the impact point and the transducer and the location of the test point.

Finally, the accuracy of the impact-echo method for concrete pavement applications was studied. By observing the large number of data points collected, it was found out that an average error of 1.5% exists for a single impact-echo reading regardless of section thickness, but this value reduces to 0.6% when the average of all test results is used while determining pavement thickness. Results of this study show that the impact-echo technique is reliable and may be used with success for the thickness determination of concrete pavements and for locating internal voids.

Keywords: Impact-Echo, Concrete Pavement, Slab Thickness, Non-destructive Testing

ÖZ

DARBE-EKO YÖNTEMİ KULLANILARAK BETON YOL KALINLIĞININ BELİRLENMESİ

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Mevcut bir yapıyı değerlendirebilmek için, geleneksel olarak karot alınması gibi yıkıntılı deney yöntemleri kullanılır. Bu yöntemler, o kesitle ilgili kesin bilgiler vermesine rağmen, hem pahalı hem de uzun zaman gerektiren bir işlemdir. Bunlardan daha da önemlisi, yıkıntılı deney yöntemleri yapıda kalıcı hasarlar bırakır ve bu hassas noktalar daha ilerideki sorunların başlangıç noktaları olmaktadır. Bütün bu nedenlerden ötürü mevcut bir yapıdan ancak çok sınırlı sayıda numune alınabilmekte ve dolayısıyla gerçek yapıyı yeterince temsil etmemektedir.

Darbe-eko test yöntemi, mevcut bir beton yüzeye zarar vermeden, kalınlığını ölçmek veya iç yapısı hakkında bilgi edinmek için en uygun yıkıntısız deney yöntemlerinden biridir. Bu yöntemle, hızlı ve güvenilir sonuçlar elde edilebileceği görülmüştür. Pulse-eko yönteminin çelik üzerinde kullanımından farklı olarak, beton gibi heterojen yapıya sahip bir malzemede var olan çimento hamuru-agrega arayüzleri ve küçük hava boşlukları, darbe-eko'da olduğu gibi düşük frekanslı ses dalgalarının kullanımını zorunlu kılmaktadır.

Bu yöntem, betonun içerisinde var olan çatlakları ve büyük hava boşluklarını belirlemekte kullanılabilir. Beton yollar, istinat duvarları, betonarme kesitler ve beton

borular gibi çeşitli şekil ve kullanım alanına sahip betonlar üzerinde başarıyla kullanıldığı bilinmektedir. İç yapının araştırılması dışında, kesitin diğer tarafına ulaşılamadığı zamanlarda, beton yol örneğinde olduğu gibi, beton kesitinin kalınlığının ölçülmesine de olanak sağlar. Bu ise özelikle kalite kontrol uygulamalarında ve hakediş ödemelerinde önem kazanmaktadır.

Bu tez çalışmasında yapılan araştırmalar mevcut beton yol kalınlığı tespiti üzerinde yoğunlaşmış ve bu yöntemin kalınlık tespitindeki hata payı laboratuvar ortamında dört farklı kalınlıkta hazırlanan 1500 x 2000 mm boyutlarındaki beton plaklarda araştırılmıştır. Hata payı araştırılırken, sonuçları etkileyebileceği düşünülen diğer parametreler de araştırılmış ve bir saha uygulaması sırasında bu değişkenler için en uygun değer aralıkları belirlenmiştir. Bunların arasında, çelik top büyüklüğünün etkisi, veri toplama ünitesi kaynaklı hassasiyet, darbe noktası ile algılayıcı arasındaki mesafe ve deney noktasının konumu gibi faktörler göz önüne alınmıştır.

Son olarak, darbe-eko yönteminin beton yol uygulamasındaki hata payı tespit edilmeye çalışılmıştır. Elde edilen çok sayıdaki veri incelendiğinde, kalınlıktan bağımsız olarak herhangi bir darbe-eko okumasında ortalama olarak %1.5 hata olabileceği, fakat çok sayıda sonucun ortalaması alındığında kalınlık tespitindeki hata payının %0.6 olduğu bulunmuştur. Bu çalışmadan elde edilen sonuçlar darbe-eko yönteminin beton yolların kalınlığı ve içerisindeki boşlukların tespiti için güvenilir bir yöntem olduğunu ve başarıyla kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Darbe-Eko, Beton Yol, Döşeme Kalınlığı, Yıkıntısız Deney Yöntemleri

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CHAPTER 1

INTRODUCTION

1.1 General

Non-destructive techniques are often used to determine the geometrical properties of various structures in the field either due to condition assessment of the structure or for quality control purposes. The cross-sectional dimensions of columns and beams, the locations of reinforcement bars, the depth of a slab or the depth of a concrete pavement are all important geometrical parameters that can be detected in reinforced concrete structures by using non-destructive techniques.

The traditional test methods used on concrete structures are destructive methods, where coring is the most widely applied option. Obtaining cores and determining the properties from that sample is a very reliable method for investigating the concrete at a particular location but is also expensive and time consuming. As an outcome of this, very few cores are taken from the structure and so they represent only a small and unrepresentative portion of the whole structure. Also, destructive methods, as the name implies, damage the structure investigated and the defects they leave behind are usually focal points for further deterioration [1].

Over the past several decades, several types of nondestructive methods have been developed for concrete to overcome the above mentioned problems of destructive testing. X-ray tomography, ground penetrating radar (GPR), and acoustic methods including ultrasound and impact-echo methods are only some of them.

The use of sound is probably the oldest and most widely used form of non-destructive testing. Tapping the object with a hammer to understand its internal state is far older than any other method. The compactness of the material can be assessed by listening to the “ringing” sound that is produced. Unfortunately, the results are very subjective, especially for concrete structures, and are limited only to near surface defects [2].

The common working principle of all echo methods is that a stress pulse is introduced into the specimen and the response is monitored by a transducer to analyze the results. In ultrasonic pulse echo method, a transducer is used to create and collect the sound waves. In impact-echo method, however, a mechanical impactor is used in conjunction with a receiving transducer.

Non-destructive testing methods based on stress wave propagation have been developed mainly to locate defects in metal inspection and therefore their use on concrete results in some problems. The heterogeneous nature of concrete together with the existence of paste-aggregate interfaces, air voids and reinforcing bars are the main cause of problems that should be overcome. They play a decisive role in connection with results especially when high frequency stress waves are used, as in the pulse-echo method, due to great dispersion caused at each irregularity.

Impact echo uses the same basic principles, but different sized steel spheres, impactors, are employed to create the necessary sound waves. This result in lower frequencies which minimize some problems related to the heterogeneity of concrete. The impact-echo method is reported to be used for determining internal flaws such as cracks, delaminations, voids, honeycombing, debonding or voids in grouted post-tensioned concrete structures [1,2,3]. It can be applied to various concrete structures such as pavements, retaining walls, dams, columns, beams, slabs, pipes and so on. Besides these, the method can also be used to determine the thickness of a concrete section for quality control or for interim payment. This is especially useful in situations where one does not have access to both sides of the section such as in concrete pavements, where thickness measurements must be made only from the accessible top surface and impact-echo can commonly be used in these situations.

1.2 Object and Scope

The object of this thesis study is to determine the basic parameters involved in the impact-echo testing procedures such as the impactor size selected or the distance from point of impact to transducer, and then to determine whether impact-echo is a convenient method for concrete pavement thickness determination. The amount of error in the output results play a major role in determining whether or not a method is suitable for investigation of that type of structure.

To determine the relative error associated with impact-echo results, four concrete slab samples with different thicknesses were produced in the laboratory and tested. A large number of data were collected from each sample and these were evaluated separately for each thickness. A mean relative error and a confidence interval were proposed at the end.

While testing for accuracy, several other testing parameters were investigated which were considered to be affecting test results. An optimum range or a limiting value for each factor was proposed at the end. Therefore, this study sums up all the necessary parameters for testing and discusses the accuracy of impact-echo associated with thickness determination.

Brief, introductory information is given in Chapter 2 about non-destructive testing, followed by impact-echo, and lastly about concrete pavements. The procedures carried out before and during experimentation are explained in Chapter 3 and the results obtained, together with their discussions are presented in Chapter 4. Finally, the conclusions are given in Chapter 5 followed by suggestions for further research in Chapter 6.

CHAPTER 2

LITERATURE SURVEY OF IMPACT-ECHO TECHNIQUE AND CONCRETE PAVEMENTS

2.1 Non-Destructive Testing for Concrete Pavement Evaluation

In a plain concrete pavement, the thickness of slab is the primary factor affecting its performance. Therefore, it is often necessary to determine the thickness of a newly built or existing concrete pavement.

Traditional and still the most widely used test method for determining the thickness of concrete pavements is to obtain cores from the pavement itself. The common practice today is to take core samples at wide intervals. According to Kentucky standards, core samples should be taken at every 305 m for concrete pavements where the thickness should not deviate more than 2.5 cm from the predetermined value [4]. Furthermore, it is stated that cores should be taken only if the pavement has an area larger than 2000 m^2. For projects smaller than this amount, visual inspection is stated to be adequate [5]. This statement is due to the problems and additional costs associated with coring. A practical non-destructive testing method capable of giving accurate results would overcome these problems and would provide a better quality control system for the employer.

Coring, on the other hand, introduces its own problems into the picture. A circular opening 10-15 cm in diameter cutting completely through the section thickness until the base layer is not something desirable for pavement maintenance and durability. Although in practice it is later filled and covered with the same material as the pavement itself, the filled portion degrades much faster than the pavement and so becomes a focal point for future deterioration [6]. It is also an expensive method.

As an alternative to the traditional method of coring, several nondestructive tests have been developed for concrete pavement evaluation and other structural materials. Each method has its own application area and advantages. Some of these methods are [1,7,8]:

- Electromagnetic Wave Propagation Methods
- Infrared Thermographic Techniques
- Spectral Analysis of Surface Waves Technique
- Ultrasonic Method
- Pulse-Echo
- Impact-Echo

2.1.1 Use of GPR

Ground-Penetrating Radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. This non-destructive method uses the reflected electromagnetic signals from the subsurface. A typical GPR system has two antennas. The transmitting antenna radiates short pulses of high frequency radio waves into the ground. When the wave hits a boundary with a different dielectric constant and returns, the receiving antenna records variations in the reflected return signal. Its main difference from sonic methods is that it uses electromagnetic energy instead of acoustic energy and so reflections occur at interfaces with different dielectric constants instead of acoustic impedances.

The advantage of this method is that pulses are generated by the machine itself; therefore, errors caused by the operator are eliminated. As an outcome of this automation, there have been several large research projects where the complete equipment has been loaded on to the back of a truck and all readings are collected while the truck is traveling at a constant speed over the pavement. At first glance, this technology seemed to greatly shorten testing time, but it has problems of its own related to accuracy.

GPR tests conducted on an asphalt pavement in Texas, U.S.A. gave results with a deviation of ±83.8 mm. The method has also been tried on concrete pavements but the accuracy of results was even lower, therefore it has been concluded that it was not very suitable for concrete pavements [4].

GPR waves attenuate rapidly in concrete, and especially in new concrete due to the free moisture and salts present in the paste matrix of concrete. Also, the dielectric contrast between concrete and its base is small for concrete pavements [9]. Due to these two factors, reflected waves from the bottom of concrete are often diminished or even totally absent; therefore, the use of GPR for accurately determining the thickness of concrete pavement is not possible or feasible. Mechanically induced waves provide more accuracy and are more feasible for use on concrete pavements [4].

The effect of saturation has also been investigated. It has been proposed that unless water is ponding on the surface or the pavement is fully saturated, water does not affect GPR results [4].

There are many applications where GPR has been used for thickness determination purposes in pavements. However, experiments reveal that the use of GPR is more suitable for asphalt pavements compared to concrete pavements due to the higher electric contrast between the pavement and its base [4].

2.1.2 Use of Acoustic Non-Destructive Techniques

The acoustic methods are the oldest form of nondestructive testing. They are based on propagation and reflection of sound waves in solids. The easiest example to this is to hit an object with a hammer and then listen to the variations in the tone of the ringing sound to detect the presence of internal voids. However, this method is highly subjective and greatly depends on the experience of the operator and is also limited to shallow near surface defects.

These methods have been used since ancient times and are still being used today. A simple non-destructive technique which does not require high-tech equipment is to drag series of chains back and forth over the concrete surface to detect horizontal cracks or delaminations, by listening to the variations in the sound that it creates. A distinctive, hollow sound occurs when the chains are dragged over a delaminated section of concrete. This technique is known as chain-dragging and has the advantage of being simple and inexpensive. However, it has the disadvantage of relying on the subjective interpretation of the inspector. In past years, the method has been automated by mounting the equipment on a hand-pushed cart with chains attached and recording the sound produced by a dragging chain with a microphone and processing these signals with a computer to distinguish between delaminated and intact sections of concrete. This method is still being widely used by most of the Departments of Transportation in the United States.

The application of modern acoustic methods for non-destructive testing requires an understanding and knowledge of wave types and their distinctions.

2.1.2.1 Types of Waves

An impact on a continuous elastic medium creates stress waves that propagate through the material as two different types of body waves: the P-wave and the S-wave. These waves propagate through the solid along spherical wave paths. The P-wave carries normal stresses where S-wave carries shear stresses. This means that the P-wave causes the point element to move back and forth along the wave path. The S-wave on the other hand causes perpendicular movement along the wave direction. Besides these body waves, there are also some other waves known as surface waves which only travel along the surface of the section, away from the impact point. Rayleigh waves (R-wave) are the most distinct surface waves. They are used in several acoustic non-destructive techniques, and by seismograms to examine the behavior of earthquakes. R-waves are slower than the body waves but the particle motion caused by the rolling action are much greater, which cause greater damage to a structure under earthquake load [10].

These different types of waves are correlated to each other by the mechanical properties of the material as shown below:

$$C_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad \text{(Equation 2.1)}$$

$$C_s = \sqrt{\frac{E}{2\rho(1+\rho)}}$$ (Equation 2.2)

where; C_p = P-Wave Speed

C_s = S-Wave Speed

E = Modulus of Elasticity

ν = Poisson`s Ratio

ρ = Density of concrete

For a Poisson's Ratio of 0.2 which is an average value for hardened concrete, the ratio of S-wave speed to P-wave speed is calculated to be 0.612. The speed of the R-wave is around 92% of the S-wave speed which means that its ratio to the P-wave is 0.563. These could be shown schematically on a graph as presented in Figure 2.1.

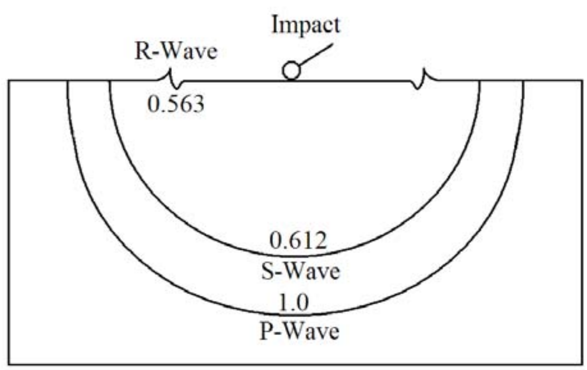


Figure 2.1 The relative position of different types of waves created by an impact. Numbers indicate relative values normalized according to P-wave speed.

2.1.2.2 Wave Velocities

The velocity of a wave in a concrete medium will not only depend on the wave type but also on the intrinsic properties of concrete. Among the different types of waves, only

P-wave velocity is usually considered and is of interest to us. The others may be found by simple relations existing between the different types of waves.

The average value for P-wave velocity for ordinary concrete at 28 days would be in the range of 3000-4500 m/s depending on its constituents and the mix design. Lower values usually indicate a poor quality concrete whereas higher values indicate high quality concrete [11].

Determination of the wave velocity of a concrete section is not a very simple task. Wave velocity is affected by several factors including test location and the degree of hydration at that point.

As stated earlier, the properties of concrete at the test point are crucial if a structure is to be modeled. This means that the surface roughnesses, texture, section geometry, relative position of the test point are all important. On the other hand, the size, distribution, shapes and type of aggregate used are not very important. However, the moisture content of the specimen at testing time might be important. A study carried out by Popovics stated the following [12]: "*through-thickness velocity measurements may differ because of material inhomogeneity. A gradient in the moisture content may cause such a difference in properties, especially in case of concrete pavements*."

The wave velocity calculated along the surface and through the thickness is not always the same and this shift is not proportional or consistent and therefore cannot be predicted [11]. Most deteriorations are caused by environmental factors, and the surface of a section gets damaged first. Velocity testing on this damaged surface would produce completely different results than through-thickness velocities.

During placement of concrete, some segregation and bleeding may occur even though not at a level as to harm the concrete. Nevertheless, the accumulation of aggregate particles near the bottom of the member increases the wave velocities correspondingly. Although this effect might not be noticeable for concrete pavements, since the thicknesses are not usually great, it may alter results especially for columns and beams [11].

Even if none of the above were to occur, still, the wave velocity in a concrete member increases over time. This is related to increased hydration products which result in more compact concrete. Especially during the first several weeks, wave velocities show great variations and must be tested each time before testing and around the area of the test points since different portions may exhibit different velocities in a specimen having a large surface area such as the slabs produced.

2.1.2.3 Reflection of Waves

When a stress wave traveling through a material encounters an interface between the present material and another material whose properties are different, a portion of the stress wave is reflected back. The amount of reflection and absorption is related to the angle of incidence, where this is maximized at an angle of 90 degrees - normal incidence, and to the acoustic impedance of the two materials. For normal incidence, the reflection coefficient, R, is given by the following simple relation [2]:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad \text{(Equation 2.3)}$$

where,

Z_1 = specific acoustic impedance of material 1

Z_2 = specific acoustic impedance of material 2

The specific acoustic impedance is related to the wave speed in that material, and the density of the material. The following table gives approximate Z-values for some materials that may commonly be encountered [2].

Table 2.1 Different acoustic impedance values for several materials

Material	Specific acoustic impedance, $kg/(m^2s)$
Air	0.4
Water	0.5×10^6
Soil	0.3 to 4×10^6
Concrete	7 to 10×10^6
Steel	47×10^6
Wood	0.1 to 1.6×10^6
Marble	10.5×10^6
Glass	13×10^6
Brick	7.4×10^6
Granite	26.8×10^6

By looking at the values given in the table, it is clear that when a wave traveling in concrete encounters a concrete-air interface, almost all of the stress wave would reflect back. Actually this is the logic behind acoustic non-destructive testing methods using stress wave propagation. Such techniques have been successful in locating defects within solids by using the difference between the specific acoustic impedance of different mediums.

2.1.3 Use of Ultrasound

Ultrasound may be used in non-destructive testing to find flaws in materials. Frequencies in the range of 2 to 10 MHz are typically used for industrial applications. Lower frequency waves, from 50 kHz to 500 kHz, are being used for inspection of concrete. However, combining the heterogeneous nature of concrete together with frequencies of such magnitude might lead to intricate results. Paste-aggregate interface or even small entrapped air voids might alter the results.

The threshold for sighting smaller sized voids in concrete is lower for ultrasonic testing, but separating and understanding these from the given results is not an easy task. The dispersion caused by the variations in the concrete section has a great effect on the test results. The dispersion is even more significant in the case of reinforced concrete.

2.1.4 Use of Pulse-Echo Method

In pulse-echo testing, a transducer introduces a stress pulse into the object. When the pulse reaches an interface or a flaw, it turns back and is then collected by the same transducer. A single transducer is used both for generation and reception of stress waves. Usually oil, grease or some kind of wax is required between the surface and the transducer for pulse-echo testing. For analysis of the received signal, time domain analysis has been usually used for pulse-echo applications used for testing concrete structures [8].

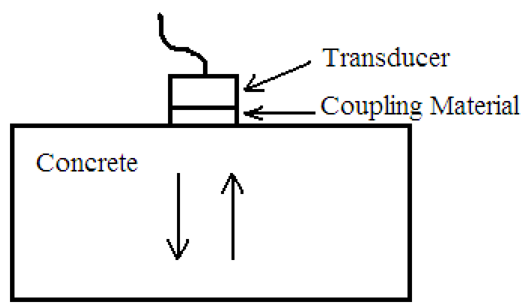


Figure 2.2 Working principle of pulse-echo method

The technique was found to be a reliable method for nondestructive evaluation of metals [2]. During the initial research period, attempts were made to use ultrasonic pulse-echo method for concrete investigation. This technology was designed for metal inspection and tests on concrete have not produced successful results due to the heterogeneous nature of concrete compared to metals [2]. The presence of paste-aggregate interfaces, air voids, and steel reinforcement results in the deflection of waves or causes multiple echoes which render the results meaningless and hides the real defects.

2.2 Impact-Echo Background

2.2.1 Introduction

Impact-echo, recognized as being one of the acoustic methods, is one of the most successfully applied methods for determining the geometry of a concrete structure. It has also been proven to be a reliable method for locating a variety of defects in concrete structures. The success is, in part, due to the result of its well-founded scientific basis derived from a long period of research that combined theory, numerical simulation, experimental verification, and field demonstrations [1,2,3]. In this section, basic information about the major principles underlying impact-echo testing and its abilities as reported by other researchers will be provided. As with most methods for flaw detection in concrete, experience is required to correctly interpret impact-echo test results.

2.2.2 History of the Method

Research conducted from 1940's to 1960's was mainly focused on classical non-destructive testing methods which were mostly used by industrial purposes. This period provided the technical basis and standards for methods such as X-ray, ultrasonic methods, eddy current methods and magnetic methods. On the other hand, there was little study on non-destructive testing of concrete structures. During the late 1970's, two major construction failures in the United States led researchers to investigate this subject [2]. The in-place concrete strength and its condition were determined to be a contributing factor for failure in both cases. As a result, a long term research program was initiated to provide a feasible and applicable test method to evaluate the properties of in-place concrete.

In 1983, this research was shifted towards the detection of internal flaws and problems. Considering the available methods applicable to concrete, it was decided to concentrate on a test method which was based on stress waves since wave propagation is closely affected by the mechanical properties of the corresponding section. Actually, perhaps the most useful leap was to investigate the effects of mechanical impact rather than ultrasonic ones [2]. The use of impact generated stress waves produces a one-time pulse of high energy which can penetrate all the way to the other side of the concrete and also be detected from the impact side. The first applications of this technique were observed in the area of geotechnical engineering. Existing long piles underneath the soil were investigated and the test results were found to be successful. This method has undergone some minor changes but is still known and used today and known as the sonic-echo or seismic-echo method. For pile investigation, the total length of the structure is very large compared to other more frequent applications such as slabs, columns or beams. This increased length actually simplifies some of the problems. Since the total travel time is increased, the initiation and arrival times of the stress waves could be easily observed and distinguished. This is harder to identify for thinner sections.

Further research involved the inclusion of numerical simulations using the finite element method, and later became known as the impact-echo method. This initial research provided the basis of the technique and showed its feasibility to monitor a structure or locate flaws in plate-like or relatively thin concrete structures [2].

2.2.3 Fundamentals

"Impact-echo is a nondestructive testing method for concrete and masonry structures that is based on the use of impact generated stress (sound) waves that propagate through concrete and masonry, and are reflected by internal flaws and external surfaces" [1]. Impact-echo can be used for a variety of reasons. It can be used to detect the internal state of various concrete sections such as pavements, walls, layered plates, columns, beams and pipes. Information can be gained about flaws inside these different types of structures such as cracks, delaminations, large voids, honeycombing or voids inside the grouted tendon ducts of post-tensioned structures. Furthermore, it can provide thickness measurements for concrete slabs where the other side cannot be reached and thus thickness cannot be measured without damaging the concrete section, as in the situation of concrete pavements. It is reported to be used successfully for a variety of different structures including highway pavements, bridges, buildings, tunnels, dams, pipes and sea walls [1, 2, 3, 13].

Although the testing phase is not very complicated, the same is not true for analyzing the results. The principles behind the technique should be well known. Impact-echo is not a black-box system where accurate results are given after inputting several initial values. Each test is unique and involves the talent of the operator. Prior experience about tests on the same type of structure is a major factor contributing to the success of the tests. Furthermore, the method is most suitable for quality control applications such as measuring the thickness of new highway pavements or for preventive maintenance programs such as routine checks on bridge decks but does not provide information about strength and other properties of concrete.

Impact-echo, as being one of the acoustic methods, is based on the use of stress waves generated by an elastic impact. Low frequency waves are produced by tapping the surface with a small steel sphere.

By using steel spheres of different diameters, the magnitude of the impact and the contact time of the sphere can be controlled. By locating the initial time of impact and the arrival of the echoing P-wave, the total travel duration can be determined. Besides this, the wave speed in that concrete section could be predetermined. By knowing these two, we can understand at which point the stress wave has encountered an acoustic impedance difference and has returned back. By comparing this experimental value with the observable thickness it can be concluded that the section is compact and flawless if the results are the same. If the output thickness value is shorter than what it should be, then this means that the stress wave has returned from some depth before encountering the bottom surface and is an indication of an internal problem at that thickness level.

These mechanical impacts should be of short duration so that the transducer which is located near the impact point can differentiate between the outgoing and incoming waves. The transducer records the surface displacement caused by the incoming waves. These are then transformed into the frequency domain and finally into plots of frequency versus amplitude graphs by using Fast Fourier Transform (FFT) analysis. Figure 2.3 given below is helpful in explaining the concept.

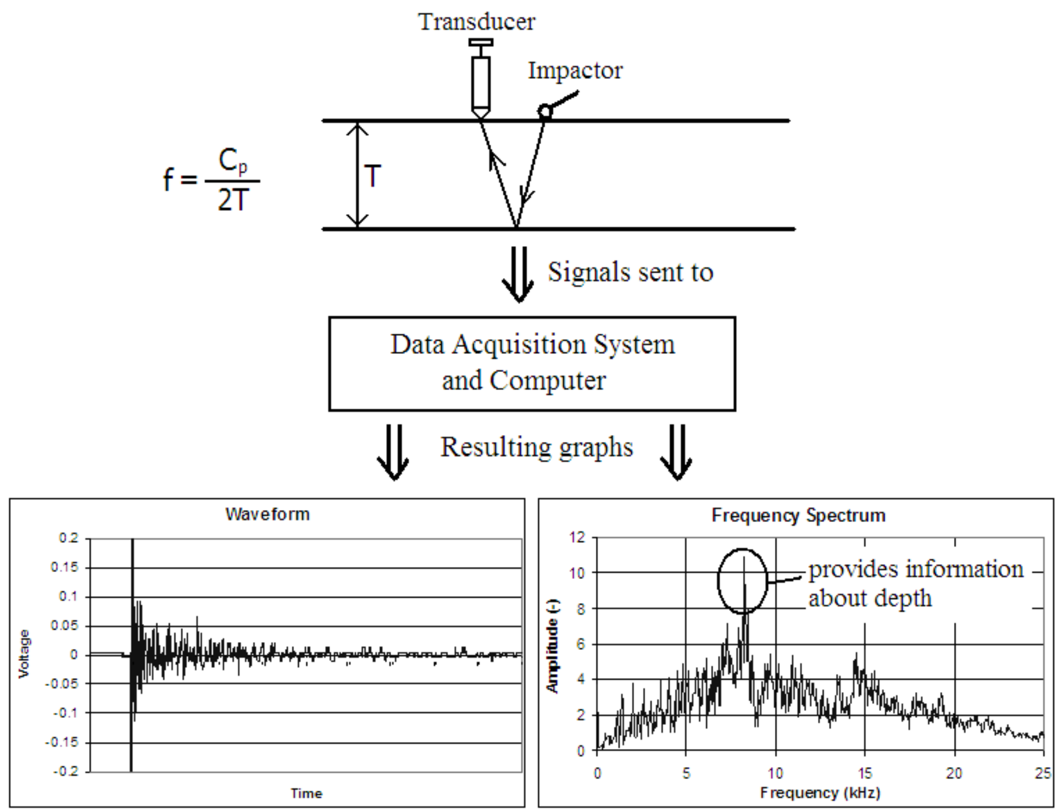


Figure 2.3 Schematic description of the impact-echo test procedure

From almost all of the tests, patterns similar to the ones given above may be encountered. This one actually was a real result obtained after a test on one of the slab specimens. The patterns observable in the waveform and distinct peaks in the spectra provide information about the structure such as existence and location of flaws or cracks or thickness of a cross-section at the point where the test is performed [1].

If flaws such as cracks, voids or honeycombed areas exist, then results change and disruptions are seen in the spectra which can be seen and quantified visually.

2.2.4 Analysis of Data in Time Domain

Initially, time domain analysis was used in the impact-echo method to analyze and interpret the results. This approach had distinct differences from the type of analysis used today.

In frequency analysis, certain correction factors are assigned while testing members of different geometry. These correction factors are found by experience, and actually their origin has not yet been perfectly explained. The time domain approach eliminates the need for these correction factors [12, 14].

Plates are the simplest and the most common structures encountered during impact-echo testing. An ideal plate is defined as a structure having two parallel surfaces and having dimensions sufficiently large so that reflections of sound waves from the side boundaries do not reach the transducer. Therefore the dominant frequency would only be caused by the multiple reflections of the P-wave from the two parallel surfaces.

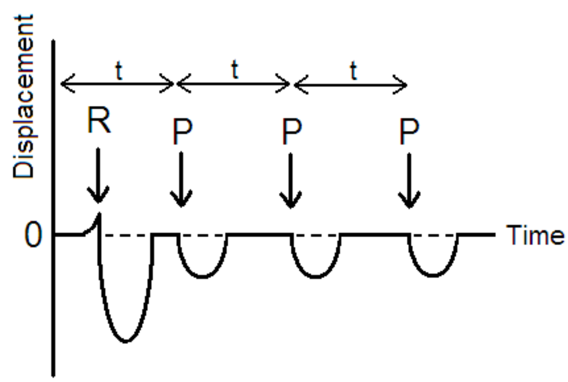


Figure 2.4 Illustration of an ideal waveform with the arrival of the R-wave and the multiple reflections of the P-wave

The initial upward displacement in advance of the arrival of the R-wave is caused by the P-wave and S-wave which are traveling in spherical wave fronts on the surface. The time separation between these two is not distinguishable because the transducer is located very close to the impact point.

For the ideal case, the time interval between successive P-wave arrivals is constant and thus they are periodic. By finding the reciprocal of this period, the dominant frequency could be found for the section, which is f=1/t.

In practice, the waveforms have some clear differences from the idealized case. When the transducer responds to a large and sudden change in the displacement, as in the arrival of the R-wave, the inertial effects in the transducer itself produce an overshoot in the waveform which results in an apparent upward displacement of the surface from its initial state [1].

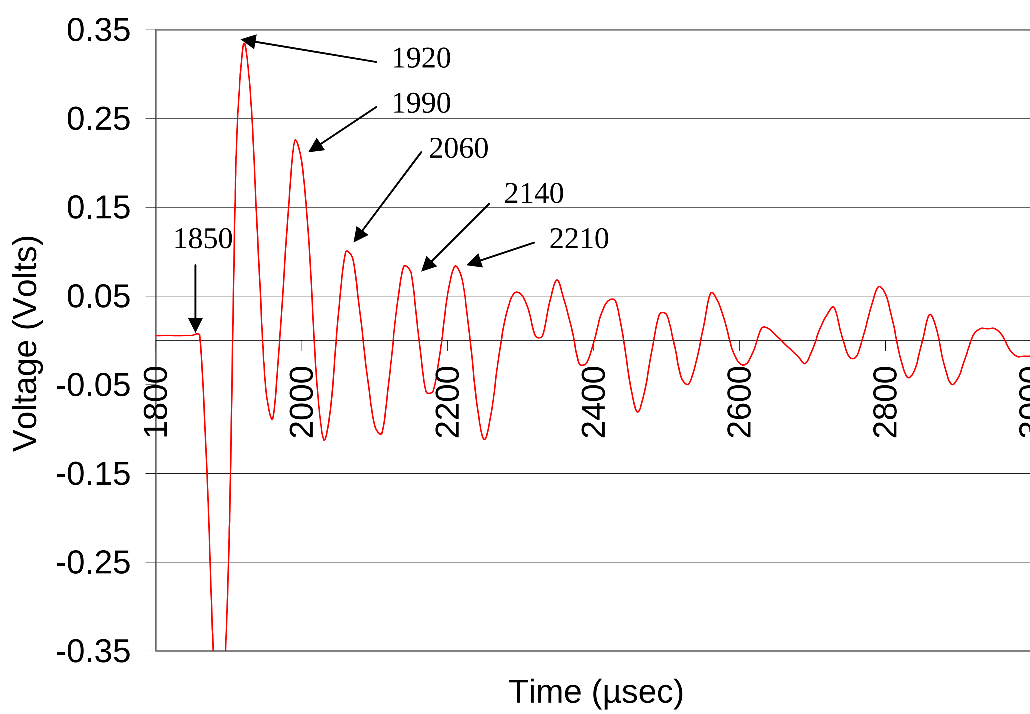


Figure 2.5 A sample waveform used for calculating the thickness frequency using the time domain approach

By denoting the arrival times of the P-waves, it was found out that the interval in between was approximately 70 µsec. Therefore, the corresponding frequency was f=1/0.07=14.29 kHz which was very close to the expected thickness frequency.

Although the time domain approach had its advantages, it was time consuming and more importantly, it was difficult to work with. The analysis phase required a longer period of time and was not suitable for interpreting the results quickly during a field test.

2.2.5 Analysis of Data in Frequency Domain

A key development in the method happened at this point. Instead of time domain analysis, frequency analysis was used to inspect recorded waveforms [1]. Output was then given as a graph of frequency values. There was a simple relation behind the calculations of each frequency.

Assuming that the receiving transducer is placed close to the impact point, the total distance traveled by the wave which is reflected back is equal to two times the section thickness. The time duration of arrival of successive P-wave reflections is equal to the total distance traveled divided by the wave speed. Frequency of this P-wave is found by taking the reciprocal of this value. Therefore, formulating this, we obtain:

$$f = \frac{C_{pp}}{2T} \qquad \text{(Equation 2.4)}$$

where
C_{pp} = the P-wave speed through the thickness of the plate section,
T = the depth of the reflecting interface

If the object being tested is a slab or a plate, then the frequency calculated by using the above formula is called the plate thickness frequency. The above formula is the basic and most important formula used in the impact-echo method. It is used to interpret the results given by the tests.

At the beginning, it was assumed that the P-wave speed was the same in a plate section and a large solid body. However, further research on the subject revealed that the wave speed in a plate section was 96% of the wave speed in a large solid body, that is, $C_{pp} = 0.96C_p$ [2, 15]. These correction factors were determined by experience for each type of structure.

In frequency analysis of impact-echo results, the objective is to determine the dominant frequency of the recorded waveform. This is accomplished by using the Fast Fourier

Transform (FFT) technique to transform the recorded waveform into the frequency domain [2]. The transformation results are plotted as the amplitude spectrum, which shows the amplitudes of various frequencies contained inside the waveform. For plate-like structures, the thickness frequency will usually be the only dominant peak in the spectrum. The value of the peak frequency in the amplitude spectrum can be used to determine the depth by expressing Equation 2.4 in a different format as follows:

$$T = \frac{C_{pp}}{2f} \qquad \text{(Equation 2.5)}$$

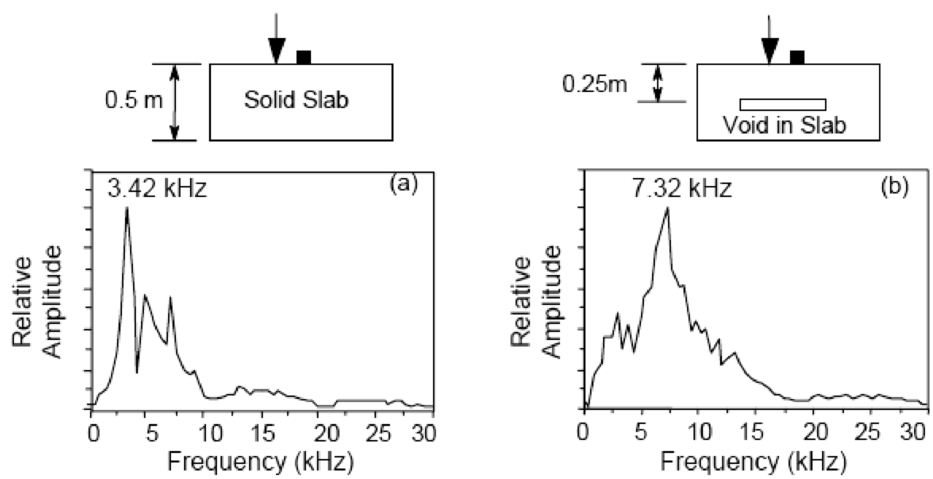


Figure 2.6 The resulting spectra with and without a void in a slab [1]

Figure 2.6 (a) shows the amplitude spectrum from a test over a solid portion of a 0.5 m thick concrete slab. As can be seen, there is a clear dominant frequency peak at 3.42 kHz for this section, which corresponds to multiple P-wave reflections between the bottom and top surfaces of the slab. Figure 2.6 (b) on the right shows the amplitude spectrum from a test over a portion of the slab containing a void at the middle depth. The dominant peak at 7.32 kHz results from multiple reflections between the top of the slab and until the void depth. The above figure is also useful in order to observe the effect of thickness on frequency values. The value of the dominant frequency peak increases as distance traveled decreases.

2.2.6 Instrumentation

The impact-echo method has three basic components:

- Different sized mechanical impactors to produce short-duration impacts, the duration of which is proportional to size,
- A sensitive transducer to measure the surface response to the P-wave echo,
- Data acquisition system to receive, process, and transmit the waveforms to the computer as output data.

Steel spheres are used as impactors because they are convenient impact sources since impact duration is proportional to the diameter of the ball [2]. The importance of impact duration is discussed in the following section. Further development in the method led to the use of steel balls attached to steel rods for ease of use and carrying purposes. Besides, the use of steel rods enables one to apply the test method in any orientation, whether it is a vertical wall or a ceiling.

The transducer contains small piezoelectric crystals inside which are protected by a metal casing outside. Piezoelectric crystals produce a voltage difference when they are displaced and vice-versa. These voltage differences are then sent to the data acquisition unit for further processing. The transducers utilized in impact-echo testing are wideband transducers having a frequency range of 0-60 kHz.

While some researchers have successfully used accelerometers for the same purpose, it is believed that a displacement transducer simplifies signal interpretation [2]. An important point about the transducers is that the transducer should not have a resonant frequency value that is close to the thickness frequencies that may be encountered during testing. For accurate testing, the transducer tip has to completely contact the concrete surface. For very irregular surfaces, a soft thin lead strip might be used which can conform to the irregular surface texture and transfer the surface motion to the piezoelectric element without altering it. This approach may reduce the time needed to conduct a successful test.

The distance between the impact point and the transducer is also important. If the distance is too large, the response is not dominated by the reflected P-wave, and the simple relationships expressed above by Equations 2.4 and 2.5 are not applicable. If the distance is too small, the response is dominated by the effect of the R-wave which travels on the surface. Sansalone and Streett have recommended that the spacing between the impact point and the transducer should be less than 40 % of the section depth [1]. Nevertheless, the reasoning behind this proposal was not given.

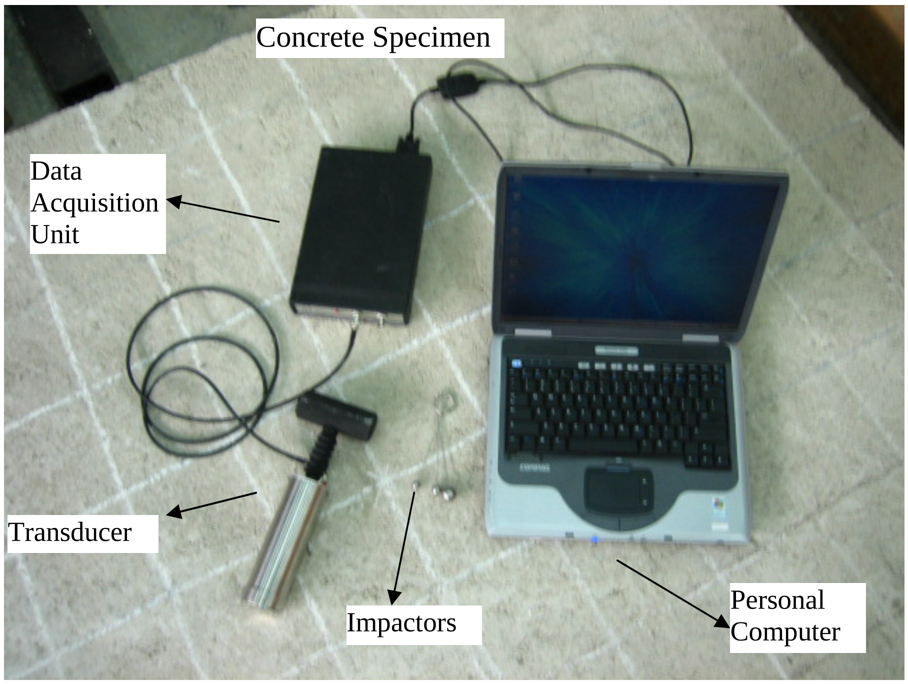


Figure 2.7 The main components of the impact-echo method

2.2.7 Impact duration

The duration of the impact is critical for the success of an impact-echo test. Correct results could only be obtained by exciting the resonant vibration corresponding to the thickness mode. In order to excite the thickness mode, the stress wave must contain the correct frequency component. The spectrum is dependent on the contact time of the impactor. The amplitude of the frequency components in the spectrum graph is directly proportional to the contact time, and the range of the frequencies contained in the stress wave is inversely proportional to the contact time. Therefore, the highest frequency component with significant amplitude enough to observe visually is inversely correlated to the contact time. Thus, as the contact time decreases, the range of useful frequencies increases but the amplitudes of these frequency components decrease [2].

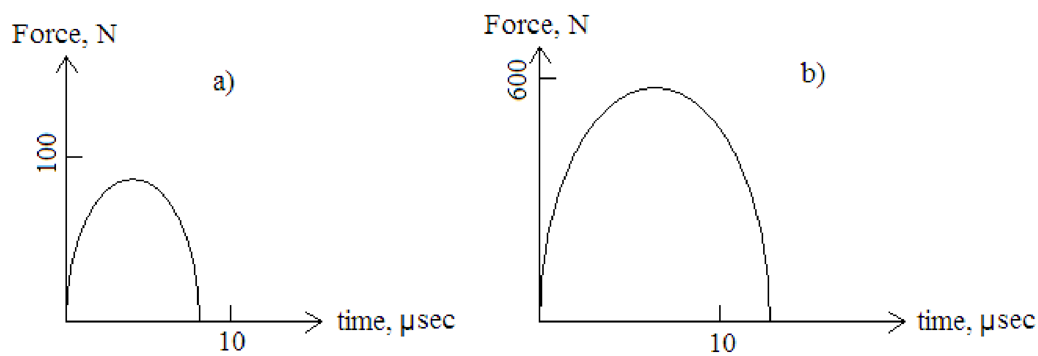


Figure 2.8 Force-time diagrams of impacts caused by two different steel impactors: a) 3 mm diameter b) 6.5 mm diameter

In the book by Sansalone and Streett, a relation has been proposed relating the diameter of the impactor to the maximum useful frequency.

$$f_{max} = \frac{291}{D} \qquad \text{Equation 2.6}$$

Where; f_{max}= maximum frequency of useful energy in kHz

D=impactor diameter in mm

There are 10 different sized impactors in a standard toolkit. According to the above given relation, the useful frequencies for each impactor could be tabulated. Also, by assuming an approximate value of 4200 m/s for the P-wave speed in concrete, the corresponding thicknesses could be found as given in Table 2.2 below.

Table 2.2 The relation between impactor size, maximum useful frequency, and measurable thickness

Diameter (mm)	maximum useful frequency (kHz)	minimum detectable thickness (cm)
3	97	2.1
4	73	2.8
5	58	3.5
6.5	45	4.5
8	36	5.6
10	29	7.0
11.5	25	8.1
13	22	9.2
16.5	18	11.2
20	15	13.4

While testing shallow defects or thin sections, the stress wave must have frequency components greater than the frequency corresponding to the flaw depth. As explained previously, the thickness frequency of a section increases with decreasing depth. For example, for a P-wave speed of 4000 m/s and a flaw depth of 0.2 m, the thickness frequency is 10 kHz. Therefore the contact time of the impact should be small enough to have a range covering the 10 kHz frequency value. Steel balls are effective impactors especially for field-testing because the contact time can be changed simply by selecting a different steel ball with a different diameter. Nevertheless, the capabilities of the method should be well known. Impact-echo cannot be used for frequencies exceeding 60 kHz. Preferably, it should be in the range of 0-30 kHz.

2.2.8 Position of Test Point Relative to Section Dimensions

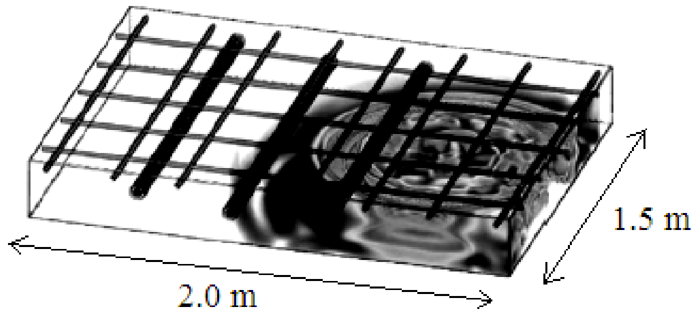
In impact-echo method, the location of the test point is very important. It is actually the through thickness at that point which is being tested. For this reason, the point of concern should more or less possess the same properties as the concrete section, and also the behavior of sound waves at that point in relation with the dimensions of the section should be well understood.

Results greatly vary near the end portions of the section. While this effect could be observed easily in concrete slab specimens, they present a serious problem during the testing of slender members such as columns and beams. Therefore it could be stated that the results obtained are dependent on the position of the test point; the proximity of areas of changing geometry.

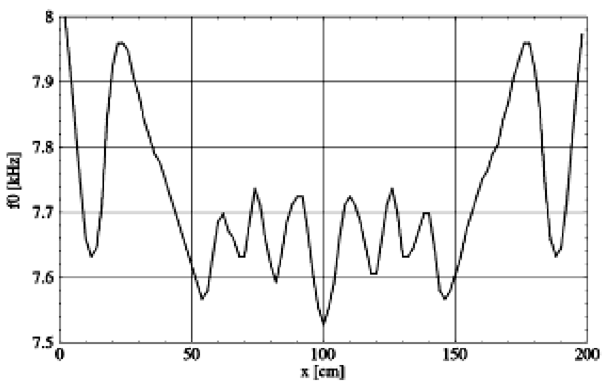
A study has been carried out for investigating this effect [3]. A concrete slab having a constant thickness of 25 cm and dimensions of 2 m by 1.5 m was used for the experiments. A line was drawn from the width of the section and readings were collected on this line. The results proposed from these tests are interesting because thicknesses found by converting frequency readings varied in the range of ±0.7 cm through the width of the section having a constant thickness, which corresponds to a variation of 5.5%. The lowest value was obtained at the very center of the slab, and the upper-most one at 25-30 cm distance from the edge of the specimen [3]. It was concluded that even if the wave speed were exactly known, the readings would still change with the position of impact relative to the edges of the slab.

The writers of that study, however, express their uncertainty about one aspect of the tests. Although their specimen was meant to model a concrete slab, they have placed a mesh of steel reinforcement and several steel tendon ducts. The readings were not collected directly on top of one of these tendon ducts, but still, their existence near the vicinity of the test point combined with the existence of steel reinforcement would alter the results.

Due to doubts on this matter, it was decided to conduct a simplified version of the experiment on plain concrete during experimental phase of the present study and results are reported in the discussions part. It is believed that the reinforcement present affects the results since the proposed pattern of results fits well with the locations of the reinforcement.



a-) 3-D view of the slab specimen used together with the reinforcing mesh and tendon ducts



b-) The resulting frequency values obtained from the length of the section of constant thickness

Figure 2.9 Results of tests conducted along section length [3]

2.2.9 Applications

The impact-echo method has been successfully used in detecting a variety of defects, such as voids and honeycombed concrete in structural members, delaminations in bare and overlaid slabs, and voids in tendon ducts [1, 2]. Experimental studies have been supplemented with analytical studies of finite element analysis to gain a better understanding of the propagation of stress waves in concrete solid sections with and without flaws [1, 2].

The impact-echo method has also been applied to evaluate the quality of the bond between an overlay and base concrete [2]. While it is not possible to estimate the bond strength or the overall compressive strength of concrete, the impact-echo method may determine whether there is extensive porosity, voids or honeycombed regions at the interface.

A series of experiments were conducted to determine whether impact-echo was suitable for quality control or not [9]. It was proposed that the major source of error was introduced during the determination of wave velocity. The measured velocities usually showed great scatter which was associated with the determination of locating the first arrival of the P-wave from the output graphs. The most reliable value was found to be the average value of all wave velocities found for that thickness, rather than the local wave speed found at a single location. By using this value, impact-echo results for slab thickness were reported to be found within 1 mm of the true values corresponding to that point, with a standard deviation of 5.8 mm [9].

The results of a different study investigating the effects of W/C ratio on wave velocities are given in Figures 2.8 and 2.9 below. Wave velocities were determined both by the impact-echo method and the ultrasonic pulse method. It can be noticed that wave velocities increased by around 500 m/s between weeks 4 and 9, independent of the W/C ratio. The main effect of the W/C ratio is its influence on the ultimate value the wave velocity can attain, much like its compressive strength. Another interesting fact that can be concluded from the graphs below is the distinct difference between wave velocities of the upper and lower portions of the specimen. This was caused by both segregation and by the extended curing at the lower portions, since specimens were placed in cups filled with water up to several cm so that their bottom layer would be continuously immersed in water.

Curing has an important effect on wave speeds. Portions immersed in liquid gain faster wave velocity both on the surface and through the thickness due to accelerated hydration products in the presence of water. This effect causes near surface wave velocities to increase faster than in-depth velocities since transportation of water through the pore system gets slower with increasing depth [11].

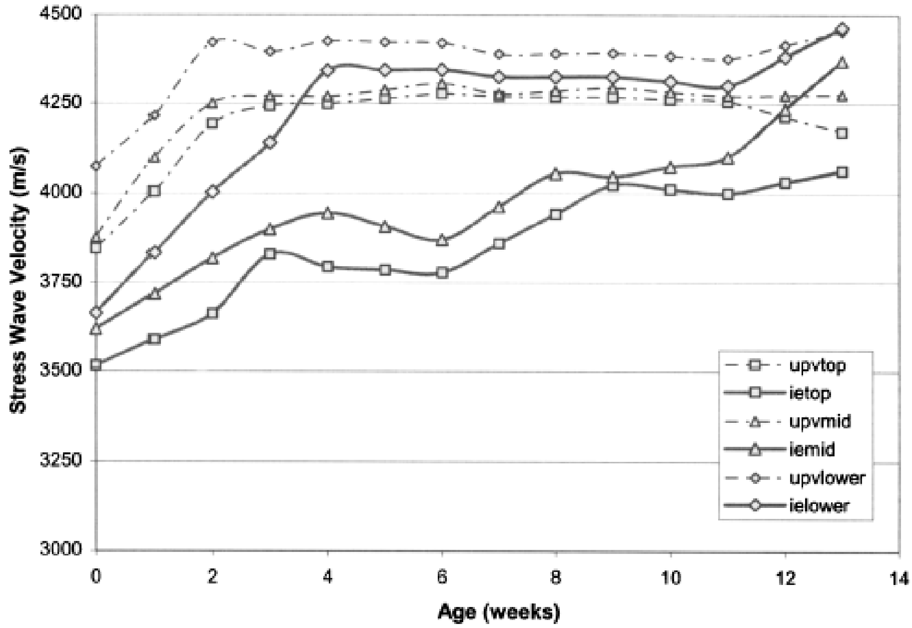


Figure 2.10 The increase in wave velocities with time in a concrete specimen with 0.45 W/C ratio. A comparison is also shown between the impact-echo and the ultrasonic pulse method. [11]

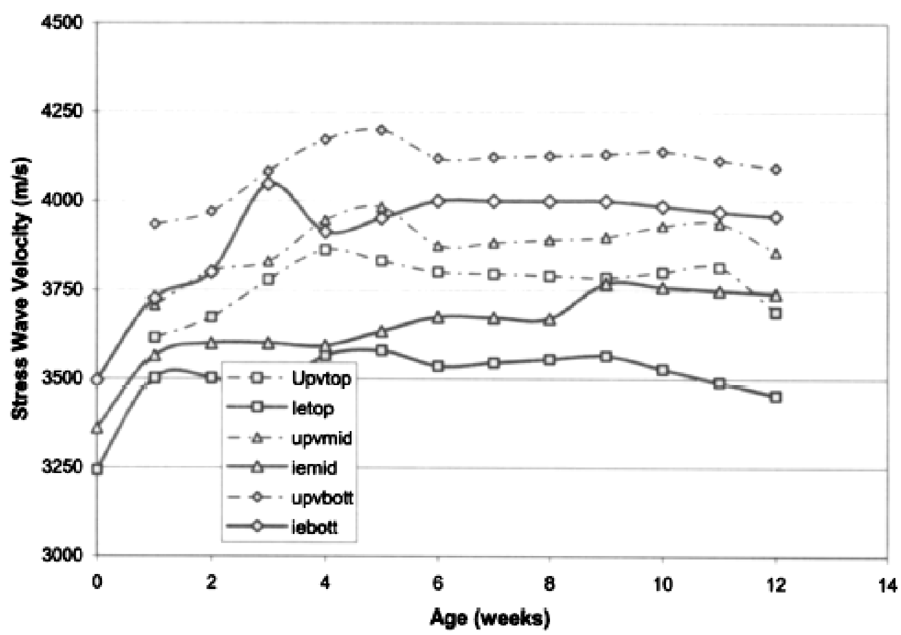


Figure 2.11 Comparative wave velocities in a concrete specimen with 0.65 W/C ratio [11]

2.2.10 ASTM Test Method C 1383-04

The development of a standard test method for flaw detection using impact-echo is difficult because of the many variables that may be encountered in field-testing. The types of defects can vary from the rather simple case of delaminations or planar voids to the complex case of distributed micro cracking on the surface or inside the member. Also, the type of structure can vary from a slab to more complex cases as of a round column or hollow pipe.

However, the measurement of the thickness of a plate-like structure is a relatively straightforward application that is suitable for standardization. In 1998, ASTM adopted a test method on the use of the impact-echo method to measure the thickness of concrete plates [16]. This standard was later revised in 2004. In the standard, a plate is defined as a structure or portion of a structure in which the lateral dimensions in both directions are at least six times the thickness. ASTM C 1383-04 includes two procedures [16]. Procedure A, which is shown on the left side of Figure 2.10 below, is used to measure the P-wave speed in the concrete. This measurement is based on measuring the travel time of the P-wave on the concrete surface between two transducers which are located at a known distance apart, 300 mm under normal circumstances. Procedure B which is shown on the right side of Figure 2.10, is to determine the thickness frequency using the impact-echo method from which the plate thickness is calculated using the measured P-wave speed and Equation 2.5. Limited comparisons with the length of drilled cores demonstrated that the impact-echo results were within 3% of the core lengths and this lies within the allowable range for several standards [16].

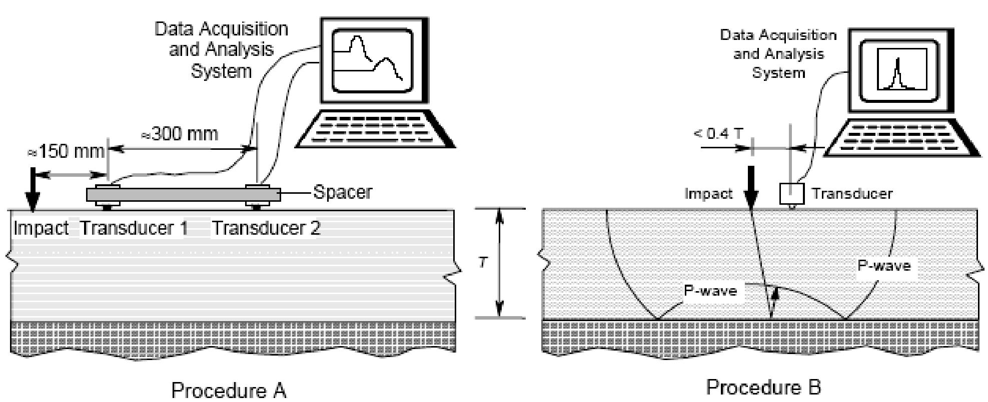


Figure 2.12 Procedure to be followed for impact-echo testing [16]

2.3 Concrete Pavements

Introductory information in brief about the history and development of concrete pavements provides valuable information about current conditions as well as future developments and trends.

During the 1st century BC, the Romans used pozzolans and stones to build their road network. The total length of their road network was 80000 km. Although this might historically be the first application, concrete pavements, as we know them today, were first built during the 19th century. The first concrete pavement applications were in Scotland between 1865 and 1879 [17, 18]. Australia (1880) and the United States followed soon after. A local street in Ohio, United States which was built in 1891 is the oldest concrete road in United States, and interestingly, it is still being used today [17].

By 1914, 3,500 km of concrete pavement was completed in United States. This value increased to 70,000 kilometers until 1970.

During 1930's, a program was initiated in Germany just before the Second World War which consisted 4,000 kilometers of concrete highway construction. Belgium, France and Switzerland followed similar programs soon after the war [17].

The situation in Turkey is not very promising. The technical properties of concrete pavements are only beginning to be understood and so there are only few applications. The current situation of the Turkish transportation network and of the existing concrete pavement applications would be explained in the sections that follow.

2.3.1 Introduction

In Turkey, more than 90% of passengers and cargo are transported by highways. If there is to have an increase in commerce and pace of industrialization, then the current trade routes must be improved to compensate for increased traffic so that transportation becomes safer, faster and more comfortable [19].

In order to manage this, existing pavements should be improved in addition to the building of new ones. Until now, common practices have been to increase the number of lanes, replacing surface treated asphalt pavements with a new, thicker asphalt pavement, and forming divided highways. By investigating the latest projects built, it can be observed that repair works for asphalt pavements start very shortly after their completion. Concrete pavements generally require fewer repairs and therefore, once built, fewer workers need to be allocated for maintenance purposes. Besides this, their useful lifetime is longer. A lasting national policy should be adopted instead of temporary solutions. Pavements built should not be designed to only save the day and last 3-4 years but should stand for at least 15-20 years [20].

All raw materials for concrete pavement construction can be found abundantly and obtained easily from national sources. The Turkish cement industry is one of the largest in the world and is capable of producing various types of cements which are in accordance with international standards [20]. Today, there are 39 cement factories in Turkey, and over 400 ready mixed concrete plants that are scattered all around the country [17].

During the first 15 years of the Turkish Republic, there was a strong public support for the transportation policy to improve and expand the railroad network. Beginning from the 1950`s however, that policy was abandoned and construction of highways was promoted. As a result, today, the proportion of transportation of passengers and cargo by sea or railroads has decreased to insignificant numbers relative to highway transportation [17, 21].

2.3.2 Current Status of the Turkish Transportation Network

According to the latest statistics of the National Directorate of Highways, the total pavement length in Turkey is 63,589 km. Of this total amount, 1775 km were built as motorways and 31,446 km as state highways. The remaining 30,368 km are municipal pavements. 18% of the total road network including motorways were built as divided highways [21]. Figure 2.11 below gives the relative percentage of different pavements.

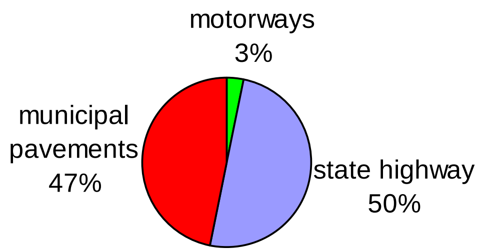


Figure 2.13 The relative distribution of pavement types in Turkey [21]

Until 1946, only 0.7% of the total pavement network was constructed as hot-mix asphalt concrete and 1.2% as surface treatment. The remaining 98.1% of roads were either stabilized or bare soil. From then on, these figures improved significantly, and according to the statistics of 2005, 79% of the total road network is of the surface treatment type, 14% as hot-mix asphalt concrete and 7% as stabilized or bare soil. It is interesting to note that all of the motorways were constructed as hot-mix asphalt pavements [21].

Nevertheless, the amount of pavement per km^2 is still considerably low compared to some other developed European countries. Table 2.3 below gives the comparative values further illustrating this position.

Table 2.3 The amount of highways per 1000 km^2 in various European countries [21, 22]

Country	Amount of pavement per 1000 km^2 (km)
Belgium	4702
Holland	2622
Luxembourg	1962
Germany	1799
France	1763
Denmark	1654
England	1504
EU Average	1476
Ireland	1313
Austria	1267
Italy	1018
Portugal	718
Greece	715
Spain	676
TURKEY	489
Sweden	302
Finland	230

The amount of highway transportation and its percentage relative to other transportation modes has increased as a result of the above mentioned improvements in pavement types and extension of the road network.

Statistical data reveal that the percentage of passenger transportation by highways has increased up to 95% of the total amount. This value was around 73% in 1960 but increased to 94.8% until 1980. From then on, although the number of passengers changed, the ratio was constant except for small annual variations, as shown in Table 2.4 below.

Table 2.4 The change in number and percentage of passenger transportation by means of highways in recent years [21]

Years	Passenger Transportation by Highways, %
1997	95,0
1998	95,0
1999	94,8
2000	95,0
2001	95,0
2002	95,4
2003	95,0
2004	95,3

The percentage of cargo transportation by means of highways presents a similar situation. This ratio was 38% in 1960 and increased to 81% until 1980 and finally became 94% in year 2004.

Table 2.5 The change in percentage of cargo transportation of highways in recent years [21]

Years	Cargo Transportation by Highways, %
1997	93.0
1998	95.0
1999	89.9
2000	89.9
2001	90.5
2002	91,9
2003	92.0
2004	94.1

The percentage of cargo transportation by heavy vehicles is very high in Turkey compared to European countries. It is estimated that around 40% of vehicles in Turkey are in this category whereas this value is between 10-15% in European countries [17]. The deformations that could be encountered on almost all of our highways are most of the time due to these repeated heavy loads. Concrete pavements are known to be more resistant to heavy loading and so must be considered during design.

2.3.3 Types of Pavements

The types of pavements constructed in Turkey and their characteristic properties will be mentioned very briefly in this section.

It is very important to choose the right type of pavement overlay. A preliminary decision is to make a selection between flexible pavements and rigid pavements. Both have their own sub-categories and different methods of construction.

Surface treatment is a flexible pavement and is the most commonly applied technique for pavement construction. This technique is sometimes also known as surface dressing. The binder material, which is bitumen or tar, is laid out on the projected surface area and a thick aggregate layer of several centimeters is placed over it and compacted by using rollers. This type of pavement can be made up of several layers; the procedure is to be repeated every time. This method requires less binding material and also there is no mixing process. Therefore, it is usually cheaper compared to other methods but is technically more suitable for pavements of low volume traffic.

Hot-mix asphalt pavements are another major type of flexible pavement. Their preparation is similar to plain concrete. Fine and coarse aggregate is mixed together with tar in special mixing plants and then the mix is placed while it is still hot and workable. The mix placed is subsequently compacted with heavy rollers. The quality and serviceability of hot mix asphalt pavements are much better than surface treatment and is suitable for high volume traffic. Nevertheless, it is expensive and therefore not widely used in Turkey except for motorways and important main routes.

Rigid pavements form a separate category of pavements. They are built by using concrete. The main difference from flexible pavements is that portland cement is used as the binding material between the aggregates instead of tar. Rigid pavements distribute the vehicle load to a large area on the base layer to minimize local stresses. Even if the base layer of pavement has deformed and created a delamination underneath the pavement, rigid pavements will not deform and crack immediately but remain intact until the load carrying capacity of concrete has been exceeded. Considering this property, it could be stated that concrete pavements could be used on top of weak bases or where there are materials susceptible to erosion or movement of fines [17].

2.3.4 Properties of Concrete Pavements

Perhaps the most important and obvious advantage of concrete pavements is their long period of serviceability. The service life of rigid pavements usually varies between 20 and 25 years. After this period, they act as a sound base layer for the new pavement on top of it [6].

This increased service life is partly due to the load carrying character of concrete and partly due to increased abrasion resistance. Most deteriorations start from the external surface of the pavement and therefore decreased surface damage results in increased service period. In applications where high strength concrete is used, the abrasion resistance becomes equal to that of natural granite.

2.3.5 Types of Concrete Pavements

Concrete used for pavements has distinct differences from structural concrete. Due to this reason, most developed countries have developed separate standards and design catalogues for concrete pavement design and construction.

The most important characteristic of structural concrete is its compressive strength. In pavement concrete, although compressive strength is still important, flexural strength and durability are also equally important.

There are several techniques for concrete pavement construction and introductory information will be given about each without going into much detail [17]. Each technique has its own technical properties and therefore sound knowledge is required before application.

2.3.5.1 Plain Concrete

This is the most basic type of concrete used for pavement construction. It does not have any reinforcement inside except tie bars and dowels used for joint connections. The lack of reinforcement usually necessitates the use of thicker sections. Plain concrete pavement thickness should be a minimum of 15 cm as given by most standards. Its maximum thickness value changes for each country. There is a limitation to the maximum section thickness in the design codes since using a too thick section becomes uneconomical after some point. It is then usually advised to use some sort of reinforcement to decrease thickness.

The American Standards allow a maximum of 30 cm for plain concrete pavements [23]. South African Standards limit this to 27.5 cm [24]. The reason this limit changes for each country is due to the fact that costs of producing concrete and reinforcement in each country are different.

2.3.5.2 Reinforced Concrete with Joints

Using reinforcement in concrete pavements has some advantages over plain concrete. First of all, since reinforcement increases the tensional and flexural strength of concrete, it results in the reduction of slab thickness. This decrease in the volume of concrete used may help decrease the total cost of the project.

Other than decreasing the section thickness, there is also another benefit which is equally important. Reinforcement helps joints and limits the amount of expansion or contraction the slab experiences. Since movement at each slab is reduced, then the intervals of the transverse joints placed in between them can also be increased. Using less joints both increases driver satisfaction and also decreases the likelihood of occurrence of focal points for deterioration.

In plain concrete, the aim is generally to collect all cracks near the joint regions. In reinforced concrete, it is not desirable for all cracks to be at a single location. Water seeping through those regions might oxidize the reinforcement and thus result in the loss of its properties and ability to keep slabs together. The neighboring slabs would then act differentially. It is preferred that cracks be evenly dispersed along the surface of the section and as small as possible in size. This way, they are kept under control and widening of cracks is being prevented.

There are several methods for reinforcing concrete pavements. The distinct property of each will be discussed very briefly.

2.3.5.3 Continuously Reinforced Concrete Pavement

In plain concrete pavements, the sections are divided by joints extending both along the length and width. Due to repeated high axle loads or due to changes in climatic conditions, expansions and contractions occur and they result in cracking. For pavements designed with plain concrete, cracks will inevitably occur but the aim is to gather all cracks near the joints. Concrete with continuous reinforcement was designed as an alternative to this. By using a continuous reinforcement system, there is no need for joints because the local stresses and volume changes are dissipated by the help of the steel reinforcement. Instead of trying to collect all cracks around a region, the crack locations are randomized throughout the pavement but their expansion is kept under control by the reinforcement.

Another advantage of using continuous reinforcement is that it allows construction without the base layer. The base layer at the middle helps the pavement slab above by compensating for some portion of the differential vertical settlement caused by the subgrade.

Like plain concrete, reinforced concrete pavement method also has a maximum allowable thickness. Although the values differ for each country, the approximate values are around 22.5 cm [23, 24, 25, 26].

2.3.5.4 Other Special Concretes

An alternative to plain or rebar reinforced concrete is to use fiber reinforced concrete. During the mixing process, steel or carbon fibers may be included into the mix to increase the tensile and flexural strength of hardened concrete. They also increase the resistance of concrete to high axle loads and especially to abrasion at the surface.

Another technology that has gained widespread use around the world is the use of prestressed concrete. By prestressing the concrete, the tensile forces and deformations caused by changes in temperature, humidity or mechanical forces exerted would not occur or at least would be reduced. This effect is taken into account during the design stage, where pavement thickness could be decreased up to 15 cm. This provides economy due to reduced material costs. It also reduces the amount of cracks that occur and so the distance between consecutive joints could be increased which would positively affect driver comfort.

If special types of forms or extensive compaction equipment are not used during construction, then flowing concrete could be used while still satisfying the strength limitations. The concrete then could be compacted by surface vibrators and this will shorten the construction period.

The use of roller compacted concrete is interestingly useful because it eliminates one of the major problems by allowing the machinery used for asphalt pavement construction to be used for concrete pavement construction also. Roller compacted concrete which looks very similar to ordinary soil in color and appearance before final set, is then surface treated and compacted by using finishers and graders much like a surface treatment pavement.

An interesting application is the use of permeable concrete. In locations where there is extensive precipitation, it is usually a problem to keep the pavement surface dry. Repeated hydroplaning could cause many casualties at that location. Accumulation of water should be prevented to satisfy a minimum adherence between the pavement surface and vehicle tires. The amount of voids in permeable concrete is intentionally high for excessive water to enter into those pores and ultimately reach the drainage system below. It is obvious that temperature should not fall below zero degrees throughout the year, where water freezes and its volume expands, or else water present in those pores would cause great tensional stresses inside the concrete and result in cracking and spalling in large pieces.

During the past few years, the use of composite pavements has increased. This is a layer of concrete pavement over asphalt pavement or vice versa. This is a very useful technique since it enables the use of existing pavements as a base layer. Regardless of irregularities on the surface or how much the pavement has cracked, existing concrete pavements act as a very sound and stable base for any type of pavement over it.

The application of an overlay of the same type as the existing pavement will increase the structural capacity of the section. Actually this is the cheapest way for such an increase. Of course, there are situations where this will not work. A concrete pavement which has suffered from alkali-aggregate reactions or where extensive freezing and thawing have created serious cracks might not be a suitable base layer. Demolition and removal of that section are necessary under these circumstances.

2.3.6 Surface Texture

The surface texture of concrete pavements plays an important role for safety considerations. During pavement construction, the surface of concrete is almost perfectly smooth after being placed and compacted by the machinery. Although smoothness of the surface is something desirable, a perfectly smooth surface is dangerous for vehicles considering the resulting prolonged brake distances. Therefore, in practice, the surface of fresh concrete is slightly rubbed with a brush in the direction of pouring before final set so that its surface has small roughnesses.

Nevertheless, this relative smoothness is adequate to drain the accumulated water faster from the surface and prevent hydroplaning. This phenomenon may be explained as the formation of a thin layer of water on the pavement surface which causes the tires to lose contact with the pavement surface and so steering ability is lost and thus safety is considerably decreased during a sudden brake [6].

Under even lower temperatures, the free water on the surface might freeze and form a thin layer of ice on the surface. This situation is even worse than hydroplaning where the driver might completely lose control over the vehicle.

The above mentioned problems illustrate the importance of drainage of water from the surface and are closely related to the effects of degradation of the surface texture. Other than hydroplaning, the formation of ruts would result in the collection of all nearby free water into the ruts and seriously reduce the friction coefficient after heavy rain.

The surface texture is also very important for impact-echo testing. The tip of the transducer should be in full contact with concrete. Failure to achieve this would result in repeated testing at a point which is time consuming.

2.3.7 Slab Dimensions

Concrete roads are not built as a monoblock but are made up of sections. These section dimensions vary for each project and they show great variations depending on the technique of construction and mainly on the availability of reinforcement.

There are several separate sections and it is expected that they act together, therefore the area between them, namely joints, have great influence on the performance of concrete pavements.

2.3.8 Joints

While designing concrete pavements, it is important to minimize and control cracks that would form due to variations in humidity and temperature. Concrete, like most materials, expands and contracts due to changes in the atmospheric conditions. This phenomenon is very important in concrete pavements and could be observed throughout the lifetime of the pavement section starting from the initial phases with drying shrinkage.

To prevent problems associated with differential movement of neighboring sections, steel and fiber reinforcements or different joint systems are being applied.

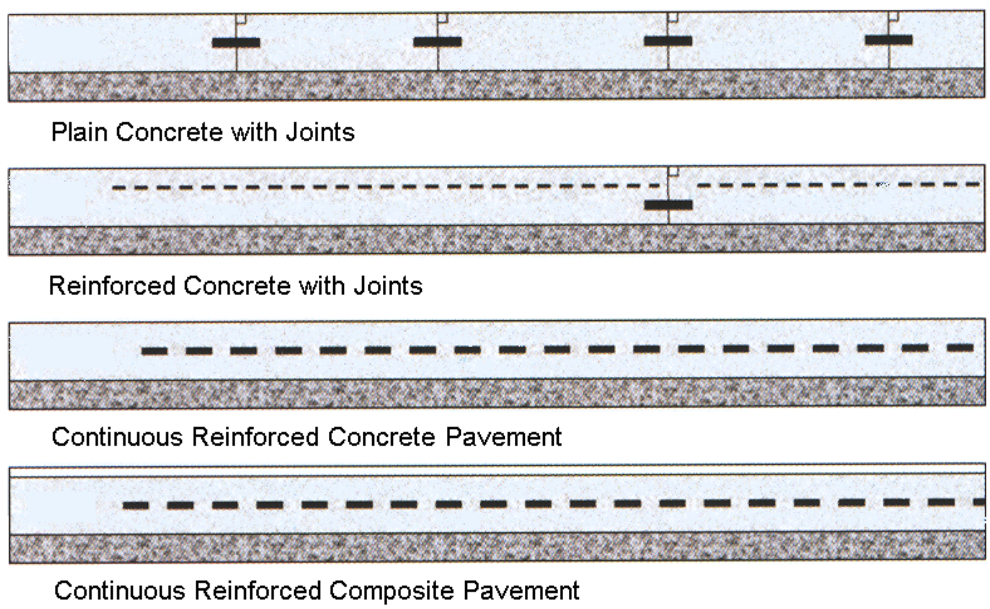


Figure 2.14 Several basic forms of concrete pavements and location of joints [17]

The type of joint and distance between consecutive joints are important for impact-echo testing since all joints, whether partially or completely cut, create a layer of discontinuity at that section. Since this method uses sound waves, the geometry of the section and remoteness of a joint play a vital role for successful testing.

Joints act as centers for force dissipation. When concrete contracts due to decrease in temperature or loss of moisture, tensile forces occur inside the pavement section. Cracks occur along the weakest plane and so they usually concentrate at or near the joints. Although not very large or serious, some cracks usually occur starting from the setting of concrete. Furthermore, the acting tensile forces help enlarge and widen those cracks.

On the other hand, compressive forces occur when the temperature or moisture of concrete increases. These forces may result in crushing of concrete along the section interfaces and may produce serious cracking or even spalling of large pieces.

Joints may be placed along the length or width of the pavement section, which are called longitudinal and transverse joints respectively. Transverse joints allow free movement of concrete section and prevent cracking. They are usually placed at 4 to 7 m intervals for non-reinforced concrete pavements. For reinforced pavements, this range further increases to 7 – 23 m. Connection between these joints is achieved either by aggregate interlock or by the use of dowels.

Longitudinal joints might not be present at all, depending on the capacity of the placing equipment and the number of lanes of highway projected. It is customary to use embedded tie bars connecting the two neighboring slabs, usually the two lanes. Their main purpose is to prevent excessive separation of lanes.

Joints may cut partially or completely through the section thickness. Partial cutting is used to gather all cracks around the weakened section. Complete cutting is used when two consecutive pavement sections are not poured at the same time, as at the end of the construction workday, or to consciously place a layer of expansion joint in between the slabs.

For concrete poured in cold weather, expansion joints allow free movement of different sections with increasing temperature. However, they are difficult to construct and maintain and often they contribute to pavement failures.

Nowadays, joint spaces are filled with elastic expansive materials which help dissipate these extra forces and are able to show volume changes without losing their material properties. In this manner, the formation of extended cracks or spalling is prevented, and also the cracks are localized and collected around the joints.

There is also another reason for using elastic materials. All joints more or less create a discontinuity on the surface of pavements and they may also cause water seepage into the base and cause further problems of erosion, swelling or freezing and thawing. Therefore, using expansive filler materials which do not easily lose their elastic properties prevent seepage of water and detrimental chemicals. After placing the required amount, the excess part should be leveled and finished to prevent greater discomfort for passengers.

It might be stated that joints decrease drivers comfort. Although joints might not be noticed by the driver while the section is relatively young, this effect is felt more as the concrete ages, due to increased cracking, local spalling of edges and deformations of the filler material.

In reinforced concrete with joints, the distance between joints has greatly increased due to the presence of reinforcement. Further increase in reinforcement would allow us to produce concrete pavements without joints. Especially if design standards necessitate so, or if increased drivers comfort is required in heavily trafficked highway pavements, then the continuous concrete pavement system could be utilized. There are no joints in this type of pavement system. The transfer of loads and load dissipation is achieved through continuous reinforcement inside the concrete pavement section [17].

2.4 Concrete Pavement Applications Around The World

Different applications and rigid pavement catalogues of several developed countries in this area were investigated initially, as part of the present study. During this investigation of different practices of other countries, detailed information was available mostly for plain concrete design and composition.

In the Engineering Manual of U.S. Army Corps of Engineers, it is stated that plain concrete pavements without any type of reinforcement should have a minimum thickness of 15 cm, and a maximum of 30 cm. If calculations result in a value above the maximum, it is then advised to use reinforced concrete. Low slump values and decreased porosity for durability requirements necessitate the use of chemical admixtures and perhaps a small amount of mineral admixtures. Plain concrete pavement slabs are usually constructed with dimensions of 3.5 meters to 4.5 meters in width and 4 meters to 6 meters in length [23].

In 1993, the U.S. Department of Transportation realized that they were behind in concrete pavement technology compared to some foreign countries such as Germany, Austria, France and Belgium, South Africa and Australia. These nations are recognized as leading nations in pavement maintenance and innovative programs [24]. Afterwards, a technical tour was arranged to these countries and different technical reports about their innovations and practices have been published [25, 26]. The technical report written after the tour of Germany revealed some interesting applications. First of all, the Germans use a well defined and extensive design catalogue for rigid pavement design and construction. High quality concrete with increased durability and high compressive strengths is used together with close quality control. It is a common phenomenon for their pavements to be used for over 25 years [25].

Maximum thickness of plain concrete pavement was allowed to be 26 cm with a compressive strength in the range of 35 – 65 MPa. The spacing between consecutive transverse joints was allowed to be at most 5 m. The use of fly ash is not allowed, and other mineral admixtures are not fully supported. Extensive use of chemical admixtures also is not used except for water reducing admixtures and air entraining admixtures. Perhaps the most distinct difference is their technique for placing concrete. Pavements were constructed in two layers where the upper layer was usually 7 cm thick. Working with thinner sections provides better compaction and less cracking but certainly increases the construction period [25].

Similar results could be seen in the report written after the South African tour. In South Africa, they have used a concrete pavement thickness of 23 cm in one of their important intercity highway projects [26]. This was designed as a plain concrete pavement without any type of reinforcement. A limiting maximum thickness for plain concrete pavements could not be found in the catalogue. Nevertheless, a value of 25 cm could be proposed considering the fact that 23 cm was used in a major intercity highway. There was a 15 cm thick cemented crushed stone section underneath it as a base. The cemented base used in this case might lead to errors for impact-echo testing. Since the acoustic impedance between the two layers is not very distinct, test results might give the combined thickness in such cases. Pozzolanic materials such as fly ash and ground granulated blast furnace slags are not usually incorporated into the mix, but a maximum of 15% is allowed if it is decided to be used. As for the filling material of joint spaces, plastic parting strips were in use until recently. Nowadays, they use low modulus silicone seal material which preserves its elastic properties over a longer period [26].

2.5 Concrete Pavements in Turkey

Perhaps the first concrete pavement application built in Turkey was the pavement section at a busy junction in Mahmutbey, Istanbul. This was a very small project where the total length was approximately 0.5 km. It was constructed by a partnership between the Turkish Ready-Mixed Concrete Association (THBB) and the National Directorate of Highways (KGM).

Interestingly, there is only one example for the application of concrete pavements in an intercity highway in Turkey. After the pavement at Mahmutbey, a trial pavement was built between Afyon and Emirdağ, and its length was around 2 km. Therefore, its thickness, mix design, slump value, compressive strength and performance were of great interest for this thesis study. Detailed catalogues containing its important parameters were studied and its properties were taken as a basis for the different sized concrete specimens produced in the laboratory.

The pavement thickness was designed to be 27 cm. It was agreed upon such a rather large value due to considerations regarding further increases in traffic loads in the area. Like many other concrete pavements, its mix design and proportions were also designed very specifically to produce a durable concrete. A pavement built in that region should be able to withstand the detrimental atmospheric conditions of the Afyon region. For decreased porosity, a water-cement ratio (W/C ratio) of 0.45 was used. The slump value was 4 cm, as is typical with concrete pavements.

Certain mineral and chemical admixtures were used to further enhance the properties of concrete. With such a low W/C ratio and slump value, water reducing admixtures were used to improve workability. Besides this, air entraining admixtures were used at an amount of 0.2 kg/m^3 to reduce the detrimental effect of freezing and thawing. Afyon has a strong inland climate, where the highest temperature at summer is 37.8° C and the lowest temperature during winter is -27.2° C. Furthermore, the average temperature during the cold months is 0.3° C and this is an indication that there are lots of freezing and thawing cycles in a year [27].

As for the mineral admixture, silica fume was implemented to increase the compressive strength of concrete. In addition to the 375 kg/m^3 of cement, 17.5 kg/m^3 of silica fume was added. This amount corresponds to approximately 5% addition of silica fume, which is rather high. At 28 days, control specimens yielded an average compressive strength of 50 MPa.

The pavement was opened to traffic in September 2004. Figure 2.15 below is a picture taken after two years of service which shows that the concrete around the joints still seems intact and no cracks are visible on the surface or around the joints. The sealing material is still in place and no voids could be found by visual inspection through the width of the pavement.

Figure 2.16 is a view from the side of the pavement showing the width of the 3-lane, 12 m concrete pavement. Each one of the rectangular slab sections was of dimensions 4m by 6m. As can be noticed, the surface texture has not been distorted or diminished.

Figure 2.15 A photograph taken at September 2006 shows that the status of the joints and of the sealing material in between is still in good condition

Figure 2.16 A photograph taken at September 2006 from the side of the pavement at Afyon showing all 3 lanes and the surface texture

Some time after the completion of the pavement at Afyon, another sample section was built according to the initial protocol between the KGM and Turkish Cement Manufacturers Association (TCMA). This was a larger project where the total length was approximately 3.5 km. Its location was at Hasdal, Istanbul.

Besides these examples, recently, a concrete pavement of 1 km length was poured in front of one of the governmental offices in Ankara. It was built over an existing asphalt pavement. Although the top surface of concrete did not show great variations in thickness visually, the bottom surface did. 25 thickness measurements were collected at random points along the length of the open side of the concrete pavement. The measured thicknesses varied in the range of 14 cm to 25 cm. The average of all data turned out to be 17 cm with a standard deviation of 2.77. For a concrete pavement that would be built on an existing layer of pavement not possessing a perfect surface, the average thickness of concrete and the total amount of concrete used for construction is vital during payment interims both for the contractor and the employer. Variations of only few centimeters in pavement construction would greatly alter the resulting costs and payments.

Although it might not be much for a pavement of 1 km length, it would mean millions of dollars for even a medium sized intercity road project. It is obvious that some kind of non-destructive technique is necessary to overcome such problems.

Figure 2.17 The concrete pavement example in front of a governmental office building in Ankara

CHAPTER 3

EXPERIMENTAL STUDIES

3.1 Introduction

The experimental study of the thesis was the determination of concrete pavement thickness using impact-echo. In order to propose a reliable error percentage applicable to different thicknesses encountered in the field, several variations in the concrete section thicknesses were required to perform a variety of tests. These thicknesses and compositions were decided on in light of the information obtained from previous examples and studies.

As for the impact-echo equipment, the standard set was used without replacing any component in order to simulate and understand the problems that could be encountered in an actual field test. It contained all the equipment necessary for testing including the impact-echo software which could be installed on a computer.

3.2 Slab Specimens

Considering the design catalogues of foreign countries such as Unites States, France, Germany, South Africa and Belgium, the mix design, compressive strength, section thicknesses and other important parameters were selected for the specimens that would be produced for experimentation.

As impact-echo tests are presumed to be sensitive to changes in geometry, the testing of different thicknesses in a single slab with different surface heights was not preferred. Instead, four separate plain concrete slabs were planned, each having the same length and width but different thickness. Literature survey revealed that almost all non-reinforced concrete pavements had thicknesses in the range of 15 cm to 30 cm. Furthermore, the use of thicker sections was strongly opposed in some countries due to increasing costs [23]. The reason for this is due to the fact that using reinforced concrete would be a more economical solution in those cases, instead of using plain concrete. Nevertheless, thickness determination of reinforced concrete by impact-echo is out of the scope of this thesis study and therefore all specimens were made of plain concrete. Steel reinforcement would distort the sound waves and their effect would have to be included in the analysis also.

After setting the thickness range to be investigated, the number of specimens was determined. It was decided that using four different specimens with 5 cm increments in thicknesses, from 15 cm to 30 cm would be adequate for representing the behavior of the test method and reliability of results by determining its accuracy.

Besides thickness, the length and width of the slabs were also important for the test. A small specimen would obviously include the effect of geometry and distort or even hide the real behavior and frequency of the section. This would not be useful for modeling the behavior of impact-echo on concrete pavements. These small variations would of course be unimportant if the accuracy results that were being investigated would not be so dependent on the precise results obtained from each reading. An excessively oversized specimen, on the other hand, would be unnecessary from the practical point of view.

The field applications of concrete pavement slabs are usually constructed with dimensions of 3.5 meters to 4.5 meters in width, and 4 meters to 6 meters in length. The pavement at Afyon has rectangular slab dimensions of 4 meters to 6 meters. Since there was four different slabs, and limited space inside the laboratory, the dimensions were selected as 1.5 meters in width and 2 meters in length, with changing thicknesses as mentioned above. Investigation of previous research conducted with impact-echo testing had revealed that the section dimensions were logical.

The total volume of concrete necessary for these various sections added up to approximately 3 m^3. Since large quantities of concrete having the same mix designs and properties are required for four of the concrete slabs, the use of ready-mixed concrete was more appropriate for this case.

Cube and cylinder forms were prepared and oiled beforehand so that specimens could be obtained to determine compressive strength at 7, 28 and 90 days. These forms were filled and compacted in accordance with ASTM standards. Figure 3.1 is showing the arrival of the truck mixer and initiation of pouring.

Figure 3.1 Concrete being placed in the laboratory

The slump of concrete was tested initially as seen in Figure 3.2. The batch had a slump value of 10 cm. Besides the slump value, unit weight and air content was also measured. The unit weight of concrete was determined to be 2400 kg/m^3. The air content was determined as 1.5%.

a-) Slump

b-) Air content

Figure 3.2 Tests for fresh concrete

For the compressive strength test, 3 samples were tested and the average of these is reported. The compressive strength obtained from 15 cm cubes were 31.7 MPa, 40.7 MPa and 42.3 MPa for 7, 28 and 90 days respectively.

During assembling of the forms, it was decided that some sort of a system was required to raise these slabs when necessary. The best alternative for this seemed to insert pipes near the two ends. Commercially available pipes with 7.5 cm diameter were used. These plastic pipes actually served for two purposes. First, the hollow pipes would be used to move the slabs if required during or after impact-echo testing. Second, that part of the slab section would be tested by impact-echo to see if the pipes could be detected, and to assess the corresponding accuracy in doing so. Using steel reinforcement for this purpose clearly would affect the readings during testing on that area. Combined with changing thickness, the two parameters which are tested at the same time could be confusing during the final analysis. The final stages of the two forms having different thicknesses are shown in Figure 3.3.

Figure 3.3 Final status of forms while placement of concrete has just begun

However, it was decided to form a void at known location and depth in one of the slabs. The void needed to be formed by another material whose density, and thus, the wave speed in that material is different. The greatest acoustic impedance should be obtained by leaving a hollow section full of air. This was not easy to achieve and practical and therefore it was decided to use a piece of foam board instead. Foam board, as being a very lightweight material and having a very large difference in the acoustic impedance compared to concrete, would act like the necessary void by creating a distinct interface. Besides, testing a concrete specimen having a foam board on one side is another very commonly encountered situation and it was considered that it might produce useful results. This case could be encountered in field applications where walls or slabs are being investigated inside a building.

The foam board used had approximate dimensions of 60 cm by 60 cm. Its total thickness was 6 cm. For it not to slip and rise to surface while the concrete was being poured over it or during the compaction phase, two pieces were put on top of each other and tightly tucked under the hollow cylindrical pipes existing near the ends as shown in Figure 3.4.

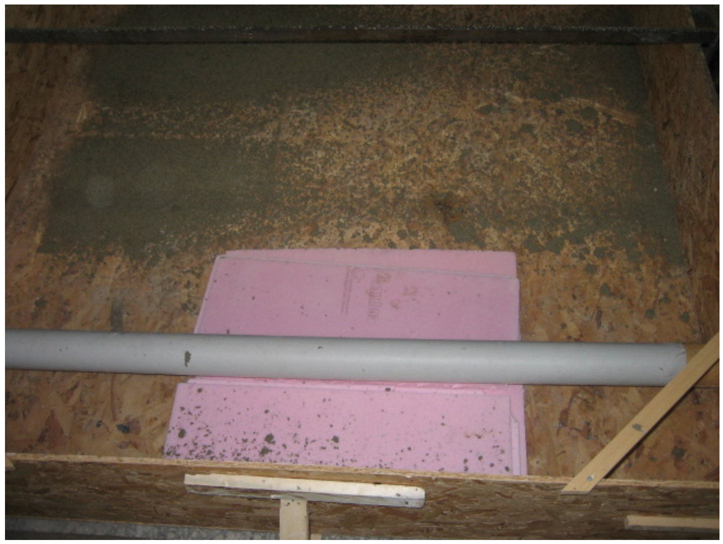


Figure 3.4 Two pieces of foam board being tucked under the pipe for the purpose of leaving a void at known depth

While concrete was being placed within each formwork, the compaction of poured slabs was conducted by using a small hand vibrator. There should not be any large air voids inside the specimens for the test results to be meaningful. After paying special attention to compaction, surface finishing was done in order to obtain a smooth surface to be used for impact-echo testing. Experience has revealed that smoothness of the surface is crucial for impact-echo. While it is possible to work with relatively rough surfaces, it takes considerable more time to obtain successful results. Figure 3.5 below shows the stage of surface smoothing of one of the slab sections.

Figure 3.5 Smoothing the surface of one of the slabs

After all construction stages were completed, the specimens were left until they had set. Then, they were covered with wetted cloths for two weeks for curing purposes. The cube specimens were left at the same place as that of slabs and were covered with the same type of cloth and were wetted together. They were not put inside a curing room because the properties of the in-place slabs were of interest and not the concrete cured under improved conditions.

After two weeks of watering, the cover cloths were removed and side forms were dismantled. After drying of the decks, their surfaces were marked in a crosshatched fashion with 15 cm intervals, to locate exact points so that tests could be repeated again at the exact location whenever required. Also, each deck was given a name depending on its thickness for proper addressing and also to simplify keeping records.

Each slab specimen was named as “IE-Deckxx”, where “IE” stands for impact-echo and “xx” is the corresponding thickness of each section. Therefore, the four names were IE-

Deck15, IE-Deck20, IE-Deck25 and IE-Deck30 corresponding to slabs with thicknesses of 15 cm, 20 cm, 25 cm and 30 cm respectively.

Figure 3.6 The mesh and legend of one of the deck samples

3.3 Test Equipment

A complete set of impact-echo equipment was used during the experiments. The set of impact-echo equipment included the following items:

- Two displacement transducers with frequency ranges from 0 kHz to 60 kHz, similar to the useful range of the impact-echo method.

- Ten sphere steel balls of different diameters connected to each other by thin metal rods. Their diameters were: 3 mm, 4 mm, 5 mm, 6.5 mm, 8 mm, 10 mm, 11.5 mm, 13 mm, 16.5 mm, 20 mm.

- A data acquisition system which enables the data transfer between the transducers and the computer by converting and storing the analog signals as digital outputs.

  An analog signal changes over time and can be represented as a mathematical function with time as the free variable and the signal itself as the dependent variable. A discrete-time signal is a sampled version of the analog signal: the values are collected at fixed intervals such as microseconds, rather than continuous recording.

  Digital signals are digital representations of discrete-time signals. Precise measurement of an analog signal would require an infinite number of digits and therefore is not possible. The resultant data stream after the approximation of this signal by a certain predefined precision is named as a digital signal.

- A steel spacer where two transducers could be tied up at a distance of 30 cm, as explained in ASTM C 1383-04 (Figure 2.10).

- Two BNC cables that connect transducers to the data acquisition system. The BNC cables are used for both analog and digital signals and are preferred by many electronic test equipment manufactured in recent years. It was designed as a cable to minimize wave reflection or loss. It was named after its bayonet mount locking mechanism and its two inventors; Paul Neill and Carl Concelman.

3.4 Test Procedure

3.4.1 Understanding of Recording Parameters

It is believed that some concepts which are vital in interpreting the results like sampling interval, sampling frequency, Nyquist frequency and resolution should be grasped before any tests are conducted and, as such, they are explained very briefly here.

The sampling interval is the time between consecutively collected samples in order to model the analog signal into a digital signal. They are of the magnitude of several microseconds for impact-echo testing and for some other non-destructive testing methods.

The term sampling frequency defines the number of samples per second taken from a continuous signal in order to transfer it into a discrete signal, to be able to process it by using some kind of a tool such as a computer. It is found by taking the inverse of sampling interval. For time-domain signals, the measuring unit of sampling frequency is hertz (Hz), which is equivalent to cycles per second.

Nyquist frequency is the highest frequency that may be accurately sampled for a given sampling frequency in order to be able to fully reconstruct the signal. Therefore it is sometimes called the critical frequency. It is one-half of the sampling frequency.

According to the sampling theorem, aliasing can be avoided and so no data would be lost while reconstructing the discrete signal only if the Nyquist frequency is greater than the maximum frequency present in the signal being sampled. As a result of this, it is necessary to use a sampling frequency of at least twice the highest frequency present in the waveform during recording.

Resolution is perhaps the most important parameter for impact-echo testing. It is calculated by dividing the sampling frequency by the number of data points. In relative amounts, resolution describes the smallest amount of change that can be detected.

$$\text{resolution} = \frac{1}{\text{Nt}} \qquad \text{(Equation 3.1)}$$

where, N=Number of Data Points

t=Sampling Interval (μsec)

Instinctively one might think that resolution may be enhanced by decreasing the time interval between consecutive recordings, the sampling interval, but this is not actually the case. To increase resolution, the number of data points may be increased together with sampling interval thus increasing the total duration of recording a signal.

Accuracy may be defined as the amount of uncertainty that exists in a measurement or, the correctness with which a measured value represents the true value.

3.4.2 P-Wave Velocity Determination

The first step to be conducted while using impact-echo is to determine the P-wave speed in the corresponding concrete section. Several recordings should be collected at various points and the average of these should be used if there are variations among them. The procedure for wave speed measurements were clearly stated in Procedure A of ASTM C 1383-04 [16].

Figure 3.7 shows an instant during wave speed measurement while the slabs were still being cured. Due to great fluctuations in wave speed in the early ages of concrete, it was difficult conduct wave speed measurement tests. It was after the second week that it was possible to conduct full scale tests with reliable results.

Figure 3.7 An instant during wave speed measurement

3.4.3 Tests for Parameters and Thickness Determination

Series of tests were conducted in order to understand how different parameters affect the impact-echo test results. The first part of the experimental study consisted of the determination of the useful range of such parameters, which was then followed by the determination of accuracy for thickness measurements.

As for the number of readings at a point, a study proposed that 10 repeated measurements should be collected for a single test point but this large a number was found unnecessary since preliminary results did not vary much at a single point [12]. Still, the number of adequate points for successful testing would be investigated at the beginning together with the repeatability of test results.

Impactor size was found to be a major factor affecting impact-echo tests. Therefore, it was thought necessary to conduct tests to better understand its limitations of the use on different thicknesses. The right type of impactor size selection was a key factor for the success of tests.

There were several recording parameters which required that a choice be made. The number of samples per recording, the duration between two consecutive samples in a recording and the range of voltage were needed to be set so as to find the optimum combination giving the best results.

Another important point to consider was the distance between the impact point and the transducer. According to a study, a limit is proposed in the broad sense such that this distance should be smaller than 40% of the section thickness [1]. The effect of this distance on the recordings and also its optimum value would be investigated systematically at several points on all slabs in order to observe its effect on different thicknesses.

It is believed that since impact-echo uses sound waves, its success primarily depends on the geometry of the specimen and on the point of testing relative to where it is located on the slab. The effect of edges on results is another parameter to be investigated.

CHAPTER 4

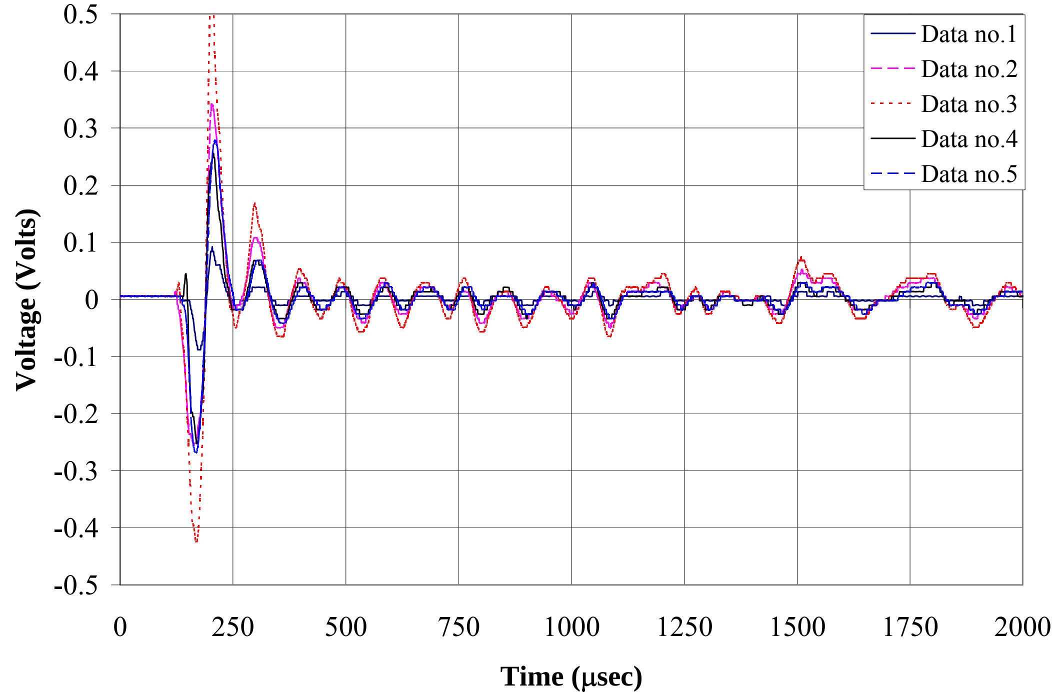
TEST RESULTS AND DISCUSSIONS

4.1 Parameters of Impact-Echo Testing

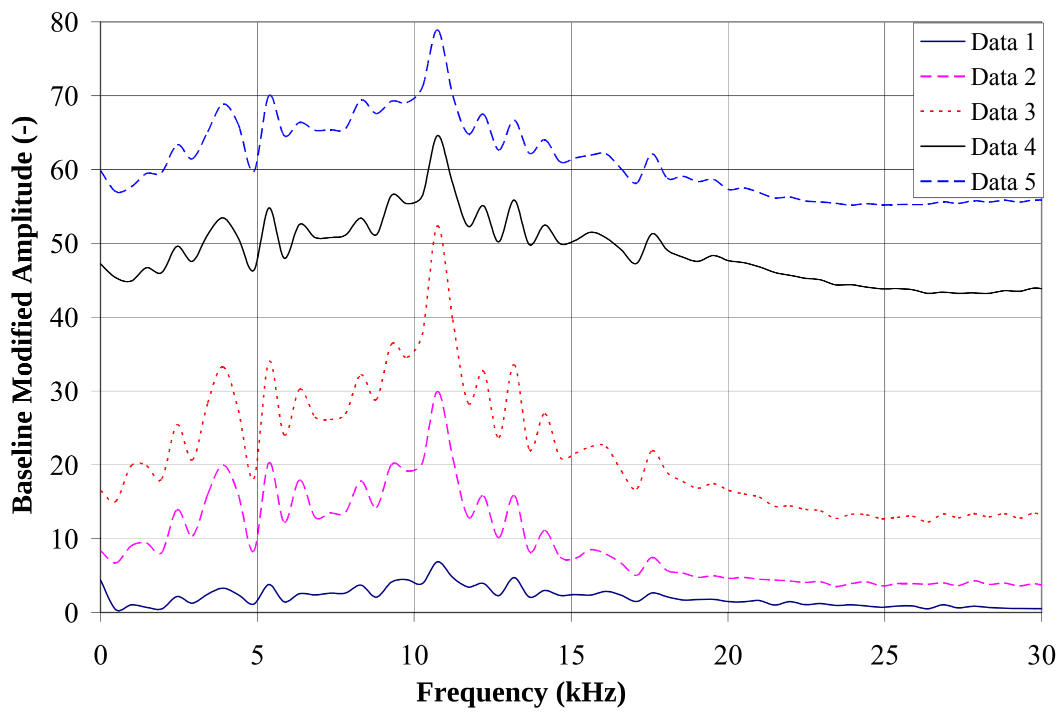
The proposed series of tests for parameters were conducted prior to thickness determination tests. Accuracy of the method is investigated in light of the information gained from these tests. The results obtained from these tests are presented in detail in the following sections.

4.1.1 Repeatability

First of all, the repeatability of the tests conducted by using impact-echo was investigated. For this purpose, a test point was selected on IE-Deck20 and several measurements were performed keeping the data acquisition parameters, the impactor size and the location of impactor with respect to the transducer constant. Therefore, the only variability would be due to the operator. This procedure was then repeated at several points. The results of waveform and their frequency spectra graphs obtained at one of those points are given in Figure 4.1 below.



a-) Plot of five waveforms and their average



b-) Frequency spectra of the corresponding waveforms

Figure 4.1 Typical results of measurements to determine the repeatability of impact-echo performed on IE-Deck20

By investigating the waveforms and spectra of five recordings obtained from the same point, it could be stated that although their amplitudes have different values, the frequency values of distinct peaks are very close to each other. Moreover, they show the same pattern and increase or decrease consistently with each other throughout the spectra. This is an indication that the impact-echo test is repeatable and that the test variability of data collected at a point is not a serious issue as to mislead the user. Other measurements performed on other decks have similar results. Therefore, it was concluded that selecting one of the graphs that seems logical at first glance compared to other test results taken at that point or the vicinity is correct and sufficient for modelling the behavior of the structure at that point.

4.1.2 Effect of Impactor Size

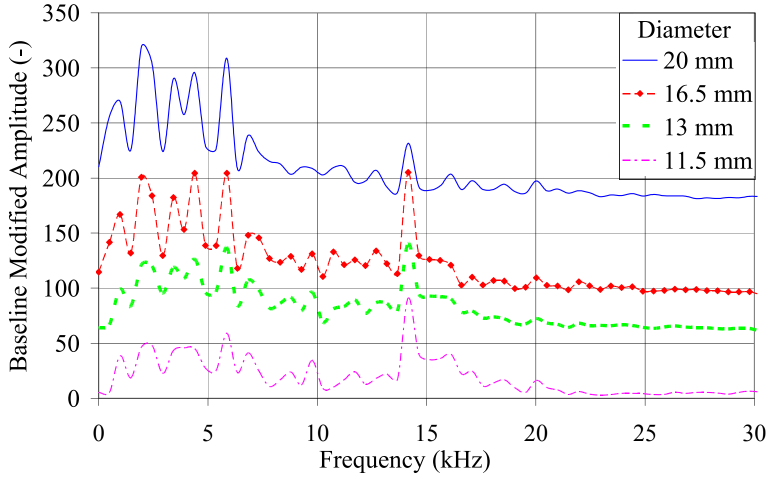
There are ten different sized steel spheres in a standard impact-echo toolkit. Before conducting a complete test on a slab, the impactor size was found to be an important parameter for the consistency and success of results since these steel spheres has direct effect on impact-echo testing as explained previously. Although it is easier to work with larger impactors, they might hide the higher valued thickness frequencies corresponding to thinner sections. On the other hand, the smaller sized impactors are not easy to work with since weaker signals are created and this requires stronger impacts to overpass the trigger voltage.

The sound waves cause the piezoelectric crystals in the transducer to vibrate which in turn transfers these vibrations into electrical current by creating a voltage difference. Smaller sized impactors usually create higher frequency stress waves which attenuate faster, and so the voltage of waveform sent to the data acquisition system becomes very low. This brings together the need to decrease the trigger voltage of the data acquisition in order to process the results, and possibly causes the user to create stronger impacts. Due to their weak signal, the amplitudes of the resulting frequencies are usually close to each other. Besides, geometrical properties of the section and flexural modes of vibration have more effect on test results, thus making it difficult to determine the thickness frequency among several peaks of similar amplitude.

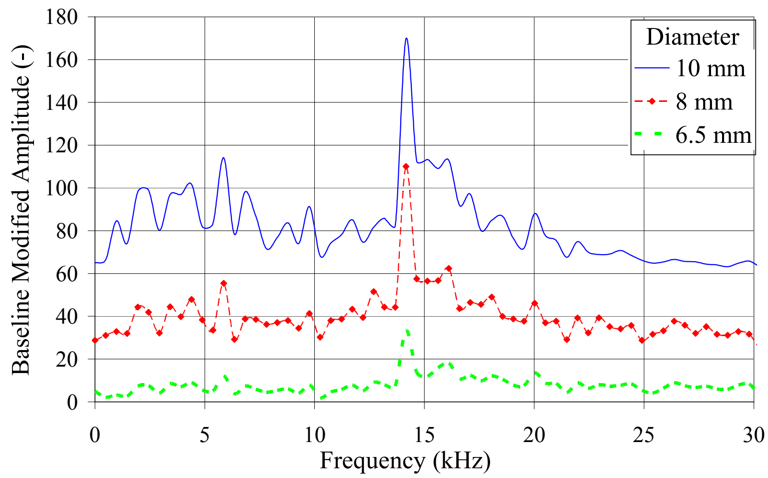
Initial tests conducted included the investigation of the optimum impactor size for each of the four slabs. Using the same impactor on all four slabs would be beneficial since one of the parameters would be kept constant but this impactor should prove to work well on all slabs otherwise it would have no meaning. Then the optimum impactor would be used for each different thickness.

During this series of tests, all impacts were created at a constant distance from the transducer at a single point, and the recording parameters were also kept constant. 2048 data points were collected with 1 μs sampling interval that corresponded to a resolution of 0.488 kHz. Accuracy of test results was not the main focus during this test and therefore this resolution was used to visually simplify the results. The point of concern here was to select an optimum impactor which did not excite the flexural mode nor did magnify the geometrical limitations of the slabs.

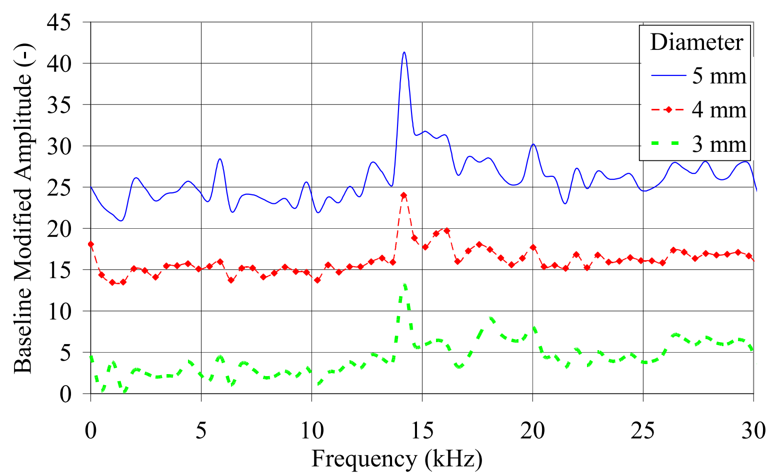
In Figures 4.2 – 4.5, there are several graphs presenting the results obtained from each of the four slabs. Test results were divided and presented as three categories for ease of view: large impactors from 20 mm to 11.5 mm, medium impactors from 10 mm to 6.5 mm, small impactors from 5 mm to 3 mm.



a-) Results of impactors from diameters of 20 mm to 11.5 mm

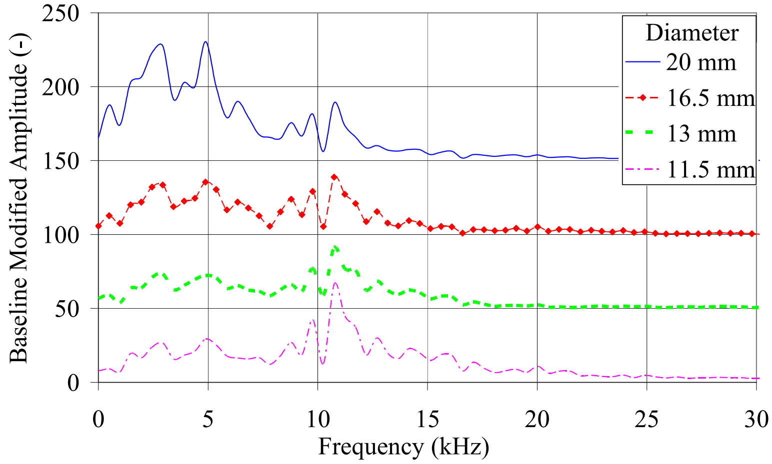


b-) Results of impactors from diameters of 10 mm to 6.5 mm

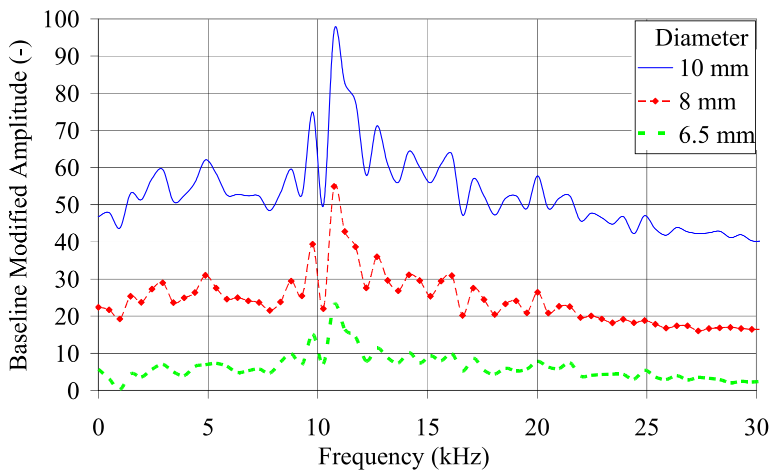


c-) Results of impactors from diameters of 5 mm to 3 mm

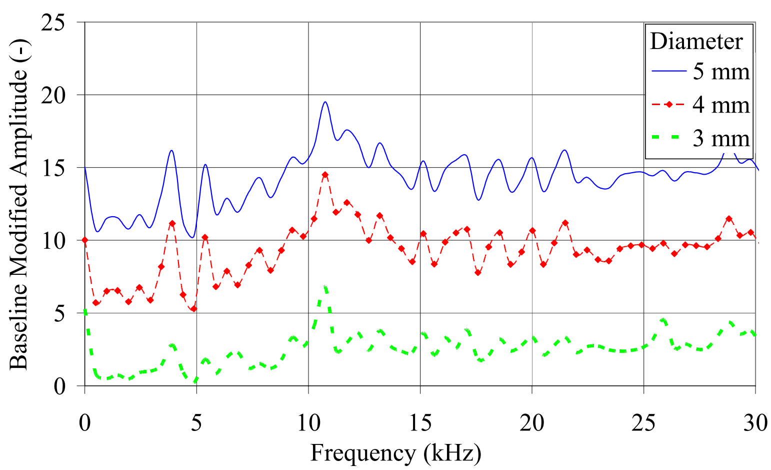
Figure 4.2 Effect of impactor size on IE-Deck15



a-) Results of impactors from diameters of 20 mm to 11.5 mm

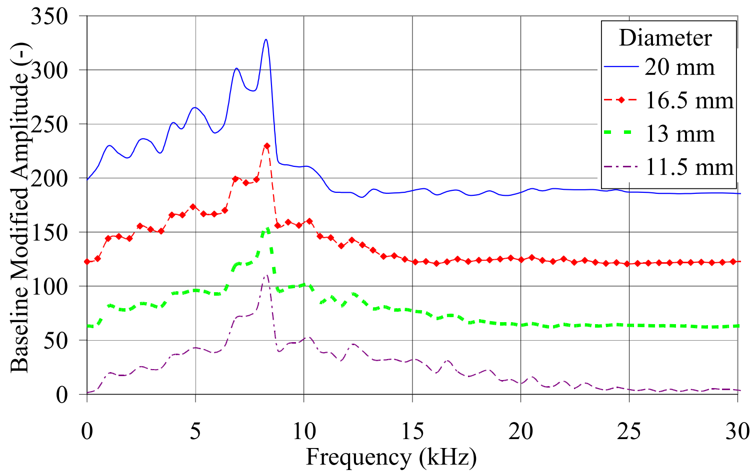


b-) Results of impactors from diameters of 10 mm to 6.5 mm

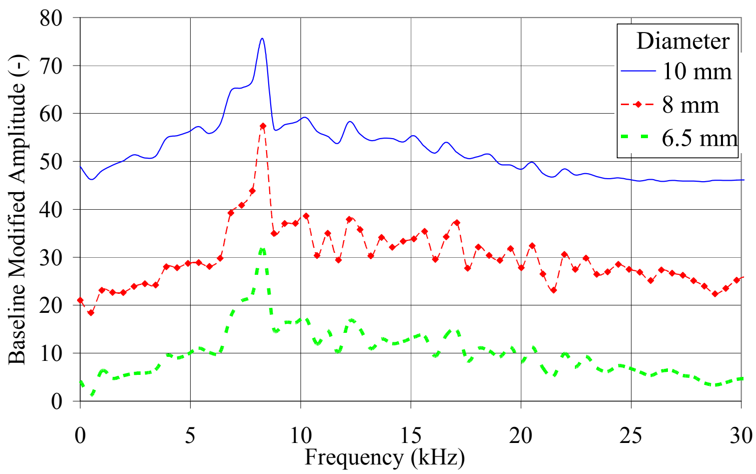


c-) Results of impactors from diameters of 5 mm to 3 mm

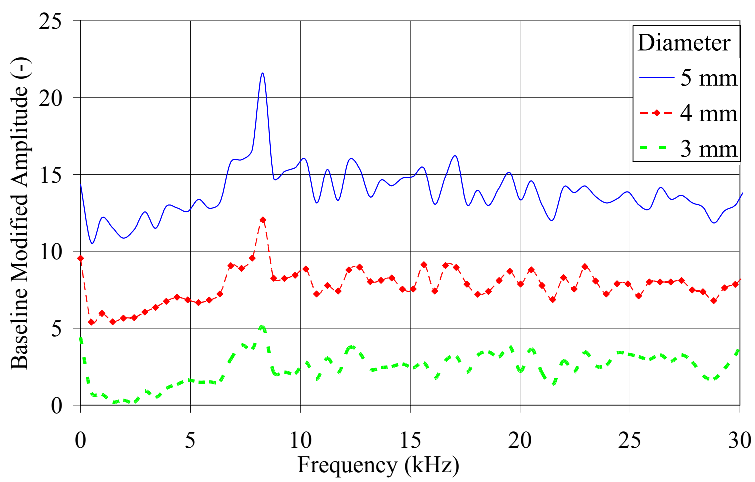
Figure 4.3 Effect of impactor size on IE-Deck20



a-) Results of impactors from diameters of 20 mm to 11.5 mm

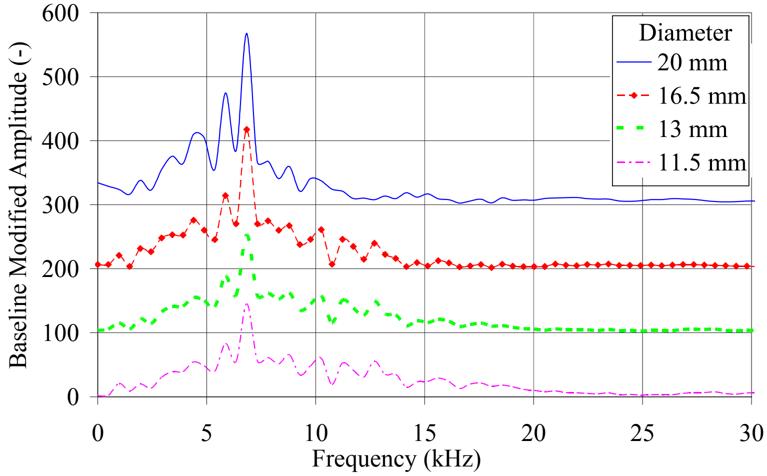


b-) Results of impactors from diameters of 10 mm to 6.5 mm

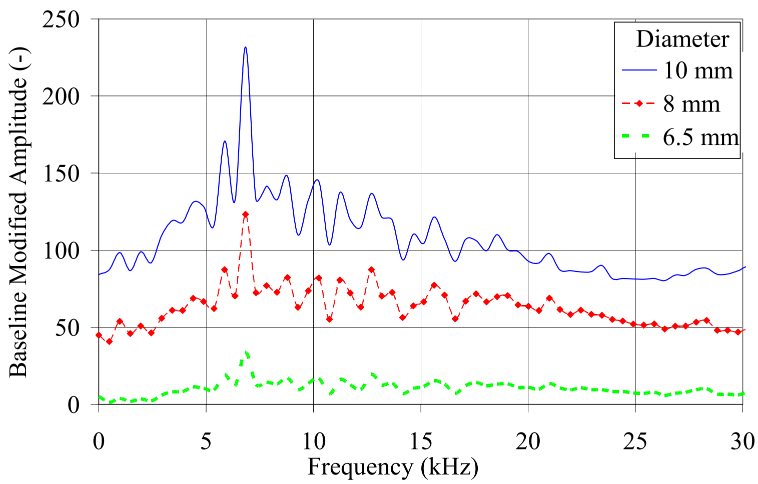


c-) Results of impactors from diameters of 5 mm to 3 mm

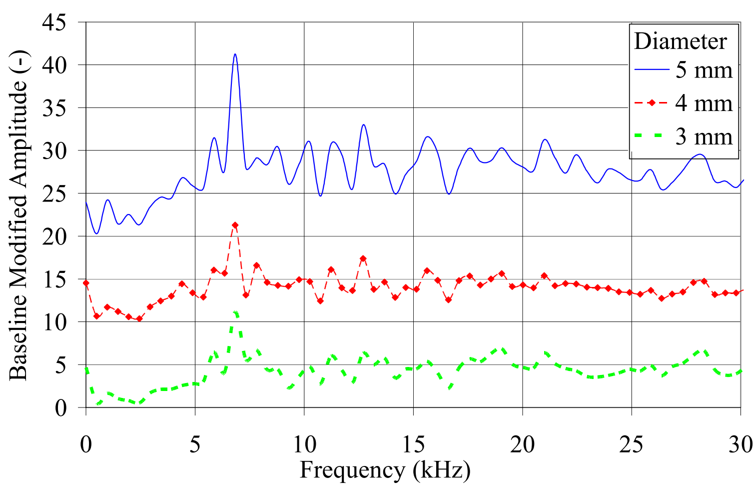
Figure 4.4 Effect of impactor size on IE-Deck25



a-) Results of impactors from diameters of 20 mm to 11.5 mm



b-) Results of impactors from diameters of 10 mm to 6.5 mm



c-) Results of impactors from diameters of 5 mm to 3 mm

Figure 4.5 Effect of impactor size on IE-Deck30

It should be noted here that the magnitude of amplitudes obtained by different impactors are not of great interest, but rather the frequency value of the most distinct peak and its magnitude with respect to other peaks of the same data are of interest.

It is interesting to note that the largest sphere which is 20 mm in diameter produced several distinct peaks at low frequencies in thinner sections, IE-Deck15 and IE-Deck20, but became more like a straight line after 8 kHz, thus obscuring the real section thickness frequency. The low frequency peaks are probably due to excitation of the flexural modes. By investigating the results of tests conducted on IE-Deck15 (Figure 4.2), it was concluded that the applicable range of impactor diameters ranged from 3 mm up to 10 mm. The larger sized impactors were not suitable for this slab thickness due to low frequency peaks that dominated the spectra.

Similar results with large impactors were also obtained for IE-Deck20 (Figure 4.3). However, the upper limit for impactor diameter increased to 13 mm. With further increase in section thickness, the diameter of impactor that could give liable results also increased. Maximum sized impactor that could be used increased to 16.5 mm for both IE-Deck25 and IE-Deck30 (Figure 4.4 and Figure 4.5).

By investigating these results, it was concluded that using a single impactor on all slabs during accuracy tests is not truly necessary. An impactor size should be selected considering the thickness to be tested, and from within the range that is found to be acceptable from the above given results.

The relation proposed by some researchers in Equation 2.6 should be used with caution. In light of the test results conducted on all specimens, it was concluded that this equation allows the use of impactors which were found to be oversized for a given section dimension and this might mislead the user.

4.1.3 Effect of Data Acquisition Parameters

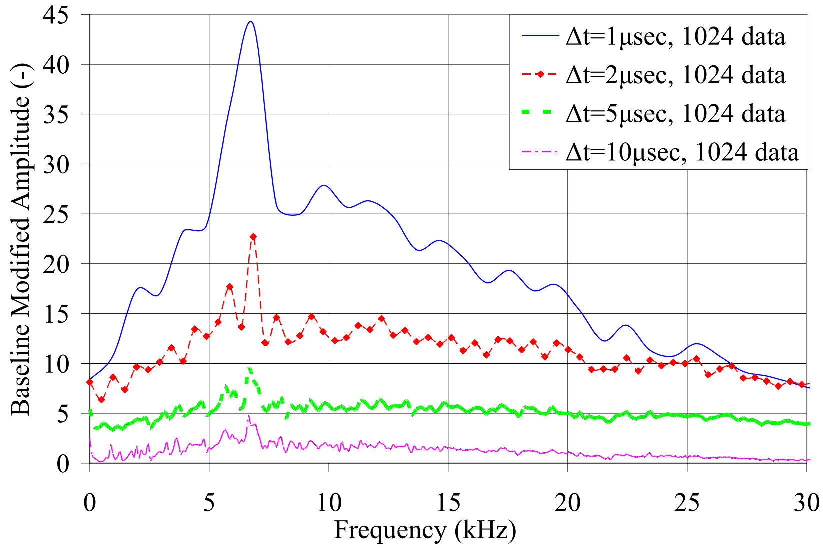
After investigating the effects of impactors, it was thought necessary to decide on recording parameters which could also influence the accuracy of test results. Therefore the aim here is to decide on recording parameters that would be used throughout the accuracy test, on all of the specimens.

Since only the equipment of a standard impact-echo kit was used, the recording parameters were selected among the available choices limited by the software and more importantly by the data acquisition unit. As explained previously, the number of data points collected and the sampling interval are correlated to each other and they affect the resolution of the recorded data.

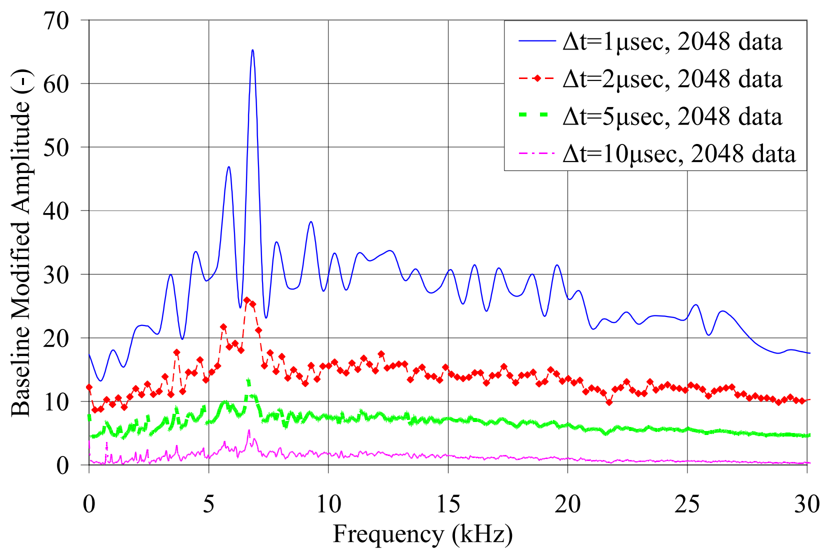
For the number of data points, two alternatives were being considered: 1024 data points and 2048 data points. Initial tests were conducted with 2048 data points but the effect of using 1024 data points was also investigated at this stage in order to observe if there is any difference and also to see the capabilities of the method.

As for the sampling interval, there were four alternatives to compare: 1 μsec, 2 μsec, 5 μsec and 10 μsec. Contrary to general belief, increasing this time interval also increases the resolution which means that the data could be modeled more correctly.

These eight recording combinations were tested on IE-Deck30 by keeping other parameters constant, such as the test point, impact distance and impactor size where 6.5 mm was used for this test. The section thickness was found to be approximately 31 cm and its corresponding frequency was calculated to be around 6.75 kHz.



a-) Results of recording 1024 data points with varying sampling intervals



b-) Results of recording 2048 data points with varying sampling intervals

Figure 4.6 The effect of using different recording parameters on test results for IE-Deck30

In order to pinpoint the frequency values of the highest peaks and to convert these into thicknesses, the following table could be useful in demonstrating the results and relative errors in each of these recordings.

Table 4.1 The results of tests conducted for determining optimum recording parameters for data set shown in Figure 4.6

Data Points	Sampling Interval (μsec)	Resolution (kHz)	Frequency Value of Highest Peak (kHz)	Corresponding Thickness (cm)	Relative Error (%)
1024	1	0.977	6.89	30.74	-1.73
	2	0.488	6.84	30.96	-1.01
	5	0.195	6.84	30.96	-1.01
	10	0.098	6.69	31.66	1.21
2048	1	0.488	6.84	30.96	-1.01
	2	0.244	6.84	30.96	-1.01
	5	0.098	6.69	31.66	1.21
	10	0.049	6.74	31.42	0.46

As can be seen from Table 4.1 above, resolution and thus recording parameters play an important role in the accuracy of results. Although a relative error of 2% might not seem much, the limit stated in most foreign standards for concrete pavement construction is also 2%. This means that the error limit has already been exceeded at the beginning of testing only due to the selection of a wrong resolution for recording. Therefore, for quality control purposes, the resolution should be as high as possible. On the other hand, increasing the resolution decreases the amplitude of frequencies in the frequency spectra and therefore becomes harder to interpret the results. It could be seen that the thickness frequencies obtained by using a resolution of 0.049 kHz or 0.098 kHz have relative errors that are acceptable for use in the accuracy tests that would follow.

Use of lower resolutions with impact-echo might be suitable for some different purposes or applications since higher resolutions produce graphs that are easy to understand but a resolution equal to or below 0.1 kHz should be used for quality control or for determining the thickness of an existing concrete section as precise as possible. It was decided that a resolution of 0.049 be used for the series of tests conducted only during testing the accuracy of the method or where exact frequency values were required.

4.1.4 Distance from point of impact to transducer

Impact-echo uses sound waves traveling in concrete, which is greatly affected by the properties of waves and also by the geometry of the section. Therefore, it is believed that the distance between the transducer and the test point should have some effect on recordings, which makes it necessary to get a better understanding of its effects before the tests for accuracy. Unfortunately, there was no clear explanation or direction related to this concept, except for some of the values proposed by one or two researchers only in a very broad sense, which suggests that the test distance should not exceed approximately 40% of the section thickness [1].

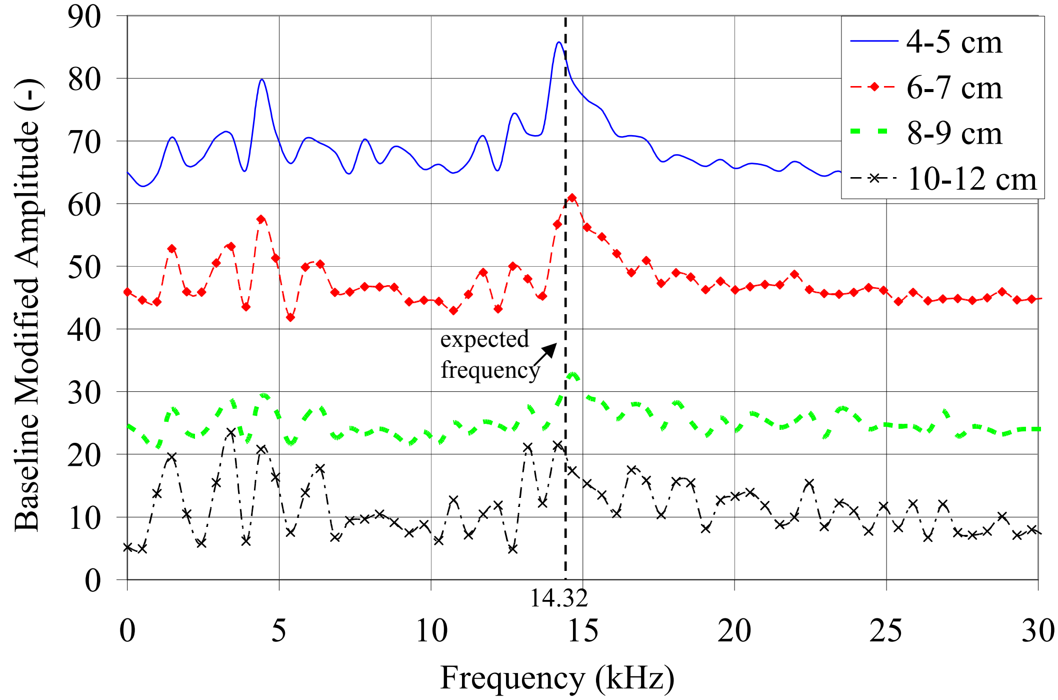
The two important physical points during testing are namely: the point of impact hit by the steel sphere impactors and the very center of the transducer which is in contact with concrete and collects sound waves. It was decided to check whether the distance between these two had any effect on test results, and if so, to try to establish the optimum range for such a distance.

The transducer has an outer shell radius of 2.75 cm. It is vital for successful test results that the steel impactors do not touch the transducer at all while it is ready for recording. As a result of this, these two points should be at least 3 cm apart and preferably a minimum of 4 cm for ease of use.

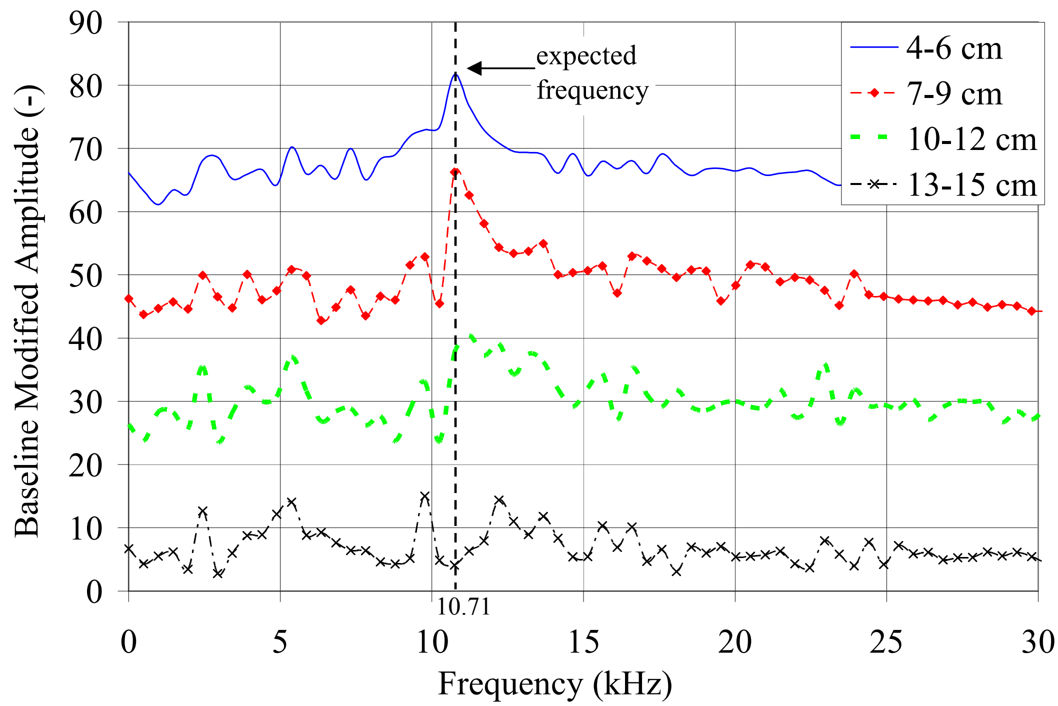
Some tests have been performed to determine the optimum distance for impact point. For this purpose, readings were collected starting from 4 cm up to 21 cm in thicker sections, with 1 cm increments. A minimum of 3 tests were conducted at each point to have adequate results to be able to make a distinction between them. Only one variable was being tested, and therefore, all others were kept constant. Only the 6.5 mm diameter steel sphere was used as the impactor since it was found out that it could be used with relative success on all four thicknesses. The recording parameters were: 2048 readings for the number of data points and 1 μsec between readings. These were kept constant throughout the test. Since the main purpose was not to determine its accuracy but rather observe the pattern of the spectra, this resolution was suitable for this case.

As there were from 9 to 18 recordings for a single slab specimen investigated, various ranges of distances from point of impact to transducer were determined and presented in Figure 4.7. These ranges were determined visually by grouping spectra that had very similar patterns.

In order to be able to make a visual distinction between the different groups, a constant value has been added to the amplitudes of each. A value of 60 has been added to the smallest distance followed by 40 and 20 for the following distances. The most distant group was not modified. This was done for better visualization of the four spectra in a single graph.

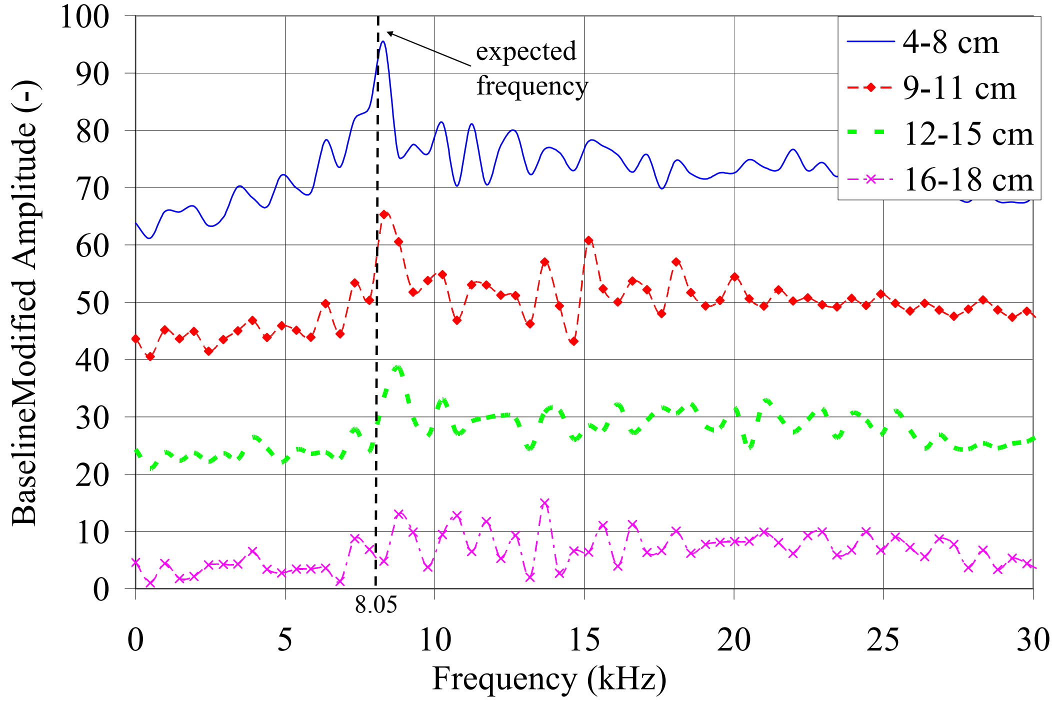


a-) IE-Deck15

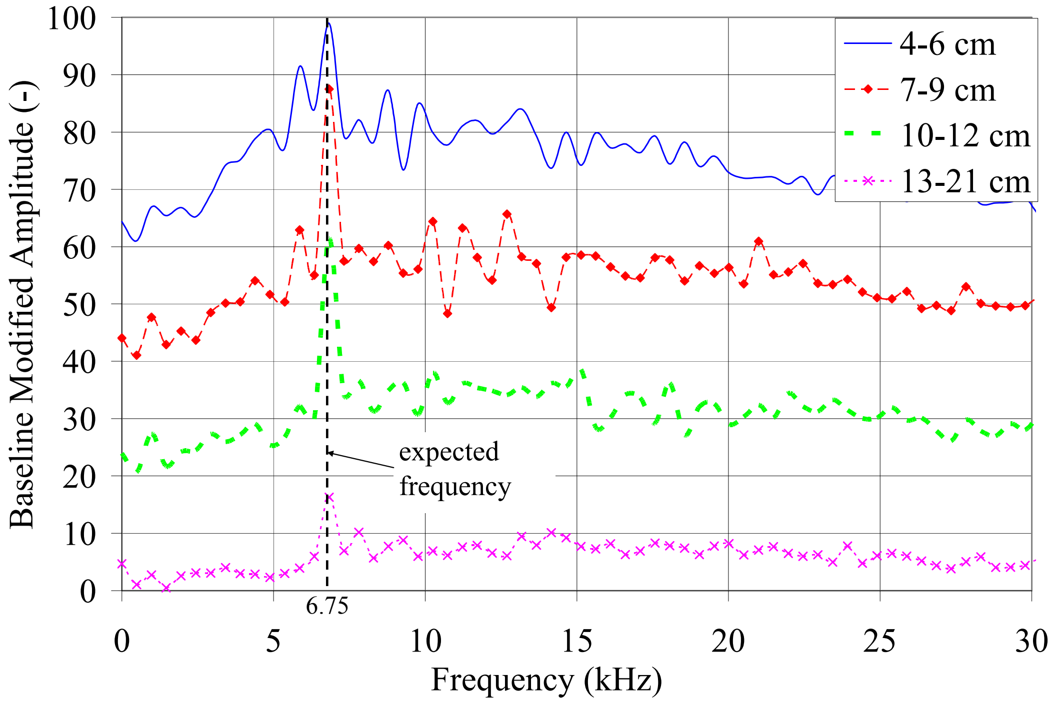


b-) IE-Deck20

Figure 4.7 (continued)



c-) IE-Deck25



d-) IE-Deck30

Figure 4.7 Illustration of the results of tests conducted to determine the effects of distance between the transducer and impact point on test results.

As shown in Figure 4.7, each thickness had its own optimum range for distance between the transducer and the impact point. However, they could be summed up as a percentage of thickness.

By observing Figure 4.7 (a), it is evident that distances from 4 to 5 cm and 6 to 7 cm were suitable but distances larger than 7 cm did not provide reasonable results. This 4-7 cm interval corresponds to approximately 27-47% of slab thickness of IE-Deck15.

For IE-Deck20, the suitable range increased to 9 cm. Above this distance value, low frequency peaks dominated the spectra and had even greater amplitude than the thickness frequency. The range of distances that could be used was from 4 to 9 cm which corresponds to 20-45% of slab thickness.

A similar situation could be observed for IE-Deck25, where the two set of ranges can be considered acceptable and two cannot. Distances from 4 to 11 cm provided curves similar to expected results. At distances from 12 to 18 cm however, the peak corresponding to the thickness frequency was not very distinct and the amplitude of peaks besides the thickness frequency were even higher at some points, which might mislead the user in thinking that an internal delamination may exist at that location. Therefore, a percentage of 16-44% of section thickness results for this slab.

IE-Deck30 slab is also interesting. It provided information which was useful in determining the final optimum range. By closely examining Figure 4.7 (d), it could be stated that the smallest range of distance from 4 to 6 cm actually was not suitable since there was another distinct peak besides the thickness frequency which was not present in other set of ranges. Distances from 16 to 21 cm were not suitable because the thickness frequency was not distinct enough compared to the rest of the spectra, much like cases in other thicknesses. The distances that produced acceptable results ranged from 7 to 15 cm which was approximately 23-50% of slab thickness.

By combining these four results, it was concluded that the optimum distance between the transducer and the impact point could be represented by giving a range as percentage of section thickness. The optimum range was found to be in between

%20-50 of section thickness. These are only the proposed limiting values; practically speaking, a distance of one third of slab thickness would produce successful results.

4.1.5 Effect of Impact Location

After investigating the effect of distance on impact-echo test results, it was decided also to investigate the effect of impact location, especially to understand its effects for tests conducted near the sides of the concrete slabs. Whether this had any effect on test results and to what degree it might modify the graphs were the primary points of concern during this test.

Stress waves created by an impact would tend to travel outwards from the impact point until they eventually reach a physical irregularity such as the edge of a section, and the stress wave would therefore change direction and inevitably become distorted. Impact-echo only uses the sound waves traveling inside the concrete section and therefore its results are very dependent on the geometry of the section.

The test point selected at 15 cm away from the side of the slab, which is on the outermost line of points of the predetermined mesh, was expected to show some distortions. Nevertheless, testing this point would help while understanding the effect of impact location on test results. In order to make a comparison between the results, a point at the middle region of the slab was tested initially. After observing these results, it would then be compared with the results obtained from near the sides of the slab where distortions caused by side effect would exist.

4.1.5.1 Testing a Point at the Center

Before testing a point at the edge of the slab, it was thought necessary to understand the effect of impact location in relation to the transducer at the middle of the section, having sufficient distance from all edges.

The tests were conducted by using 2048 test points and 1 μsec sampling interval which resulted in a resolution of 0.488 kHz. Since the main purpose is to visually observe the changes in the frequency spectra and not to exactly determine the accuracy of results, this resolution was adequate for the purpose of this test.

Besides these, the distance between the transducer and the impact point was selected to be 6 cm for all readings. 5 readings were recorded for each angle and the averages of these were used while making a comparison. Readings were collected not at a single point but at marked locations with 45 degree increments.

To present the output data in a more amenable form, some of the data were grouped together. Three groups were made according to the relative location of the impact point to the transducer: at the inner side, at the outer side, equidistant to an edge.

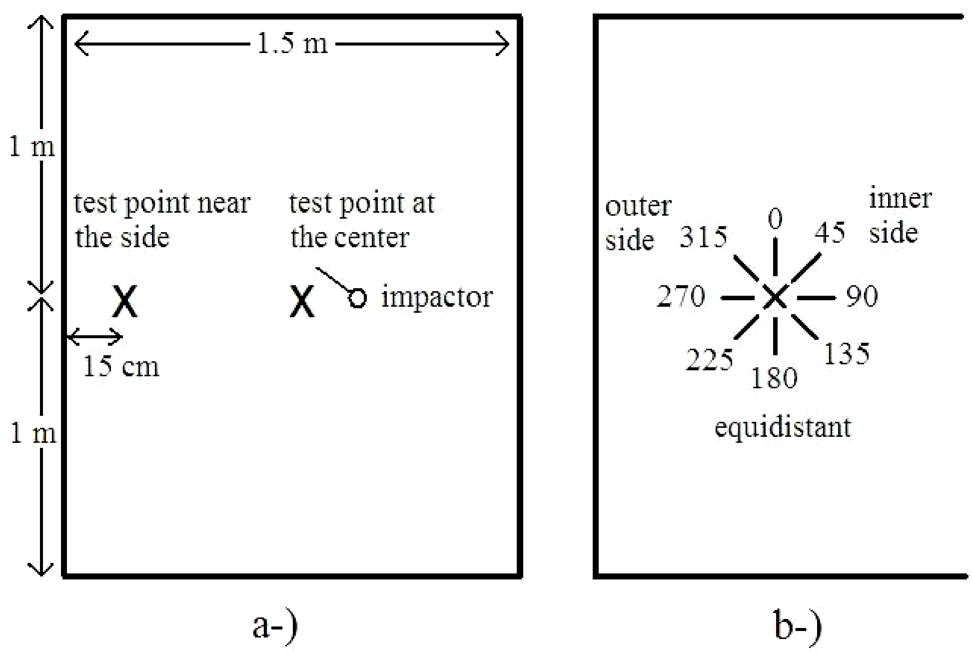


Figure 4.8 Schematic view of the test locations
a-) Location of test point at the center and near the side
b-) Grouping of recordings obtained at various angles

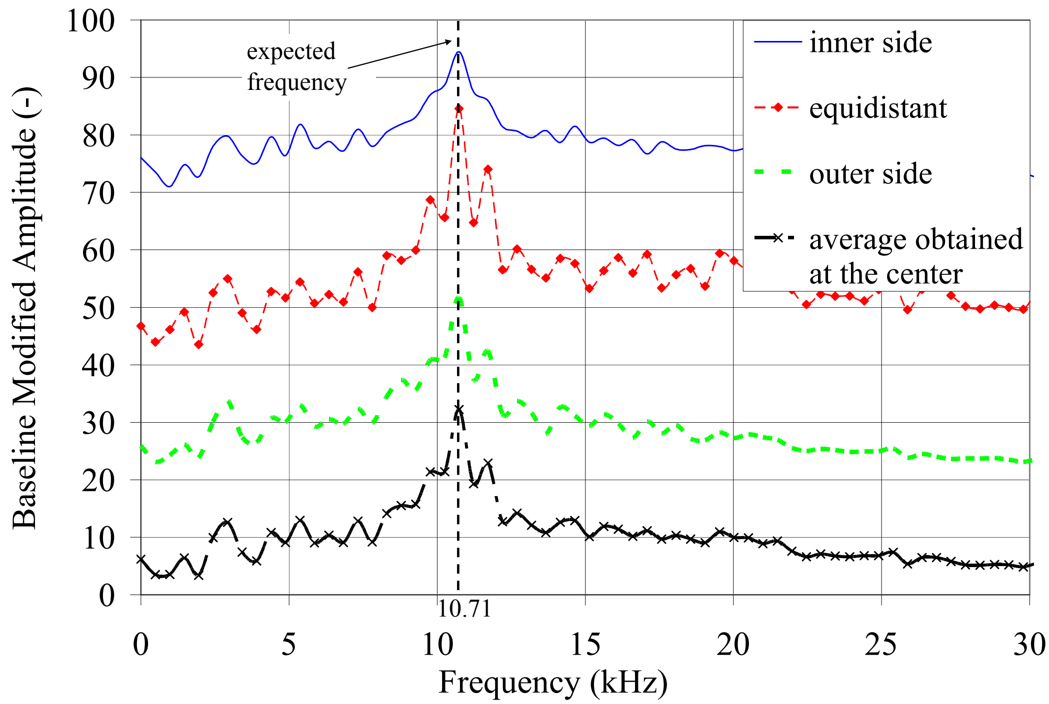


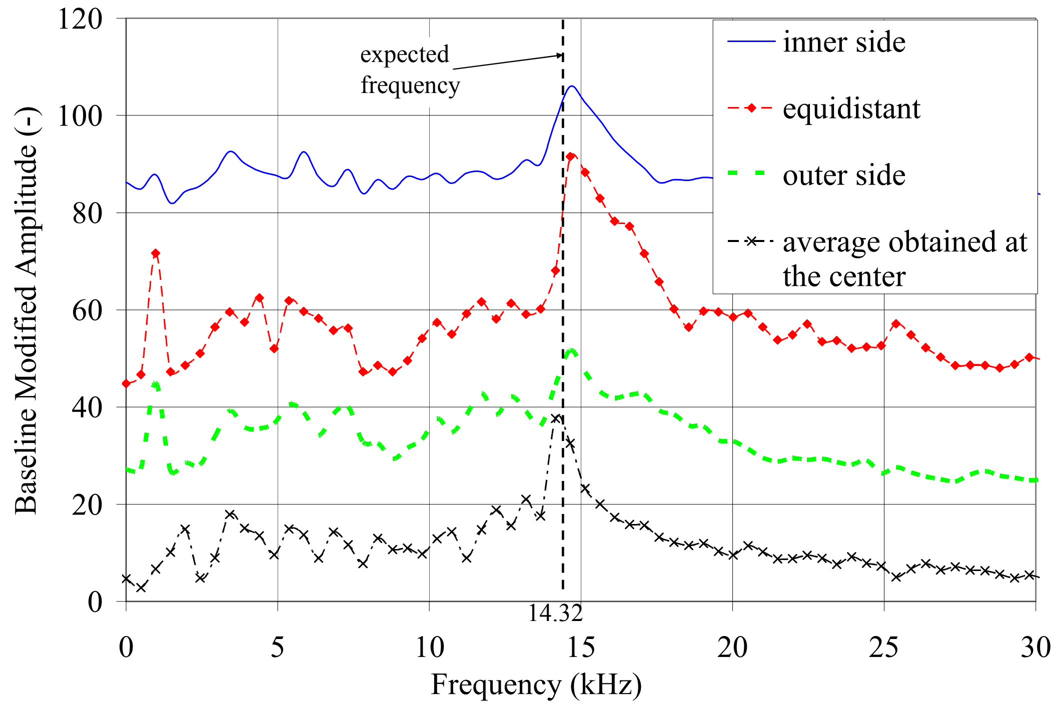
Figure 4.9 Results of data collected from the middle portion of the slab with 45 degree increments grouped into 3 categories

As can be seen from the above figure, the results are very similar to each other. The spectra do not show any unexpected behavior. Also, the thicknesses found by using the thickness frequencies were all the same. The average spectrum of all readings was also plotted on the graph besides the three categories. The average spectra obtained at the center for each thickness was decided to be used while making a comparison between recordings collected at the center and at the side of the specimen.

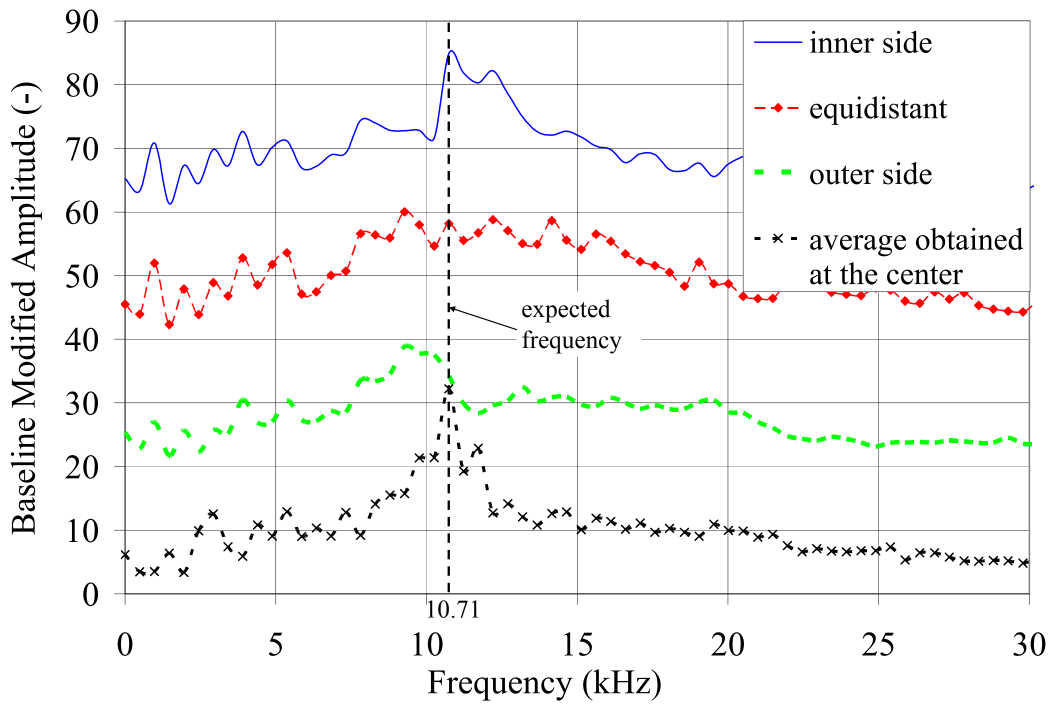
4.1.5.2 Testing a Point Near the Edge

The test was conducted on all of the slabs in order to observe its complete effect on various thicknesses. As mentioned before, all slab specimens were marked in a mesh-like manner with each interval 15 cm wide. Since the main focus was to determine the effect of impact location near the sides, the test point was selected near to only one of the sides of the specimen rather than at the corner. The point was selected at the middle of the longer side of 2 m length and at the outermost point on the mesh. The test point location is shown schematically in Figure 4.8.

The same parameters as with testing at the center were used in order to make reasonable comparisons. The recording parameters of the data acquisition unit, the impact distance and the impactor size were kept the same. In the resulting graphs that follow, the average spectra found by testing a point at the center of the corresponding specimen is given together with the results in order to be able to make a comparison.

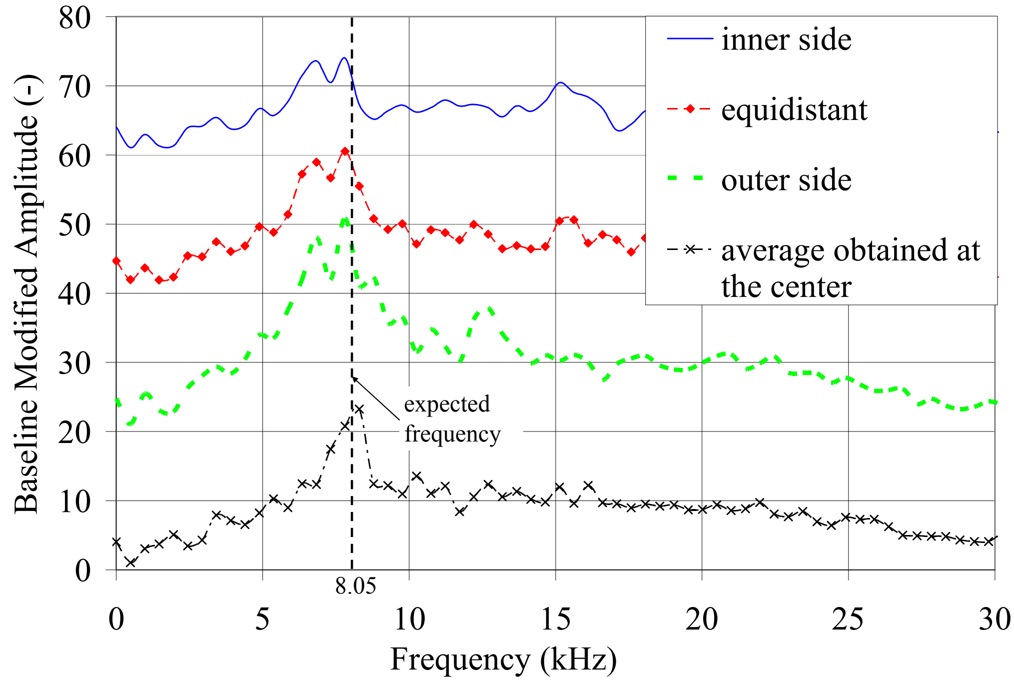


a-) IE-Deck15

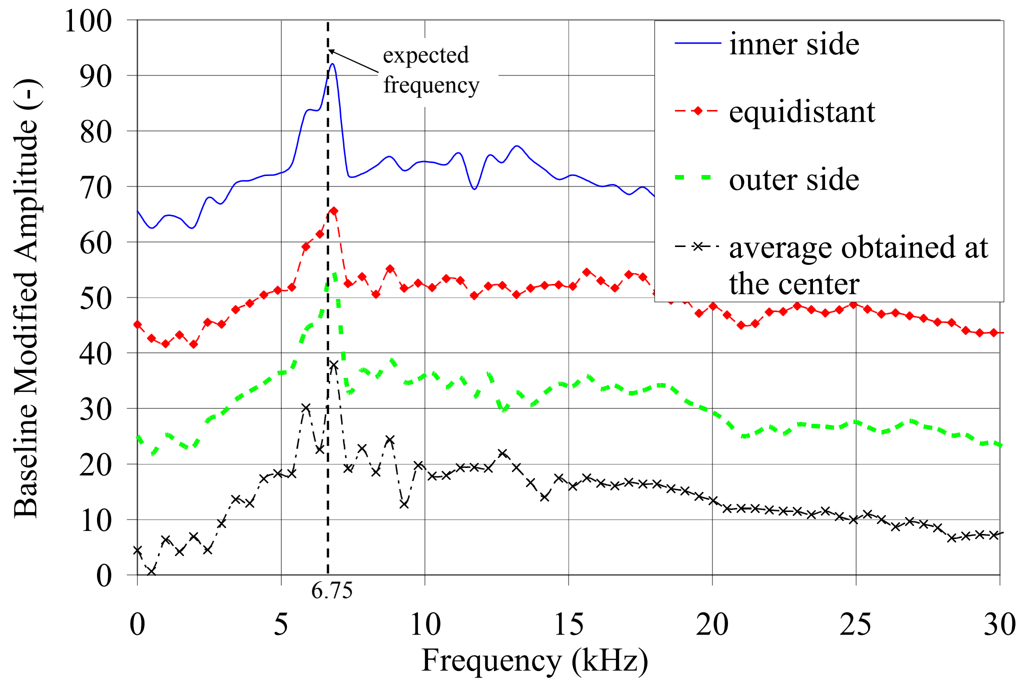


b-) IE-Deck20

Figure 4.10 (continued)



c-) IE-Deck25



d-) IE-Deck30

Figure 4.10 Results of tests conducted near the edge of each slab with 45 degree increments

As can be noticed, test results obtained from a vicinity of a geometrical irregularity are not very easy to interpret. There were problems with some of the spectra. Some looked distorted and had several high peaks while some did not show any peaks at the expected frequency.

One of the reasons for the peaks observed at lower frequencies could be the flexural mode of each section. By nature, each cross-section has a unique frequency for its free vibration. There are a number of modes but the first mode will be the most distinct peak. The first modes were calculated for each section to distinguish them from other peaks. The following equations were used during the calculations [28];

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad \text{Equation 4.1}$$

$$\omega_1 = 4\sqrt{2\left(\frac{1}{a^4} + \frac{2^8}{3^2 \times 7^2} \bullet \frac{1}{a^2 b^2} + \frac{1}{b^4}\right)} \bullet \sqrt{\frac{D}{\overline{m}}} \qquad \text{Equation 4.2}$$

where, D = flexural rigidity,

$\overline{m}$ = mass per unit area

E = modulus of elasticity

ν = Poisson's Ratio

ω = frequency of free vibration

a, b = half dimension of length and width

h = thickness

First, the modulus of elasticity was calculated by using the proposed formulas in different standards which correlate modulus of elasticity to compressive strength. It was found that an average value of 34700 MPa is a suitable assumption.

By using Equations 4.1 and 4.2 and the calculated value of the modulus of elasticity, the first flexural mode of each section was calculated. IE-Deck20 yielded a natural frequency of 2.17 kHz and the others yielded 2.89 kHz, 3.61 kHz and 4.33 kHz for IE-Deck20, IE-Deck 25 and IE-Deck30 respectively. However, it should be noted that these peaks were not always clearly visible as they were not excited by the impactors.

For the results of IE-Deck20, no distinct peak could be observed at the expected frequency for impact points at the outer side or which are equidistant to the transducer.

Interestingly, there are two distinct peaks in the resulting graphs of IE-Deck25. The slightly higher peak corresponds to the section thickness but the other peak yields a distance that could be found by calculating the hypotenuse of the triangle formed by sides 15 cm and 25 cm, which are the distance to edge and the thickness for this slab. This means that the created sound waves are strongly reflected by the bottom corner of the slab and this is of sufficient magnitude as to affect the results while testing near the edge.

Considering all results obtained near the edges, it was concluded that the impact location relative to the edges was not of primary importance so as to affect the test results. The three categories made did not indicate superiority over the other ones. Variability in test results always occurred when there was an irregularity in section geometry. Therefore it is suggested that while testing near the side of a slab, the number of repetitions should be increased and recordings should be collected from both sides of the transducer. Although this does not solve the problems completely, it gives better results than choosing the impact point randomly. Besides, the natural frequency of each section was also calculated and it was decided that the flexural modes did not really distort the resulting graphs and so were not a serious problem.

4.2 Thickness Determination

For thickness determination, each of the four slabs was investigated and the results, together with corresponding error percentages and confidence intervals are given.

The recording parameters were selected so as to produce the highest resolution since small variations could change the final results. For this reason, 2048 data points with sampling intervals of 10 μsec were used, which were the limiting values allowed by the data acquisition system, and so a resolution of 0.05 kHz was obtained.

As for the distance between the transducer and the impact point, the resulting ranges obtained from the previous section were used. The allowable distances for each slab were calculated and all impacts were conducted from within that distance range.

A different sized impactor was used for each slab with different thickness. Its size was chosen in accordance with the results obtained previously. As the section thickness increased, the size of the impactor also increased. For IE-Deck15, the impactor diameter was selected as 5 mm. For IE-Deck20, IE-Deck25 and IE-Deck30, the impactor diameters were 6.5 mm, 8 mm and 10 mm, respectively.

There were 9 points in a row on the mesh drawn on the surface of the slabs, and 12 points in a column. This results in a total of 108 points for each of the slab samples. A test was conducted at each of the test points regardless of its location.

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
Row 12	x	x	x	x	x	x	x	x	x
Row 11	x	x	x	x	x	x	x	x	x
Row 10	x	x	x	x	x	x	x	x	x
Row 9	x	x	x	x	x	x	x	x	x
Row 8	x	x	x	x	x	x	x	x	x
Row 7	x	x	x	x	x	x	x	x	x
Row 6	x	x	x	x	x	x	x	x	x
Row 5	x	x	x	x	x	x	x	x	x
Row 4	x	x	x	x	x	x	x	x	x
Row 3	x	x	x	x	x	x	x	x	x
Row 2	x	x	x	x	x	x	x	x	x
Row 1	x	x	x	x	x	x	x	x	x

Figure 4.11 The top surface of a slab specimen with the mesh of points and the notations used for denoting the rows and columns. The dashed lines show the approximate location of the hollow pipes.

4.2.1 Results Obtained

Impact-echo tests were conducted at all of the predetermined points and a sample reading, which looked acceptable after visual inspection of the waveform and the spectra, was recorded for further analysis. These were then exported to the computer program Microsoft Excel for further analysis. The peak with the highest amplitude was chosen and reported. Although there were several other distinct peaks in some of the graphs, they were not considered while determining the accuracy of the method. Therefore, only one value was given for a test point which enabled the use of statistical methods for interpreting the results.

After selecting the frequency with the highest amplitude, the P-wave speed in each of the slabs was required in order to be able to convert them to thicknesses as given in the basic relation of Equation 2.3. Wave speed measurements were conducted separately on all of the slabs at this stage. Several recordings were collected at different points for a slab and the averages of these were calculated to be the P-wave speeds as presented in Table 4.2.

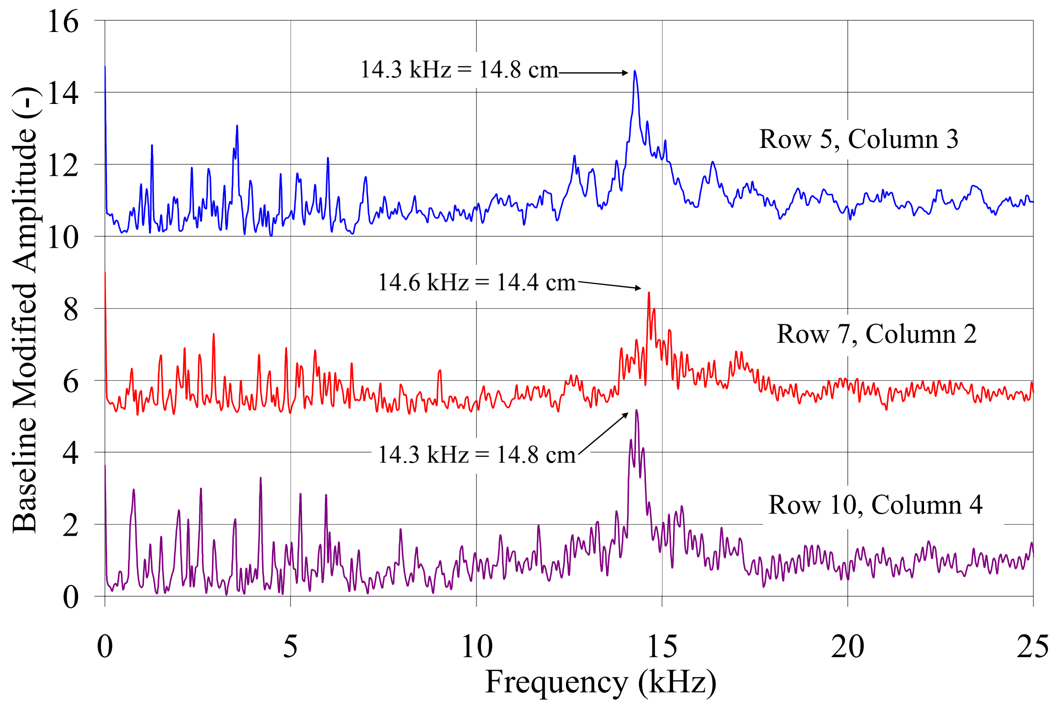
Table 4.2 The average P-Wave speed found for each of the slabs

Slabs	Average P-Wave Speeds (m/s)
IE-Deck15	4227
IE-Deck20	4278
IE-Deck25	4237
IE-Deck30	4236

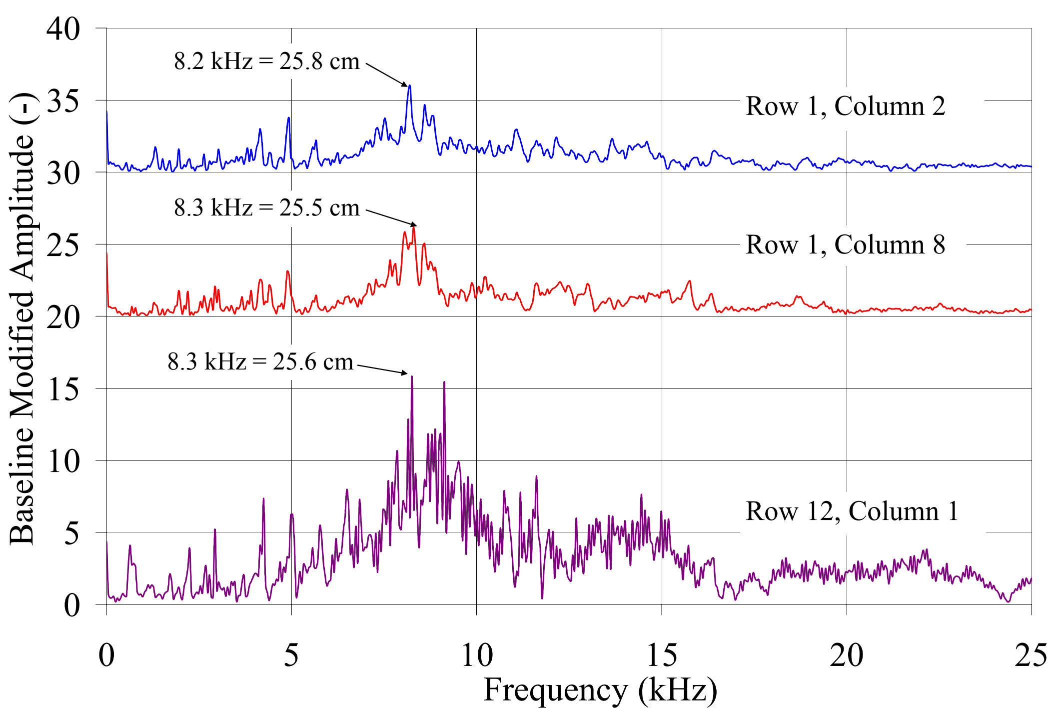
There was no major difference between the P-wave speeds as may be expected from a concrete which is several months old. One reason for this is that the concrete composition in each slab was actually very similar to the other, which is something desirable for the purpose of this test.

By using the corresponding P-wave speed value from the above table, the frequencies were converted to thicknesses at each point of the mesh. Therefore, a theoretical thickness found by using impact-echo for each test point was present. However, it was thought that the real thickness at each point could vary due to limitations of the tools used during concrete placement and surface finishing. A few millimeters difference in the true thickness would result in a considerable amount of error during comparison. Therefore it was thought necessary to determine the true thickness of the slab at each point. For true thickness determination, a straight, horizontal wooden beam of known height was placed on top of the slab and the distance from the surface of concrete to this beam was measured. These were then subtracted from the known beam height in order to find the correct thickness at each test point.

In Figures 4.12 - 4.15 below, there are several sample spectra obtained from each of the slabs which demonstrate the selection process of the most distinct peak. After giving these samples, it is then followed by the complete list of results obtained at each point on all four slabs.

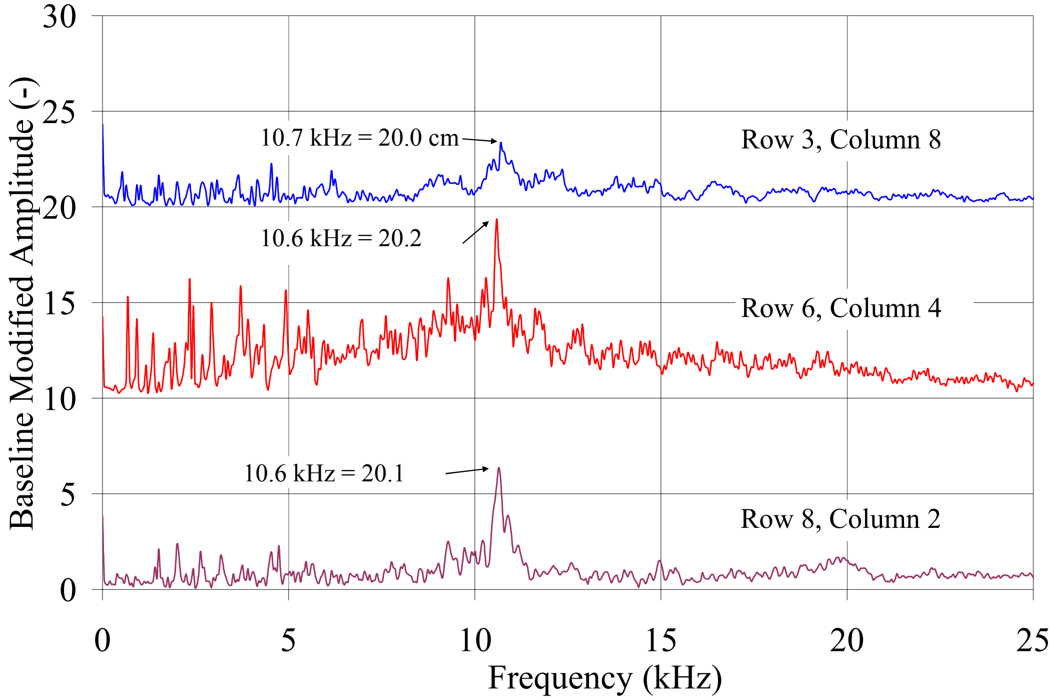


a-) Spectra obtained from the inner region

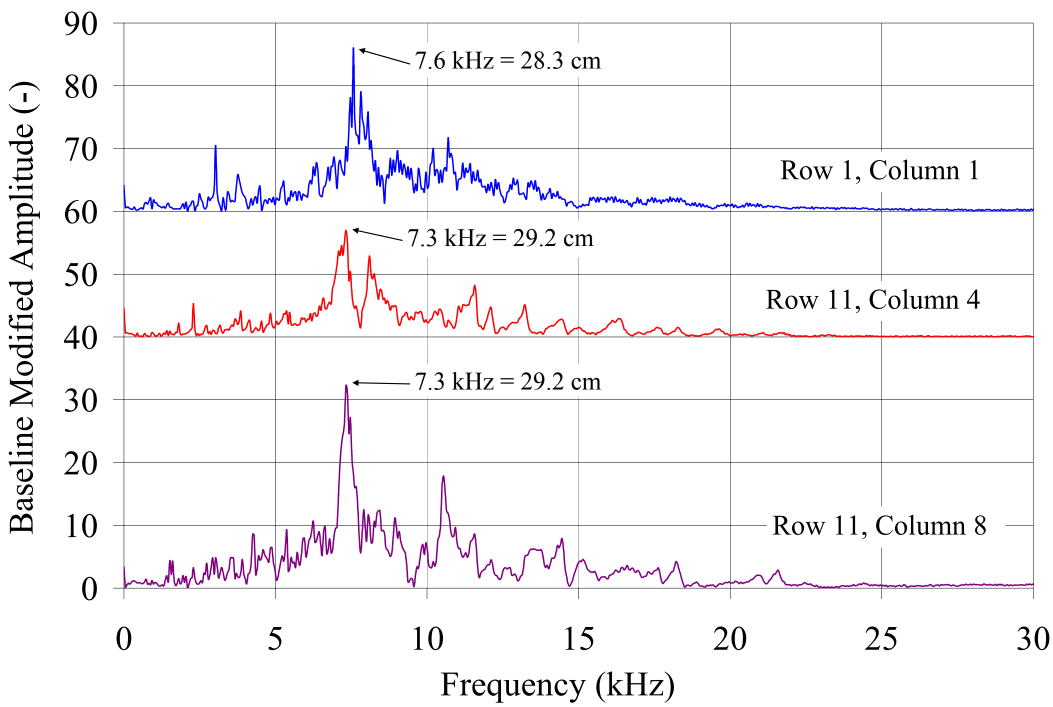


b-) Spectra obtained from the outer region

Figure 4.12 Typical spectra obtained from IE-Deck15

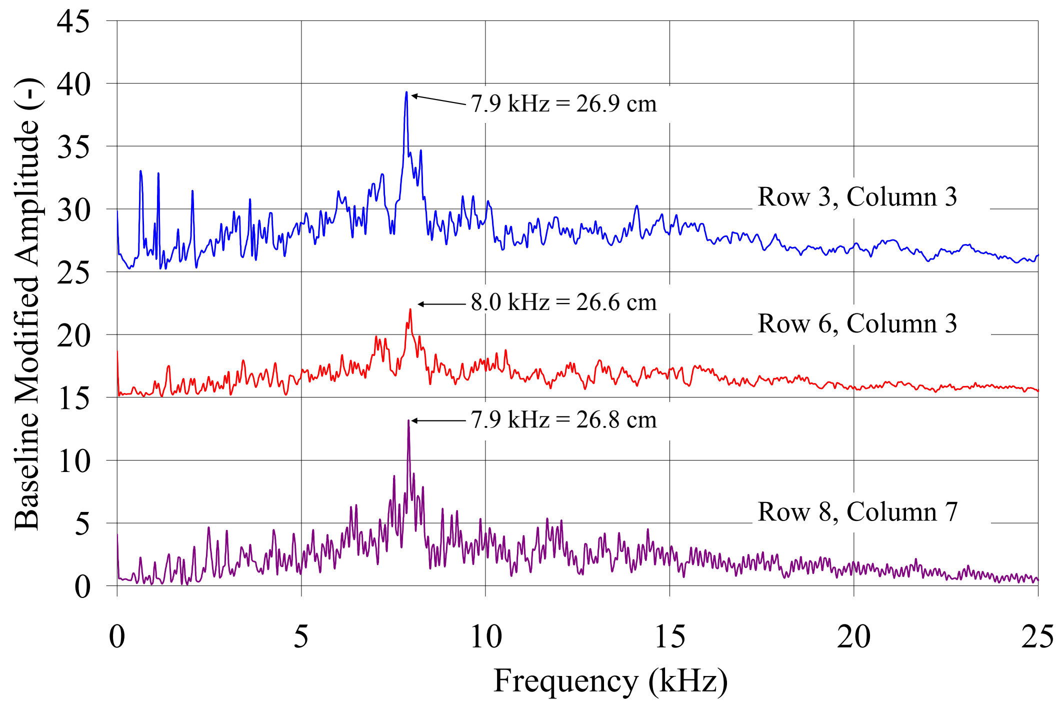


a-) Spectra obtained from the inner region

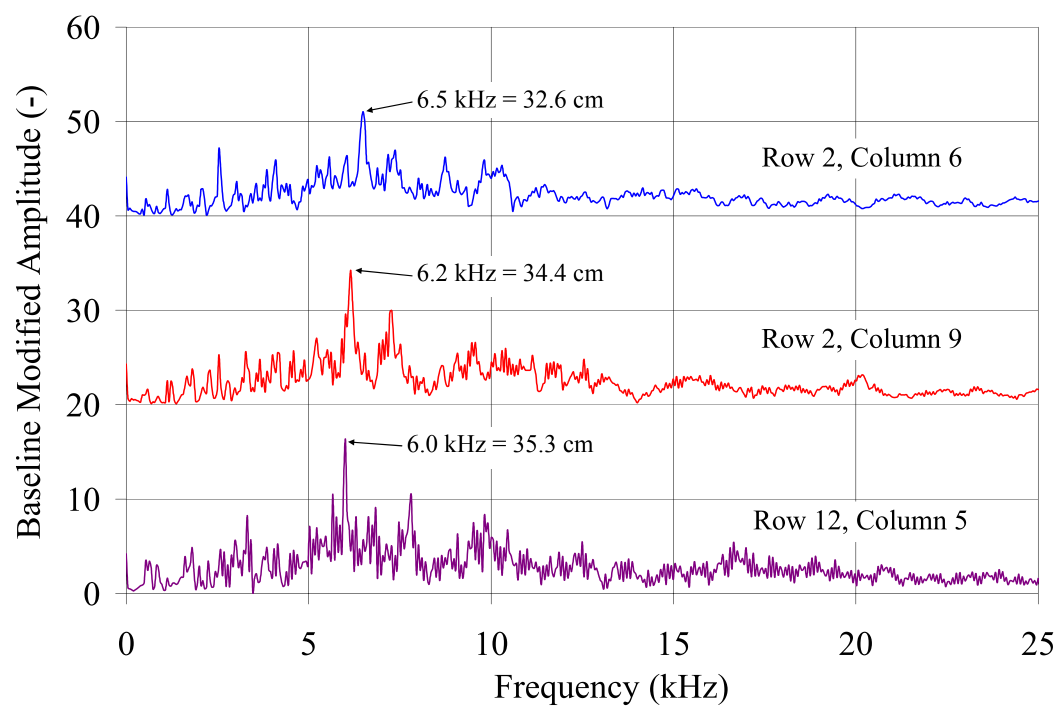


b-) Spectra obtained from the outer region

Figure 4.13 Typical spectra obtained from IE-Deck20

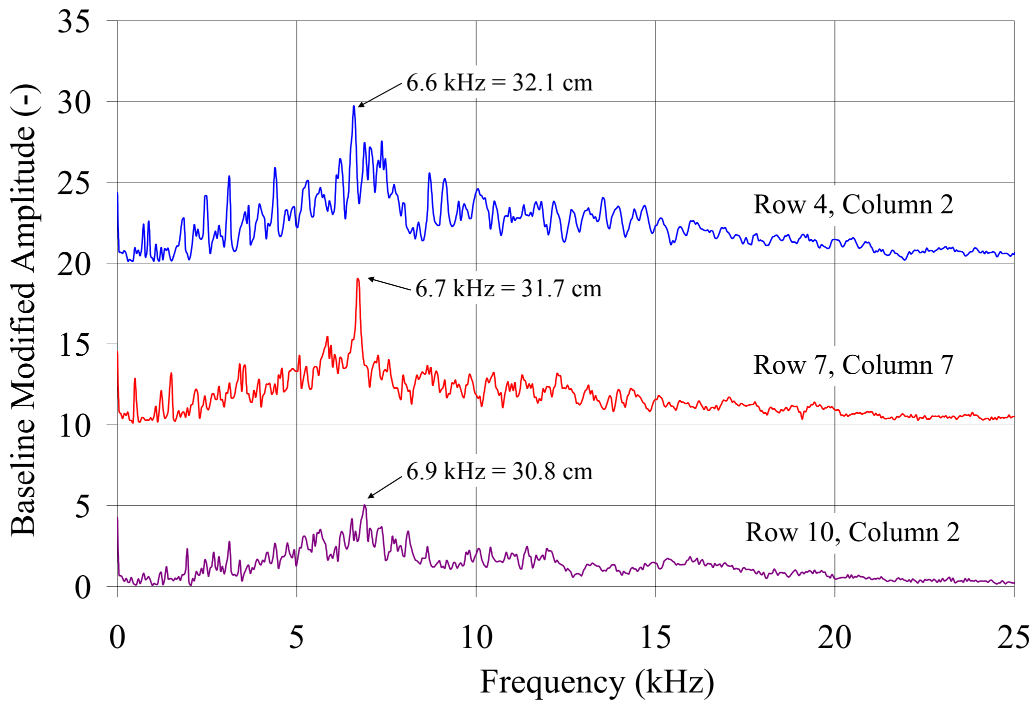


a-) Spectra obtained from the inner region

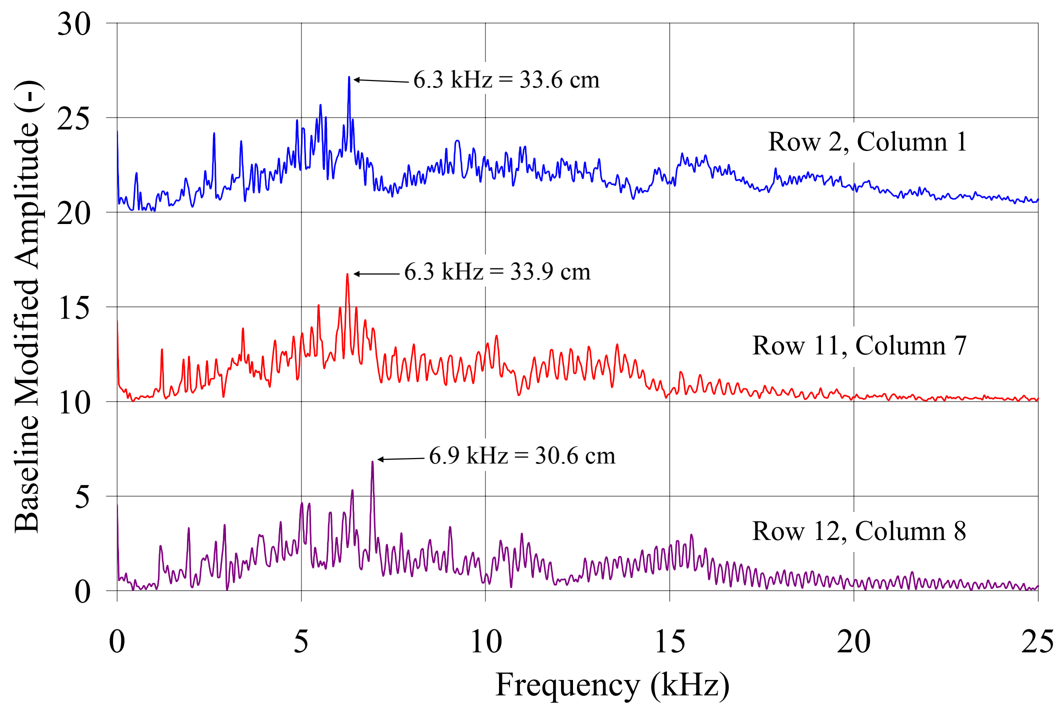


b-) Spectra obtained from the outer region

Figure 4.14 Typical spectra obtained from IE-Deck25



a-) Spectra obtained from the inner region



b-) Spectra obtained from the outer region

Figure 4.15 Typical spectra obtained from IE-Deck30

25.62	20.91	25.31	15.18	14.72	14.72	14.53	14.10	13.83
23.91	15.03	22.90	14.82	15.18	14.77	14.77	13.74	13.57
14.19	14.19	14.15	14.77	14.77	14.87	14.77	14.82	14.10
14.15	14.48	14.63	14.63	14.53	14.82	14.87	14.82	14.77
14.15	14.38	14.43	14.38	14.48	14.77	14.93	14.82	14.68
13.83	14.43	14.38	14.38	14.63	14.72	14.82	14.68	14.87
14.77	14.77	14.72	14.98	14.63	14.63	14.93	14.98	14.72
14.77	14.77	14.82	14.93	14.87	14.98	14.98	15.09	15.03
14.43	14.82	14.72	14.58	14.72	14.53	15.14	15.24	15.29
14.19	14.93	14.58	14.87	14.87	15.18	15.29	15.40	15.40
18.03	15.14	15.35	15.24	14.53	15.40	15.46	15.46	15.29
25.46	25.77	27.06	25.77	25.77	25.77	27.06	25.46	26.22

a-) The calculated thicknesses found from the results of impact-echo analysis (all values in cm)

15.1	14.7	14.6	14.8	14.8	14.9	15.0	15.1	15.1
15.1	14.9	14.9	14.9	15.0	15.0	14.9	14.9	14.9
14.8	14.7	14.7	15.0	15.0	14.8	14.9	14.8	14.8
14.7	14.7	14.7	14.8	14.9	14.7	15.0	14.9	14.8
14.6	14.5	14.6	14.6	14.7	14.8	14.9	14.9	15.0
14.7	14.6	14.6	14.6	14.6	14.6	14.7	14.6	14.7
14.7	14.6	14.6	14.7	14.7	14.8	14.9	14.9	15.0
15.0	14.9	14.9	14.8	14.8	14.8	14.8	14.8	15.0
14.9	14.8	14.9	15.0	14.9	15.0	15.0	15.0	15.0
14.7	14.7	14.7	14.7	14.7	14.8	14.9	14.9	14.8
14.7	14.8	14.7	14.7	14.8	14.7	14.7	14.8	14.7
14.9	15.0	15.1	15.0	14.9	15.0	15.1	15.1	15.0

b-) The true thicknesses of each test point (all values in cm)

69.66	42.21	73.37	2.59	0.55	1.22	3.16	6.63	8.40
58.33	0.89	53.68	0.53	1.22	1.54	0.88	7.77	8.96
4.09	3.44	3.76	1.54	1.54	0.50	0.88	0.14	4.73
3.76	1.52	0.50	1.17	2.51	0.82	0.84	0.53	0.21
3.11	0.84	1.19	1.52	1.52	0.21	0.17	0.53	2.15
5.91	1.19	1.52	1.52	0.18	0.81	0.82	0.53	1.18
0.47	1.16	0.81	1.90	0.50	1.17	0.17	0.53	1.88
1.54	0.88	0.53	0.85	0.50	1.21	1.21	1.93	0.21
3.18	0.14	1.22	2.83	1.22	3.16	0.93	1.59	1.95
3.44	1.54	0.84	1.18	1.18	2.59	2.64	3.39	4.08
22.68	2.30	4.41	3.66	1.85	4.79	5.18	4.47	4.03
70.90	71.83	79.21	71.83	72.98	71.83	79.21	68.63	74.81

c-) Absolute value of the percent error between the calculated thickness and the true thickness (given as %)

Figure 4.16 Results of thickness analysis on IE-Deck15

24.20	22.93	19.57	18.71	18.71	19.22	18.88	19.46	18.17
29.38	29.22	29.38	29.22	28.11	29.79	29.22	29.22	27.56
19.82	20.10	20.18	20.10	20.18	20.10	20.18	20.18	19.82
19.73	20.10	20.18	20.01	20.01	20.10	20.01	20.18	20.18
18.25	20.10	20.01	20.10	20.10	20.01	20.10	20.10	19.82
20.18	20.10	20.01	20.18	20.18	20.10	19.73	20.10	19.73
20.18	20.10	19.92	20.18	20.18	20.01	20.01	20.10	19.05
19.82	20.01	20.10	20.10	20.01	20.01	20.18	20.01	19.73
19.55	19.46	20.01	19.55	19.92	19.46	19.73	20.10	20.01
17.81	19.82	19.22	19.46	19.46	19.57	19.46	20.01	19.73
21.16	19.31	19.46	19.46	21.37	19.46	19.82	19.92	19.73
28.26	28.26	28.63	28.63	29.02	21.89	21.89	23.30	23.05

a-) The calculated thicknesses found from the results of impact-echo analysis (all values in cm)

19.8	19.8	19.6	19.7	19.6	19.6	19.4	19.5	19.9
19.9	20.0	19.8	19.7	19.7	19.6	19.7	19.7	19.8
20.1	19.8	19.8	19.7	19.7	19.7	19.7	19.8	19.7
20.2	20.0	19.9	19.7	19.7	19.7	19.7	19.8	19.8
20.0	19.7	19.5	19.6	19.6	19.6	19.6	19.7	19.7
19.9	19.5	19.5	19.6	19.7	19.6	19.7	19.9	19.9
20.1	19.6	19.7	19.6	19.7	19.6	19.7	19.7	20.0
19.4	19.4	19.5	19.6	19.7	19.7	19.7	19.8	20.0
19.5	19.4	19.4	19.5	19.6	19.6	19.8	19.7	19.9
19.5	19.5	19.5	19.6	19.7	19.8	19.9	19.9	19.9
19.5	19.5	19.5	19.6	19.7	19.7	19.9	19.9	19.9
19.9	19.9	19.9	20.0	20.2	20.2	20.1	20.1	20.1

b-) The true thicknesses of each test point (all values in cm)

21.96	15.91	0.25	4.81	4.52	2.15	2.58	0.29	8.49
47.80	46.40	48.09	48.18	42.68	52.15	48.63	48.03	39.07
1.18	1.43	2.02	2.05	2.43	2.05	2.43	2.02	0.43
2.46	0.72	1.45	1.47	1.83	2.05	1.52	1.92	2.07
8.56	1.94	2.72	2.36	2.57	2.09	2.46	2.15	0.43
1.61	2.99	2.72	2.75	2.43	2.78	0.06	1.12	1.04
0.64	2.57	1.35	2.96	2.43	2.09	1.83	2.05	4.53
2.19	3.14	3.09	2.57	1.57	1.57	2.43	1.06	1.34
0.37	0.53	2.93	0.16	1.61	0.60	0.14	1.84	0.45
8.71	1.66	1.60	0.90	0.95	0.96	2.05	0.65	0.79
8.28	0.90	0.29	0.50	8.47	1.40	0.28	0.02	0.64
42.06	42.13	44.11	43.46	44.04	8.17	8.76	15.81	14.62

c-) Absolute value of the percent error between the calculated thickness and the true thickness (given as %)

Figure 4.17 Results of thickness analysis on IE-Deck20

35.25	37.10	35.25	28.17	35.25	28.36	29.71	28.36	35.55
35.25	33.10	35.02	32.64	35.25	33.10	29.71	35.25	31.20
28.36	26.45	26.95	26.61	26.95	26.95	27.62	26.12	27.62
29.92	26.45	26.78	26.78	26.61	26.61	26.95	25.52	26.61
28.55	26.45	26.61	26.61	26.78	26.12	26.78	25.99	26.45
29.10	25.68	27.13	26.78	26.78	26.78	25.52	25.84	29.51
24.81	25.84	26.61	26.45	26.45	26.28	26.95	25.68	25.52
26.45	25.68	25.84	25.68	26.61	26.61	25.84	25.37	25.68
27.99	26.12	26.12	25.68	26.61	26.12	26.12	25.37	25.52
26.28	25.52	26.95	26.95	25.68	26.78	25.52	25.52	29.92
34.73	28.36	29.92	29.51	35.02	32.64	34.73	28.55	34.45
27.62	26.95	27.13	27.62	27.62	27.30	28.36	35.25	27.62

a-) The calculated thicknesses found from the results of impact-echo analysis (all values in cm)

26.8	26.6	26.8	26.7	26.8	26.5	26.3	26.3	26.2
26.5	26.8	27.0	27.0	27.1	27.4	27.3	27.0	27.1
26.5	26.6	26.6	26.6	26.8	26.8	26.7	26.6	26.5
26.8	26.7	26.9	26.7	26.9	26.7	26.5	26.3	26.3
26.8	26.7	26.6	26.5	26.7	26.7	26.6	26.5	26.4
26.4	26.4	26.4	26.3	26.5	26.7	26.5	26.5	26.6
26.5	26.7	27.0	26.9	27.0	27.2	27.6	27.6	27.7
26.7	26.6	26.6	26.5	26.6	26.5	26.5	26.4	26.4
26.5	26.4	26.2	26.2	26.3	26.0	25.8	25.7	25.7
26.3	25.9	26.0	26.0	26.1	26.0	25.9	25.8	25.5
26.0	25.6	25.5	25.5	25.8	25.7	25.3	25.4	25.5
25.8	25.5	25.5	25.6	25.6	25.4	25.4	25.8	25.8

b-) The true thicknesses of each test point (all values in cm)

31.58	39.58	31.68	5.67	31.77	6.86	12.85	7.75	35.62
32.97	23.42	29.55	20.72	30.31	20.99	8.96	30.65	15.17
7.02	0.57	1.33	0.05	0.57	0.57	3.45	1.80	4.23
11.78	1.09	0.47	0.38	0.88	0.40	1.75	2.80	1.08
6.69	1.02	0.13	0.28	0.31	2.02	0.61	1.84	0.03
10.14	2.88	2.90	1.91	1.07	0.23	3.68	2.36	11.01
6.53	3.24	1.50	1.53	2.04	3.37	2.27	7.03	7.72
0.83	3.46	2.91	3.03	0.24	0.36	2.47	3.75	2.84
5.45	0.98	0.37	1.84	1.20	0.32	1.33	1.36	0.53
0.10	1.53	3.67	3.67	1.42	3.17	1.34	0.99	17.39
33.83	10.78	17.57	15.71	35.99	27.01	37.54	12.41	35.35
6.97	5.53	6.54	7.98	7.89	7.40	11.48	36.84	7.14

c-) Absolute value of the percent error between the calculated thickness and the true thickness (given as %)

Figure 4.18 Results of thickness analysis on IE-Deck25

35.54	30.34	33.35	30.56	33.89	30.56	30.56	30.56	32.39
33.09	33.09	30.34	30.13	31.19	31.19	33.89	33.09	33.35
30.96	30.78	31.19	32.63	30.78	31.66	31.66	30.96	31.66
33.09	30.56	31.42	31.19	32.14	31.42	31.42	30.78	31.42
30.34	30.78	31.19	31.42	31.66	30.96	31.42	31.42	33.62
30.56	30.78	30.78	31.19	31.66	31.66	31.66	31.42	31.66
33.62	30.56	32.39	32.14	31.66	32.14	32.39	31.42	31.66
31.90	30.78	31.66	31.19	32.39	33.62	31.66	30.96	31.66
31.19	32.14	31.42	31.19	29.92	29.92	31.42	29.92	32.14
30.96	30.78	30.56	27.47	25.21	25.67	28.93	30.56	30.78
33.62	33.62	30.34	29.29	31.90	31.66	31.19	31.90	34.16
30.56	33.35	30.56	27.98	31.66	31.66	31.90	29.09	32.63

a-) The calculated thicknesses found from the results of impact-echo analysis (all values in cm)

30.5	30.5	30.6	30.9	31.1	31.0	31.2	31.2	31.2
30.5	30.7	30.6	31.0	31.1	31.2	31.2	31.1	31.1
31.3	31.4	31.5	31.5	31.5	31.3	31.5	31.2	31.1
31.6	31.5	31.5	31.8	31.7	31.6	31.9	31.6	31.6
30.7	30.7	30.9	31.0	31.0	31.0	31.1	31.0	30.9
30.7	30.7	30.8	31.0	31.1	31.2	31.2	31.3	31.1
30.6	30.7	31.0	31.1	31.3	31.2	31.3	31.6	31.5
30.8	31.0	31.3	31.7	31.9	32.2	32.1	32.3	32.6
30.6	31.0	31.0	31.2	31.2	31.3	31.4	31.4	31.5
31.0	31.1	31.2	31.4	31.7	31.8	31.7	31.8	31.9
30.6	30.9	31.0	31.2	31.3	31.4	31.3	31.3	31.2
30.4	30.7	31.0	31.2	31.4	31.2	31.3	31.3	31.1

b-) The true thicknesses of each test point (all values in cm)

16.55	0.45	9.11	0.96	9.14	1.54	2.14	2.11	3.77
8.58	7.94	0.97	2.88	0.30	0.04	8.75	6.27	7.18
1.13	2.08	0.85	3.67	2.27	1.08	0.38	0.63	1.86
4.59	2.91	0.30	1.79	1.39	0.68	1.43	2.64	0.43
1.06	0.15	0.92	1.43	2.29	0.18	1.08	1.50	8.69
0.35	0.15	0.08	0.69	1.96	1.41	1.50	0.53	1.70
9.79	0.58	4.60	3.41	1.15	2.95	3.34	0.43	0.57
3.53	0.76	1.05	1.72	1.68	4.41	1.28	4.07	2.86
1.84	3.81	1.40	0.09	4.12	4.42	0.05	4.85	2.13
0.05	0.89	2.17	12.57	20.46	19.22	8.61	4.01	3.56
10.01	8.73	2.05	6.23	1.91	0.95	0.41	1.97	9.35
0.40	8.72	1.47	10.21	0.83	1.34	1.97	7.11	5.07

c-) Absolute value of the percent error between the calculated thickness and the true thickness (given as %)

Figure 4.19 Results of thickness analysis on IE-Deck30

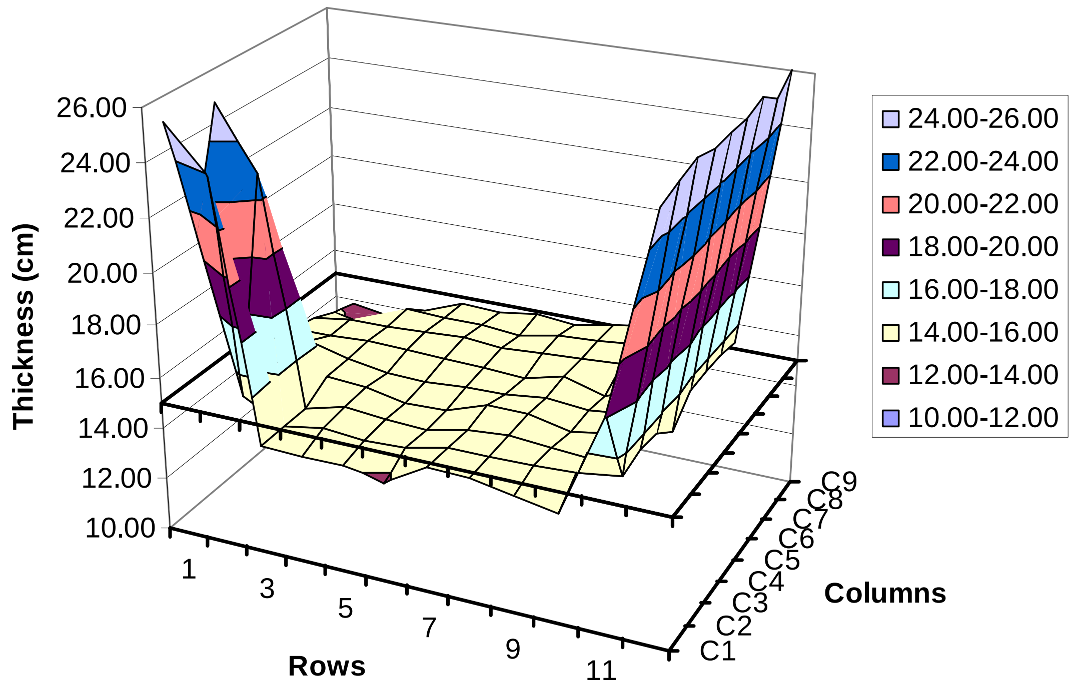
The results given above in Figures 4.16 through Figure 4.19 are the complete results after the analysis of test results. There are 12 rows and 9 columns in each chart and each value represents a point on the mesh. In Table 4.3 below, the corresponding mean and standard deviation values are presented both for the complete set of data and for the inner portion of the predefined mesh.

Table 4.3 A summary of the results of tests conducted on all four slabs

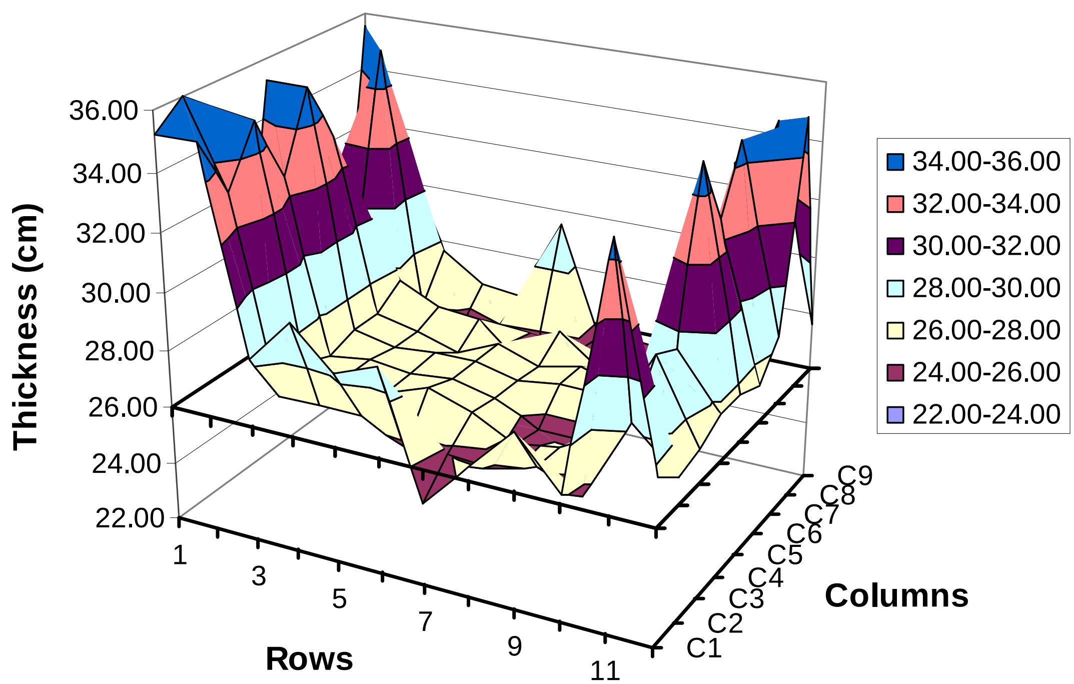
		IE-Deck15		IE-Deck20		IE-Deck25		IE-Deck30	
		all points	inner portion	all points	inner portion	all points	inner portion	all points	inner portion
calculated thickness	mean	16.12	14.75	21.16	19.98	28.24	26.33	31.37	31.38
	std. dev.	3.60	0.26	3.11	0.24	3.17	0.55	1.48	0.70
true thickness	mean	14.83	14.78	19.73	19.66	26.40	26.51	31.22	31.32
	std. dev.	0.15	0.14	0.19	0.12	0.53	0.39	0.40	0.37
corresponding error	mean	10.82	1.25	8.39	1.85	8.62	1.74	3.38	1.76
	std. dev.	22.79	0.88	14.84	0.79	11.17	1.34	3.93	1.40

4.2.2 Effect of Test Point Location

One of the first outcomes after examining the above results was that the error percentages are greatly magnified and also remain completely outside the acceptable limits near the ends of the slab. The remaining points were more or less uniform and therefore it was thought necessary to understand the effect of test point location so that healthier statistical comparisons could be carried out.



a-) Thickness values found by using impact-echo from IE-Deck15



b-) Thickness values found by using impact-echo from IE-Deck25

Figure 4.20 Graphical representation of calculated thickness values clearly showing the edge effect on test points near the sides

One of the first conclusions that could be drawn from the above given figure is that impact-echo is not suitable for testing near the sides of concrete pavement slabs. This effect is more pronounced in thinner sections. Perhaps its effect might be negligible after 30 cm of thickness because the error percents show a decreasing trend with increasing thickness. Nevertheless, it is not common practice to construct plain concrete pavements which have more than 30 cm of thickness due to reasons explained previously.

By investigating the above figures, it could be concluded that the effect of sides of the slab is much more pronounced at the two shorter edges due to the combined effect of the hollow pipes that were placed to raise and move the slabs when necessary. The relative errors caused due to this effect vary from 10% in thicker sections up to 70% in thinner ones.

Another interesting result that is related to these hollow pipes is that they tend to decrease the frequency of sound waves and thus increase the value of calculated thickness rather than increasing the frequency due to decreased travel distance. In most graphs, several distinct peaks existed due to distortion of the sound waves both by the corners of the slab and also by the cylindrical hollow pipe. The effect of hollow pipes on test results together with whether their location could be detected or not will be investigated in the sections that follow. Regardless of these, the peak with the highest amplitude was chosen during this analysis phase.

It was concluded that these large relative errors are caused by the hollow pipes combined with the effect of irregularities in the geometry near the test point and not related to the true accuracy of the impact-echo method. Therefore, since the aim of these series of tests was to determine the accuracy of the test method only, points showing such behavior were decided to be discarded during statistical analysis.

For this reason, one column of points at the outermost left and right hand side together with two rows of points at the top and bottom were discarded during the calculation of average errors and their standard deviations.

One exception to this is IE-Deck30 where an additional row of data was discarded while selecting the inner points for statistical analysis. The reason for this is that, before pouring of concrete, two pieces of foam board on top of each other were tucked tightly underneath the pipe so that this would allow additional tests to see whether impact-echo is capable of locating internal thickness variations or flaws. The total thickness of the foam board layer created became 6 cm. Investigating the results given in Figure 4.16 (a), it is apparent that this layer can only be detected where there are no pipes or any other geometrical distortions. The values in the middle columns of the third row from the bottom point out to an irregularity at that location. Resulting thicknesses are very close to the distance from the surface of concrete to the foam board at the bottom. Unfortunately, extensive tests could not be carried out because of the limited area remaining after excluding the ones near the edge and above the pipe.

There were no exceptions for the rest of the slabs. The inner portion of the charts presented in Figure 4.16 to Figure 4.19 marked by a dashed line represents the remaining data points that would be used for average calculations. They too had some variability among them but not at a magnitude as compared to the outer region.

The variations of the output frequencies for points of constant thickness on an imaginary line were also tested at this point as stated in chapter 3.5. Several columns and rows were investigated separately from several slabs but results did not agree with the ones proposed in the corresponding paper. Therefore it may be assumed that the same frequency results could be obtained from points of same thickness. Of course there are variations in test results but not in a constant pattern that would match every result in a line.

As a last remark to the above discussions, it is suggested that during a field test on concrete pavements, the location of test points should be selected such that the distance to a joint or any other geometrical irregularity should be a minimum of 20 cm.

4.2.3 Statistical Analysis

After selecting the points of interest, statistical tests were conducted to understand the nature and distribution of errors. It is preferable that these errors are distributed with a Gaussian distribution and clustered around zero. Furthermore, a hypothesis test was carried out in order to determine if the true thicknesses and the calculated ones were statistically the same.

As mentioned in the previous section, some of the outermost points showed distortion and high errors not related to the accuracy of the method. For this reason, only the points in the remaining inner area were used during statistical analysis.

In order to plot the necessary graphs and find the required variables, the statistical analysis software, 'Statistical Package Program for Social Sciences' (SPSS) was used. Analysis was conducted for four of the slabs and they showed similar distributions.

The mean and the standard deviation are perhaps the most widely used measures for data description. The standard deviation is used as a measure of statistical dispersion, measuring how widely spread the values in a given data set are. If the data points are close to the mean, then the standard deviation is small. Results of all slabs have been presented in Table 4.4 (a) below.

Two tests were conducted to test the normal distribution of the data found. The "df" in Table 4.4 (b) stands for the degrees of freedom. The degrees of freedom for an estimate equals the number of data minus the number of additional parameters estimated for that calculation. As we have to initially estimate more parameters, the degrees of freedom available decreases. This value is 56 for this analysis where this is the number of data points in the inner region that is tested. "Statistic" gives the value that would be used on a t-test to find the result if this procedure was carried out manually. "Sig." stands for the observed significance level (or p-value). If this value exceeds the predetermined significance level, usually chosen as 0.05, then it is concluded that the null hypothesis cannot be rejected. Here, it was shown that the data was normally distributed.

Table 4.4 Results of the statistical analysis conducted for the error percentages found

a-) Presents the descriptive statistics for the error percentages

Deck Labels	Mean	Standard Deviation	95% Confidence Interval for Mean	
			Upper Bound	Lower Bound
IE-Deck15	-0.201	1.524	0.207	-0.609
IE-Deck20	1.597	1.235	1.928	1.266
IE-Deck25	-0.692	2.102	-0.129	-1.255
IE-Deck30	0.200	2.251	0.847	-0.447

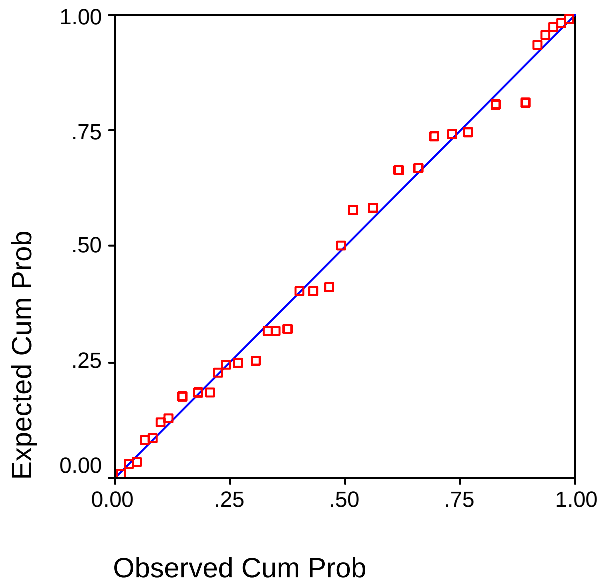
b-) Results of the two tests for normality

Tests of Normality

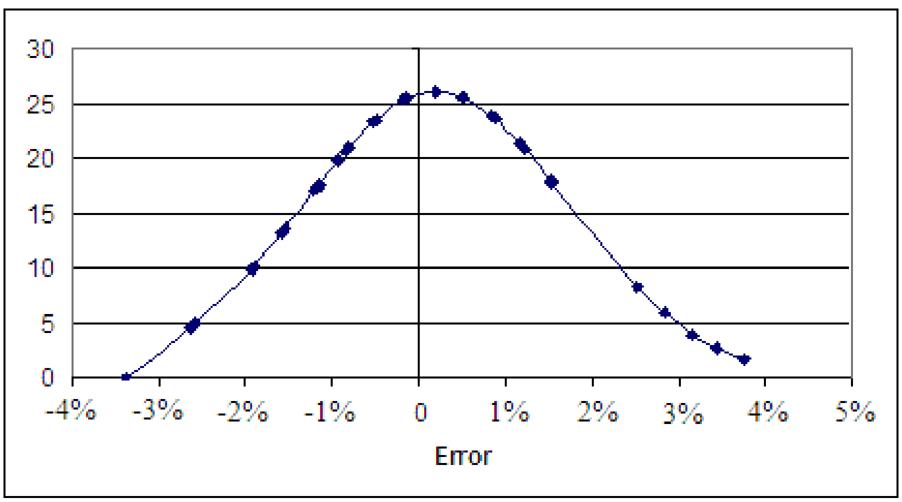
	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
tests for error percentage	.101	56	.200	.982	56	.573

The results for the mean error change for each thickness but are usually less than 2%. The upper and lower bounds for the interval of expected mean values for a confidence of 95% were also presented in Table 4.4 (a).

Tests for normality suggest that the distribution is normal. This is further strengthened by the P-P plot in Figure 4.21 (a). There are two things to look for in a P-P plot. First, the data points should not be too far away from the line at the middle. Second, the number of points below and above the line should be more or less equal. Both of these conditions are satisfied as is seen in Figure 4.21 (a). Results of the remaining slabs yielded similar results and therefore only one is given for visualization.



a-) Normal P-P plot of error percentages



b-) The graph of 56 data points drawn as a probability density function (pdf)

Figure 4.21 Graphs of normal distribution of the resulting data for IE-Deck15

After determining the important parameters and the types of distribution for the variables, it was decided to conduct a hypothesis test in order to check the validity of what has been done. The t-test was used to check whether the calculated and the true thicknesses are correlated to each other. Error percent found should be zero if the calculated and the true thicknesses are equal. However, if these are independent or weakly correlated, then the value found as the error would not have much meaning.

H_0 (null hypothesis): Error = 0

H_A (alternative hypothesis): Error $\neq$ 0

Level of significance = 5% $\rightarrow \alpha = 0.05$

If the observed significance level is greater than 0.05, then do not reject H_0

Table 4.5 Results of hypothesis test conducted

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
error percent	.986	55	.329	.2008	-.2074	.6091

It could be observed that the significance level was above 0.05. The reason the test was conducted as 2 tailed is because if the error is not zero, it could be either negative or positive, but the null hypothesis would be wrong in either case. The hypothesis suggests that the errors should be zero under normal circumstances with a confidence interval of 95%.

4.2.4 Relative Error

The widespread use of any non-destructive technique depends on its ability to collect data rapidly and accurately. All data collected have some amount of error but these should be below the acceptable limits in order to provide useful information about the sample investigated.

There are two methods that are used for error determination. Each has its own logic and could be chosen depending on the available data and on the purpose for which it would be used. They are explained here and the results presented altogether as a table at the end.

As stated before, the outermost points have large errors which are not directly related to the accuracy of the test method. Therefore results obtained from these points should not be included during the final error calculations.

The first alternative is to compare the two different thicknesses at each point: the calculated thickness, which was obtained by converting the frequency outputs from impact-echo results into thicknesses by using the P-wave speed, and the true thickness measured at each point. The absolute value of these error percents could then be determined for every point by dividing this difference to the true thickness and the average of this new complete set of data could be found in order to find a single average error for the complete structure investigated. This method of error calculation is the most logical one if the main point of interest is in the determination of the average amount of error at each point or more specifically, for each test data.

A second approach would be not to use the absolute value during error calculation at each point. Some points would show negative errors which means that the calculated thickness is smaller than the true thickness, and some would show positive values. Again, their average and standard deviation could be used to interpret the status of the sample at hand. This approach would result in lower average error values, since some of the positive values would cancel out the negative values, but higher standard deviation since data would be more spread out on both sides of the axis. However, its use is logical when the average thickness of the structure plays a more important role than the thickness at individual points as in the case of most applications including quality control of new concrete pavements where internal problems are not expected initially. It carries the investigation from the point scale to a macro scale.

Results of the analysis conducted by the two methods mentioned above are given in Table 4.6 below. Only the points at the inner region of each slab were presented in the following table due to the fore-mentioned problems associated with the outermost points.

Table 4.6 Results of error percents found by using two different approaches

Results of errors calculated by the two methods		IE-Deck15	IE-Deck20	IE-Deck25	IE-Deck30	All Four Slabs Combined
calculated thickness	mean	14.75	19.98	26.33	31.38	-
	st. dev.	0.26	0.24	0.55	0.70	-
true thickness	mean	14.78	19.66	26.51	31.32	-
	st. dev.	0.14	0.12	0.39	0.37	-
% error with absolute value	mean	1.25	1.85	1.74	1.76	1.5
	st. dev.	0.88	0.79	1.34	1.40	1.0
% error without absolute value	mean	-0.20	1.60	-0.69	0.20	0.6
	st. dev.	1.52	1.23	2.10	2.25	1.7

Furthermore, the combined mean and the standard deviation of the error values found for the inner points of all four slabs by using the percent error with absolute value method were found to be 1.53% and 0.979 respectively. Therefore, each data recorded has an error percent in the range of 1.53% ±1.958 which corresponds to (-0.43%, 3.49%) with a confidence of 95%. Outliers were discarded from the combined data set before calculating the mean. Each test point may have positive or negative errors independent of its relative location or results of adjacent cells. The above given range is the combined percent error and is valid while examining single test results obtained by the impact-echo method at varying thicknesses and should be kept in mind while using this technique.

By similar operations including the exclusion of the outliers from the set of data, the mean and standard deviation of inner points analyzed by using percent error without absolute value method was found to be 0.56% and 1.732 respectively. For a 95% confidence interval, the range is defined by 0.56%±3.464 which corresponds to (-2.90%, 4.02%). While modeling a complete structure or a concrete pavement with many test points, the mean value of the error percent actually decreases to yield very accurate results compared to the accuracy of one test result only; however, the standard deviation is greatly increased due to higher dispersion of data points and thus the range of values obtained for a given confidence interval increases considerably.

Using the absolute value of the difference between the true and the calculated thickness at each point produced the highest mean error of 1.53%. This value is the average error that is present in a single test record. Not using the absolute value for the difference produced a mean error of 0.56% which is the error percent of the impact-echo method for determining concrete pavement thickness. This value might actually be considered as very accurate according to certain standards.

In light of the above discussions and results, it was concluded that the impact-echo method may be used on plain concrete pavements with acceptable success. The results of the average error percents were found to be acceptable. Comparison of error percent results with the actual concrete pavements investigated at several sites enhanced the success and the need for such a method. However, the standard deviations still present problems that can not be overlooked. They increase the expected range of values for a given confidence level which necessitate the need to collect a large amount of data for it to be dependable.

4.3 Locating Defects

4.3.1 Cylindrical Hollow Pipes

After determining the accuracy of the impact-echo method, it was decided to investigate whether it could pinpoint the location and depth of the hollow pipes which were placed inside the concrete slabs initially in order to use for raising and moving around. This last application was thought to be important since similar hollow pipes could be encountered in the field especially on bridge decks or concrete pavements where post-tensioning has been applied.

These hollow pipes were placed near the two ends of each slab. Therefore, there are a total of 8 pipes embedded in concrete for testing. Their lengths were the same as the width of the slabs, which was 1.5 m, but their depths were different. Recordings were collected again at 15 cm intervals which corresponded to 9 test points for each pipe. These points were selected so that they were on top of the center line of the pipes.

The distance of the upper level of each pipe to the surface of the slab was measured. Since this distance was as low as 2 cm at some points, the smallest impactor of 3 mm diameter was decided to be suitable for the purpose and all recordings were conducted with the same impactor afterwards. It should be noted here that although the smallest sized diameter was chosen as the impactor, still, some of these hollow pipes corresponding to shallow ones could not be located in the frequency spectra. The two pipes were located approximately 2 cm and 3.25 cm below the top surface in IE-Deck15, which corresponded to frequencies of 101 kHz and 62 kHz respectively. As mentioned previously, the capability of impact-echo to detect sound waves is from 0 to 60 kHz, but used best for frequencies not exceeding 30 kHz.

Table 4.7 Results of tests for locating hollow pipes embedded in concrete

	expected thickness frequency (kHz)	distance of pipe to the surface (cm)	expected frequency due to pipe (kHz)	error percent (%)
IE-Deck15	14.32	2.0	101.4	NA
	14.32	3.3	62.4	NA
IE-Deck20	10.71	4.0	51.3	NA
	10.71	4.3	48.3	NA
IE-Deck25	8.05	8.3	24.7	0.20
	8.05	9.0	22.6	4.61
IE-Deck30	6.75	13.8	14.8	-2.32
	6.75	14.0	14.5	-0.97

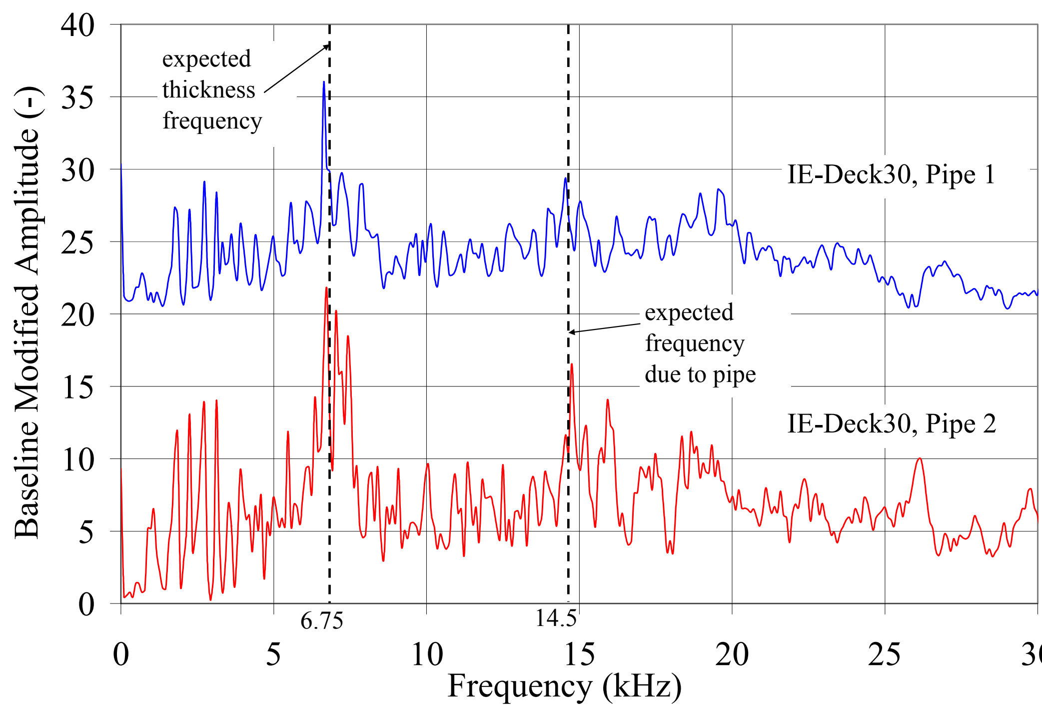


Figure 4.22 Two of the resulting spectra obtained from pipes in IE-Deck30

As can be seen from Table 4.7, no frequencies could be observed above 60 kHz and so error percents could not be calculated. Likewise, error percents could not be calculated for thicknesses over 30 kHz because they were not found to be truly reliable. A peak might be observed at one point and completely missing at the consecutive point. However, a peak could be distinguished at most of the test points for pipes being embedded more than 8 cm from the surface and so having frequencies of less than 30 kHz. Figure 4.22 gives two examples as to how the spectra look like.

It is concluded that for impact-echo to detect hollow sections similar to pipes, such as in post-tensioned tendon ducts, the distance from the top of the duct to the surface should be a minimum of 8 cm or should have a maximum frequency of 30 kHz which is both correlated to depth and the P-wave speed.

Nevertheless, locating the depth of pipes presented difficulties. Using small sized impactors reduces the amplitude of all peaks thus increasing the number of peaks in the frequency spectra and therefore making it harder to distinguish between any two consecutive peaks. A number of peaks occurred in some tests which makes it harder to be certain about a test result; whether the peak is caused by the pipe or due to some other reason such as an error during testing. The peak having the highest amplitude was chosen for reporting during this series of tests.

The mean error and the standard deviation were found to be 1.52% and 3.00 respectively when values corresponding to pipes which are placed less than 8 cm from the surface were discarded. It should be noted that the depth and location of these pipes may not have been found if there was not any prior information regarding the pathway of these pipes or they might had been completely ignored if there was no information provided about their existence.

4.3.2 Detecting Planar Voids

As another application, it was decided to check whether large planar voids parallel to the surface may be detected or not. In order to achieve these large voids, two slabs were selected and then put on top of each other as shown in Figure 4.23. IE-Deck15 and IE-Deck20 were used for this purpose where the former one was at top. The reason why these two samples were selected is because they had the smoothest top surfaces and also since the addition of these two would yield the least thickness.

Figure 4.23 Two slabs placed on top of each other for further testing

Tests were then conducted at each point on the previously defined inner area. Initially it was thought that a thickness of 15 cm would be detected at points where there was no contact with the concrete below but a thickness of 35 cm may be observed at points where there was contact. However, after two sets of tests with two different sized impactors, it was observed that the thickness corresponding to the top layer, which was 15 cm, may be easily detectable but the total thickness of 35 cm was very hard to distinguish and actually was noticed in only very few of the test results. By further investigation of the two slabs and the interface in between, it was observed that actually the two slabs were in contact with each other by a very small area, which corresponded to few points. Regardless of how smooth the top surface is, even small variations of several mm would create a planar void and thus affect test results.

Two different impactors were used for the two tests. The first was the impactor with 6.5 mm diameter and the second was 8 mm. After testing all of the predetermined points, results were tabulated and analyzed as explained previously. In almost all recordings, it was easier to detect the thickness corresponding to the upper layer than the combined thickness. Three sample results obtained by using the 6.5 mm impactor are given in Figure 4.24 below. The complete set of data collected from the tested inner area is presented in Figure 4.25. Nevertheless, it should be noted that not all results were easy to interpret. There were distortions and several low frequency peaks that complicated the resulting graphs.

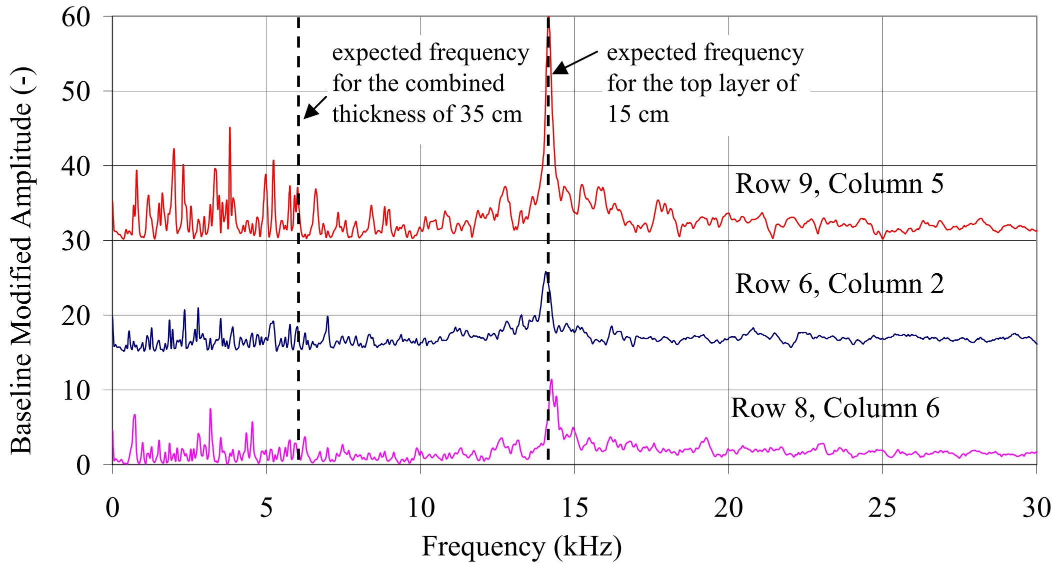


Figure 4.24 Sample resulting graphs while testing planar voids inside the concrete section

0.12	0.12	-0.49	-0.49	0.50	0.17	0.85
-0.50	-1.86	-1.17	-1.84	1.54	-0.14	0.17
-2.44	-2.12	0.18	1.54	1.21	0.89	0.53
-0.51	0.53	0.18	1.16	-1.86	1.54	2.59
2.59	1.51	0.82	0.47	-0.21	0.89	0.89
-0.18	0.89	1.57	1.21	-0.83	2.30	2.59
0.85	-2.18	-1.19	-0.88	-0.49	0.21	2.32
1.54	-1.19	2.26	1.54	1.21	1.61	2.27

Figure 4.25 Results of analysis for detecting planar voids, all given as percent error

After these sets of tests, it was concluded that large planar voids inside a concrete section can be detected by the impact-echo method. The corresponding mean error percent for locating these defects was found to be 0.4% with a standard deviation of 1.3. Under these situations, however, only the depth of the planar void may be detected rather than the total thickness of the section, and so a reliable error percent could not be proposed for the total thickness.

4.3.3 Effect of Base Layer

The impact-echo method may be used on concrete structures where one or more sides of the section may be covered or in contact with soil. Concrete pavements are not an exception to this situation. Usually, pavements are built on top of base courses made up aggregates with a suitable grading. Sometimes, some amount of cement may be mixed with these aggregates to even further strengthen this base layer. In this section, the effects of having an aggregate layer beneath the concrete section would be investigated for the two cases that are mentioned.

4.3.3.1 Aggregate Base Layer

A combination of two slabs was again used for these tests. The top sample was raised initially and a fully compacted aggregate layer was formed in between the two slabs. A total of 273 kg of aggregate was used to obtain a layer which was 10 cm thick. Fine and coarse aggregates with different sizes were used and their gradation is presented below in Figure 4.26.

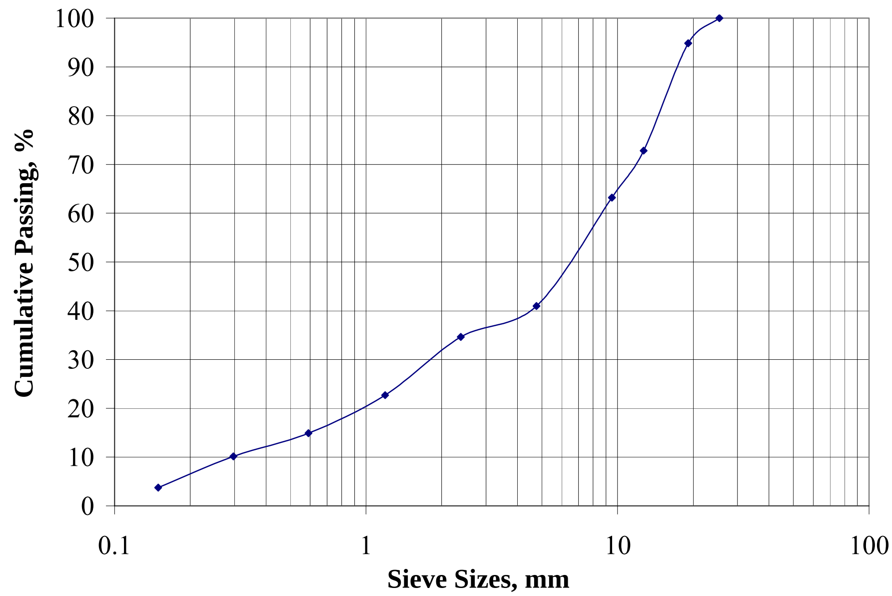


Figure 4.26 The gradation of the aggregates used to create a layer in between the two slabs

The reason why the aggregate layer was formed on top of the bottom slab is because such thicknesses for the aggregate layer are used in practice only when a very strong subbase is present. The thickness would be greater if the subbase is not that strong. The concrete slab placed underneath would provide the necessary strong subbase and so testing conditions would better simulate the actual applications.

Figure 4.27 The state of the two slabs and the aggregate layer in between before testing

Results provided valuable information regarding the usability of the impact-echo method under these circumstances. The thickness corresponding to the top slab was detectable. The results showed some scatter and unexpected behavior at several test points but did not have a major effect on the accuracy of test results. After analysis, it was found out that a mean error of 0.4% exists for the thickness determination with a standard deviation of 2.1. Sample resulting graphs collected from the same points used while testing the effect of planar voids are given in Figure 4.28 below, followed by the tabulated results of all points in Figure 4.29.

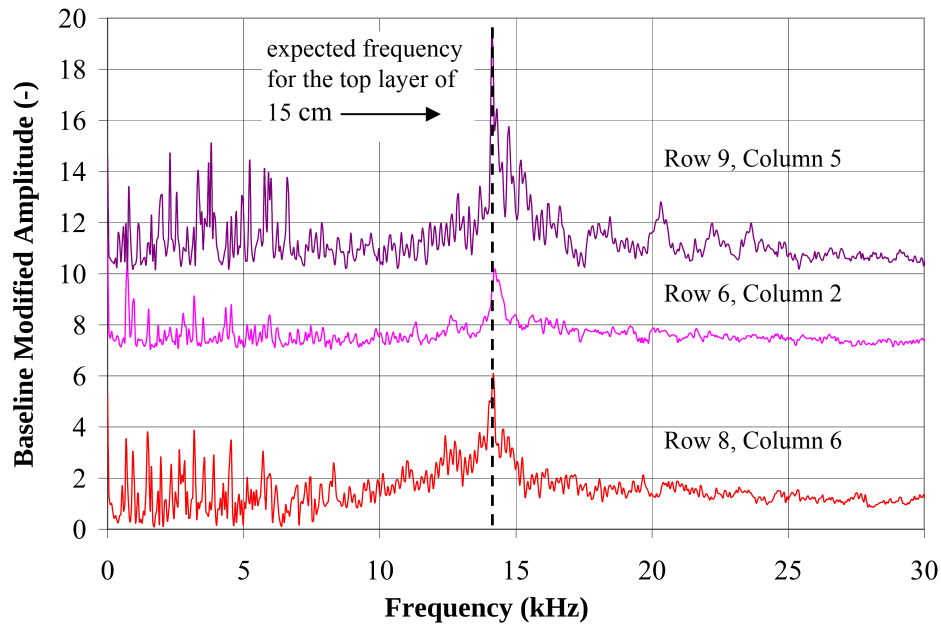


Figure 4.28 Sample resulting graphs while testing the effects of base layer when there is an aggregate layer below the concrete section

-5.91	-0.16	-0.14	-1.54	0.50	0.17	0.85
-5.91	-1.86	-0.55	-1.84	1.90	-0.14	-0.53
0.87	0.53	-0.51	-0.84	0.85	0.53	-0.53
3.33	0.53	0.18	0.81	1.87	1.54	2.23
1.16	1.87	2.26	1.18	1.57	-1.22	0.89
-0.18	-0.18	1.57	1.57	2.30	1.93	2.96
-0.83	-0.18	-5.05	-2.51	-2.49	0.57	2.70
-0.84	2.26	1.54	2.62	2.30	3.01	4.53

Figure 4.29 Results of analysis for the effects of base layer made up of well-graded aggregates, all values given as percent error

After these sets of tests, it may be concluded that the effect of the base layer made up of well-graded aggregates is not a primary concern for impact-echo testing. Although resulting graphs were somewhat distorted, still, peaks could be detected at the expected frequencies and so accuracy of results was not greatly affected.

4.3.3.2 Lean Concrete Base Layer

While investigating the effects of the base layer, it was decided to check whether the addition of some amount of cement into the aggregate mixture would alter the results. For some concrete pavement applications, it is known that certain amount of cement is mixed together with the aggregates to form a stronger base layer. Nevertheless, such a mix is much weaker and more porous than the concrete used for the pavement. Although they still remain as two distinct layers, impact-echo measurements may sometimes measure the combined thickness. The validity of this would be checked by the following series of tests.

The previously placed aggregate layer was removed and thoroughly mixed together with 45 kg of cement. A W/C ratio of 0.4 was used since workability was not the main point of concern here. Figure 4.30 is a picture taken during the mixing process and at the end of placement of concrete.

Figure 4.30 Aggregates were mixed with cement in order to produce a lean concrete in between the two slabs

Two sets of tests were conducted on the predefined points at the inner area of the top slab, again with the impactors of 6.5 mm diameter and 8 mm diameter. Accuracy measurements did not seem to be greatly affected by this new layer placed in between. Again, the mean error was found to be 0.6% for the thickness of the upper slab specimen with a standard deviation of 1.6. However, a peak at the expected frequency was hard to distinguish and practically not possible at some points, and this necessitates the need to collect more data from a certain area in order to better understand the nature of the section at the vicinity of the point.

Figure 4.31 shows three sample resulting graphs intentionally collected from the same points used while testing the effects of the aggregate layer and of the planar void in between the two slab specimens. The graph at the bottom of Figure 4.31 presents a graph obtained from one of the points where the expected thicknesses could not be observed regardless of the number of repetitions. Figure 4.32 presents the complete set of results in tabulated form.

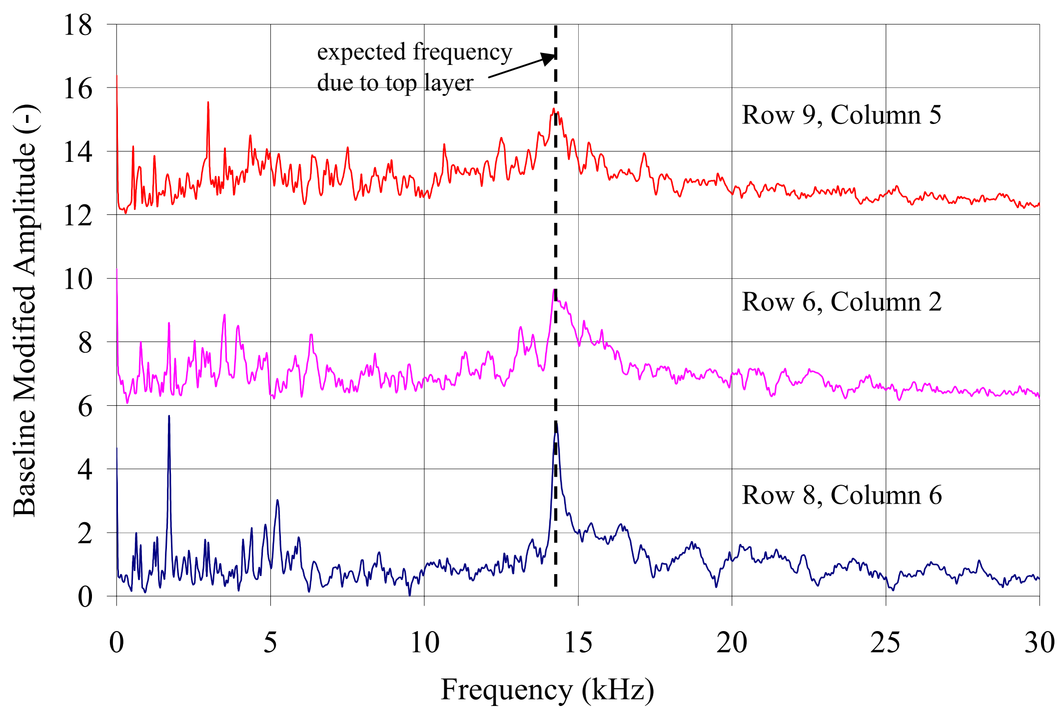


Figure 4.31 Sample resulting graphs collected while there was a lean concrete layer in between. The first three recordings present peaks at the expected frequency whereas the last one does not.

-2.79	0.12	-1.19	-0.49	0.14	-0.18	-2.52
-0.84	0.47	-0.83	-1.84	1.54	-0.14	0.17
1.50	1.16	0.18	1.90	0.85	0.17	-0.18
-0.85	0.53	1.87	-4.39	2.23	1.18	2.96
1.87	1.51	-0.16	0.82	-0.55	0.17	1.25
-0.53	0.17	0.85	-0.21	-0.83	0.14	1.57
0.14	-0.53	-0.84	0.17	-2.49	0.93	2.70
4.03	1.54	1.90	1.90	2.30	2.64	4.53

Figure 4.32 Results of analysis for the effects of base layer made up of lean concrete, all given as percent error

CHAPTER 5

SUMMARY AND CONCLUSIONS

Concrete pavements have been applied and tested for over 100 years around the world. Their construction has started recently in Turkey. There needs to be a quality control system in order to determine whether the thickness of concrete pavements produced is in accordance with the design thickness, since thickness is a major factor affecting the strength and thus the service life of a pavement. A deficiency in pavement thickness would lead to early failure of the pavement that would mean a large overburden for the national treasury even for a medium sized inter-city road project. The need for an accurate and reliable method is not only for using it as quality assurance but also for cost calculations. The traditional method of coring is accurate at that test location but at the same time it is expensive and time consuming. The core locations may become focal points for further deterioration, and also the small number of core tests represent only a very small sample of the actual pavement.

Impact-echo technology is relatively new but it has been proposed that the method has been successfully used as a non-destructive technique on various concrete structures and especially on concrete pavement applications. The validity of this, together with the investigation of its important parameters affecting test results and its accuracy were investigated by experimentation. After extensive series of tests, it was concluded that impact-echo is not a black-box system where the exact results are given after inputting several initial values. Each test is unique and includes the talent of a skilled operator. Prior experience about tests on a particular type of structure is a major factor contributing to the time required and success of the tests. Therefore, the method is strongly user-dependent. While the use of frequency analysis has simplified the analysis phase and the results given as the computer output, still, experience is needed in interpreting the test results, setting up optimal testing conditions, recognizing reasonable recorded waveforms, and analyzing test results.

Several important parameters were investigated before initiating the tests for accuracy determination on concrete slab-like structures. The effect of impactor selection is perhaps the most important factor for the accuracy of the test results after the recording parameters of the data acquisition unit. Using an oversized impactor for a thin section or where there are internal problems, results in a direct loss of information by hiding the corresponding frequencies.

Interestingly, the distance between the transducer and the impact point also plays an important role for the accuracy of results. This distance should neither be too large, nor too small. The optimum range for impact distance was found to be 20%-50% of section thickness.

One of the drawbacks of using impact-echo for concrete pavement thickness determination is that the method is not suitable for use near the edges of the slab. This may not cause any problems if the slab segments are large. Nevertheless, it limits the area that can be investigated. It was found out that the distance to any side of a slab, including joints or any other geometrical irregularity, should be a minimum of 20-25 cm in order to exclude the effects of edges.

Besides the effect of edges, it was found out that the method is not very accurate when determining the depth and location of hollow pipes, which may be post-tensioned tendon ducts existing in a concrete pavement. There exists a strict limitation to the minimum depth that a pipe could be detected. Although this value is dependent on the wave speed inside the concrete section, an approximate value of 7-8 cm may be reasonable. If there is a pipe or some other problem at a distance smaller than the proposed one, then their chance of detection is very low.

The detection of planar voids was also investigated. Two slabs were placed on top of each other and the air void in between was tested. Results were very accurate in presenting the thickness of the layer above the planar void, and thus the depth of the void, but reliable results could not be obtained for the total thickness of the section.

During statistical analysis of the results, it was interesting to note that the errors fitted almost perfectly on to a normal distribution graph. Furthermore, the mean values were found to be within the allowed limits for the tests conducted. From the results of the experiments carried out, an average error of 0.6% was found for an impact-echo test result while testing a large number of points. However, an average error of 1.5% was found for a single test result.

After the tests for accuracy, it was decided to investigate the effects of the base layer on test results. A base course aggregate layer of 10 cm was formed in between the two slabs. The aggregates were well-graded and fully compacted. Recordings were collected at the predefined points and analyzed for accuracy. Then, the aggregates were mixed with some amount of cement to form a lean concrete in between the slabs. Results showed that the effect of base layer on test results was not very significant. Although the mean error was 2-3 times the mean error observed for that section, still, mean error percents were below 0.6% which means that different base layers does not greatly affect test results.

In light of the results, it was concluded that the impact-echo method may be used on plain concrete pavements fairly successfully. The results of the average error percents were found to be acceptable. Comparison of error percent results with the actual concrete pavements investigated at several sites enhanced the success and the need for such a method. However, the standard deviations still present problems that cannot be overlooked. They increase the expected range of values for a given confidence level which necessitate the need to collect a large number of data for it to be dependable.

CHAPTER 6

SUGGESTIONS FOR FURTHER RESEARCH

In this study, the main focus was on the usability of the impact-echo technique on concrete pavements made of plain concrete. Therefore samples used were made only of plain concrete. In order to further advance this study, tests could be conducted on slab specimens made of reinforced concrete.

In the first part of the experiments, some of the important parameters were investigated and some ranges were proposed. It is advised that any researcher who wishes to work with the impact-echo method should first fully understand the effects and limitations dictated by the several parameters discussed in this study.

For an extensive research program that would follow, it is believed that the design and use of a simple device for standardizing the height and velocity of the impacts created could be useful. A trigger system attached to a spring would be a good start for this purpose. This tool should be devised so as to include all set of impactors. Standardizing the impacts would be useful for eliminating a variable and so provide more objectivity for test results.

REFERENCES

1. Sansalone, M., and Streett, W. B., *Impact-Echo: Nondestructive Testing of Concrete and Masonry*, Bullbrier Press, Jersey Shore, PA, 1997.

2. Carino, N. J., "The Impact-Echo Method: An Overview", Proceedings of the 2001 Structures Congress & Exposition, May 21-23, Washington, D.C., 2001.

3. Schubert, F., Wiggenhauser, H., Lausch, R., "On the accuracy of thickness measurements in impact-echo testing of finite concrete specimens-numerical and experimental results", Ultrasonics, Elsevier B. V., 2004.

4. Willett, D. A., Mahboub, K. C., Rister, B., "Accuracy of Ground-Penetrating Radar for Pavement-Layer Thickness Analysis", Journal of Transportation Engineering, January 2006.

5. "Coring Rigid Pavement for Thickness", Kentucky Standard Method 64-309-03, February 2003.

6. Yoder, E. J., and Witczak, M. W., *Principles of Pavement Design*, 2. Edition, John Wiley and Sons, U.S., 1975.

7. Erdoğan, T. Y., *Beton*, METU Press, Ankara, May 2003.

8. Malhotra V.M., Carino N.J., *Handbook on Nondestructive Testing of Concrete*, CRC Press, ASTM International, 2004.

9. Maser, K., "NDE methods for quality assurance of new pavement thickness", The International Journal of Pavement Engineering, Vol. 7, No. 1, March 2006.

10. Aki, K., Richards P.G., *Quantitative Seismology*, University Science Books, Sausalito, CA, 2002.

11. Boyd, A. J., Ferraro, C. C., "Effect of Curing and Deterioration on Stress Wave Velocities in Concrete", Journal of Materials in Civil Engineering, March/April 2005.

12. Popovics, J. S., Song, W., Achenbach, J. D., Lee, J. H., Andre, R. F., "One-Sided Stress Wave Velocity Measurement In Concrete", Journal of Engineering Mechanics, December 1998.

13. Sansalone, M., Carino, N. J., "Impact-Echo: A Method For Flaw Detection in Concrete Using Transient Stress Waves," NBSIR 86-3452, National Bureau of Standards, September 1986.

14. Gibson, A., Popovics, J. S., "Determination of Pavement Thickness Using a Time Domain Approach", Review of Quantitative Nondestructive Evaluation, Vol. 21, American Institute of Physics, 2002.

15. Yaman, İ.Ö., İnci, G., Yeşiller, N., Aktan, H.M., "Ultrasonic Pulse Velocity in Concrete Using Direct and Indirect Transmission", ACI Materials Journal, Nov. 2001.

16. ASTM C 1383 - 04, "Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates using the Impact-Echo Method", ASTM International, West Conshohocken, Pennsylvania, June 2004.

17. "Bir Seçenek Daha Var: BETON YOLLAR", 2. Baskı, Türkiye Hazır Beton Birliği, İstanbul, Ekim 2003.

18. Erdoğan, S.T., Erdoğan, T.Y., "Bağlayıcı Malzemelerin ve Betonun Onbin Yıllık Tarihi", ODTÜ Yayıncılık, Nisan 2007, pp. 49-50.

19. "Ulaştırma Özel İhtisas Komisyonu Raporu", 8. Beş Yıllık Kalkınma Planı, Ankara, 2001.

20. Journal of Turkish Cement Manufacturers' Association, Vol:8, No:48, March-April 2004, pp. 3-12.

21. "Karayolu Ulaşımı Özel İhtisas Komisyonu Raporu", 9. Kalkınma Planı, Devlet Planlama Teşkilatı, May, 2006.

22. "2. Ulusal Demiryolu Kongresi Bildiriler Kitabı", Tisamat B.S., Ankara, 1997.

23. "Engineering and Design; Rigid Pavements for Roads, Streets, Walks and Open Storage Areas", Engineer Manual No. 1110-3-132, U.S. Army Corps of Engineers, April 1984.

24. "Pavement Preservation Technology in France, South Africa and Australia", FHWA International Scanning Program, U.S. Department of Transportation, October 2002.

25. "Summary Report - U.S. Tour of European Concrete Highways – Follow-up Tour of Germany and Austria", FHWA-SA-93-080, October 1993.

26. "FHWA Study of South African Pavement and Other Highway Technologies and Practices", U.S. Department of Transportation, May 1997.

27. "Geleceğin Yolu-Afyonkarahisar'daki Beton Yolun Hikayesi", Turkish Cement Manufacturers' Association, R&D Institute, Ankara, May 2005.

28. Szilard, R., Theory and Analysis of Plates, Classical and Numerical Methods, Civil Engineering and Engineering Mechanics Series, Prentice Hall, 1974, pg. 35, 433-442.

29. "Benefits of Concrete Highways", Cement Association of Canada, 2001.

30. Hu, M.T., Lin, Y., Cheng, C.C., "Method for Determining Internal P-Wave Speed and Thickness of Concrete Plates", ACI Materials Journal, Vol. 3, No. 5, September-October 2006.

31. Zaniewski, J. P., Effect of Pavement Surface Type on Fuel Consumption, Portland Cement Association, Skokie, Illinois, 1989.

32. Yiching, L., Chang C., Kuo, S. F., Liou, H. C., "A Simple Device for Detecting Impact Time in Impact-Echo Testing of Concrete", NDT&E International, Elsevier Ltd., 2004.

33. Kesner, K., "Cross-Sectional Modes In Impact-Echo Testing Of Concrete Structures", Journal of Structural Engineering, May 2001.

34. Gassman, S. L., "Nondestructive Assesment of damage in Concrete Bridge Decks", Journal of Performance of Constructed Facilities, ASCE, November 2004.

35. Afshin, Sadri, "Application of Impact-Echo Technique in Diagnoses and Repair of Stone Masonry Structures", NDT&E International, Elsevier Science Ltd., 2003.

36. "Improved Prediction Models for PCC Pavement Performance-Related Specifications, Volume 1: Final Report", Publication No. FHWA-RD-00-130, U.S. Department of Transportation, September 2000.

37. Paksoy, N.G., *Evaluation of Cement Mortars by Ultrasound*, M.S. Thesis, METU, Ankara, 2006.

38. Larsen, R. J., Marx, M. L., *An Introduction to Mathematical Statistics and Its Applications*, Pearson Prentice Hall International Edition, Upper Saddle River NJ, Fourth Edition, 2006.

39. Wetherill, G. B., *Elementary Statistical Methods*, Butler & Tanner Ltd., Great Britain, 1967.

40. Weatherburn, C. E., *A First Course in Mathematical Statistics*, Cambridge University Press, Great Britain, Second Edition, 1962.