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ESCOLA POLITÉCNICA

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**Assessment of the accuracy of an ultrasound imaging system for the
measurement of the thickness of pavements' concrete slabs**

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**Assessment of the accuracy of an ultrasound imaging system for the
measurement of the thickness of pavements' concrete slabs**

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RESUMO

SEIFFERT, Henrique Luiz de Lima. **Assessment of the accuracy of an ultrasound imaging system for the measurement of the thickness of pavements' concrete slabs**. 2019. 114p. Dissertação (Mestrado em Ciências) — Escola Politécnica, Universidade de São Paulo, São Paulo, 2019.

A espessura de placas de pavimentos de concreto simples com 150mm e 250mm de espessura foram medidas com um sistema de formação de imagem de ultrassom e então com sondagem rotativa. As medidas de espessura determinadas com sondagem foram consideradas a situação fática. A precisão das espessuras determinadas por imagem de ultrassom foram aferidas em termos de erros absolutos, erros relativos e o R^2 . A significância das mudanças nas medidas de precisão com mudanças na faixa de espessura das placas e na frequência central dos pulsos foram investigadas. As espessuras determinadas por imagens de ultrassom eram, em média, imprecisas medidas da espessura das placas de concreto. A dispersão nos erros absolutos e erros relativos para toda frequência central era, contudo, significativa o suficiente para que a correção daquelas medidas fosse incerta. Ainda, os erros absolutos e relativos eram, em média, menores com aumentos na frequência central. Os erros absolutos das medidas de espessura não-destrutiva das placas menos espessas eram, em média, significativamente menores que aqueles das placas mais espessas. Os erros absolutos das medidas não-destrutivas das placas menos espessas não se alteraram com mudanças na frequência central. Por outro lado, os erros absolutos das medidas não-destrutivas das placas mais espessas eram, em média, menores com aumentos na frequência central. A correção das medidas de espessura não-destrutivas considerando a faixa de espessura seria, contudo, igualmente incerta, pois os erros absolutos em questão também apresentaram alta dispersão. Os resultados encontrados para os erros relativos em função da faixa de espessura foram condizentes com isso. Portanto, o sistema de imagem de ultrassom mediu as espessuras das placas com 150mm e 250mm de espessura com diferente precisão. Os efeitos das mudanças na frequência central também forma diferentes para as placas com 150mm e 250mm de espessura.

Palavras-chave: Imagem por ultrassom. Ensaios não destrutivos. Pavimentos rígidos.

ABSTRACT

SEIFFERT, Henrique Luiz de Lima. **Assessment of the accuracy of an ultrasound imaging system for the measurement of the thickness of pavements' concrete slabs**. 2019. 114p. Thesis (Master of Sciences) — Escola Politécnica, University of São Paulo, São Paulo, 2019.

The thickness of 150mm and 250mm thick slabs of plain concrete pavements was measured with an ultrasound imaging system and then with coring. The thickness measures determined with coring were taken as the gold standard. The accuracy of the thickness measures determined with the ultrasound imaging system were assessed in terms of absolute errors, relative errors, and the R-Squared. The significance of the changes in the accuracy measures with changes in the thickness range of the slabs and in the central frequency of the transmitted pulses was investigated. The thickness measures determined with the ultrasound imaging system for every central frequency were, on average, very inaccurate measures of the thickness of the concrete slabs. At the same time, the dispersion in the absolute and the relative errors for every central frequency was of such significance that the rectification of those measures with the mean errors would be uncertain. Furthermore, the absolute and the relative errors were, on average, smaller with increasing central frequency when the thickness range was disregarded. At the same time, the absolute errors of the thickness measures determined on 150mm slabs were, on average, significantly smaller, than the ones determined on the 250mm slabs. The absolute errors of the thickness measures determined on 150mm slabs were also not dependent on the central frequency. However, the absolute errors of the thickness measures determined on 250mm slabs were dependent on the central frequency, namely, they were, on average, smaller with increasing central frequency. The rectification of the measures on 150mm and 250mm slabs with their respective mean absolute errors would be uncertain too, because of the considerable degree of dispersion in those errors. The results for the relative errors was consistent with the above. The thickness of the 150mm and the 250mm thick slabs was measured by the ultrasound imaging system with different accuracy then. The implications of the changes in the central frequency was also different for the 150mm and the 250mm thick slabs.

Keywords: Ultrasound imaging. Nondestructive evaluation. Concrete pavements.

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LIST OF SYMBOLS

v_c	Central frequency of the transmitted pulse
$g(t)$	Time-domain signal
$f(x,y)$	Ultrasound image
t_d	Delay of the signal acquisition system
c	Pulse velocity
h^*	Vertical position of the brightest pixel of an ultrasound image
h	Raw evaluated thickness measure
h_e	Evaluated thickness measure
h_s	Standard thickness measure
e_a	Absolute error of the evaluated thickness measure
e_r	Relative error of the evaluated thickness measure

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1 INTRODUCTION

The accurate measurement of the (as-built) thickness of the surface layer (concrete slabs) of concrete pavements is crucial for their structural evaluation. Deficiencies in the thickness of a pavement's concrete slabs increase the slabs' maximum tensile stress and, thus, contribute to the development of cracks in the slabs and in turn to losses in the pavement's structural and functional integrity (BALBO, 2009).

The standard method for the measurement of the thickness of a pavement's concrete slabs is coring. Coring is, though, expensive, laborious, and damaging to the slabs. An alternative to coring is the use of nondestructive methods. Nondestructive methods are, in comparison to coring, less expensive in the long term, quicker, and, obviously, non-damaging to the slabs (BALBO, 2015; MASER et al., 2006).

Among the nondestructive methods available for that purpose,¹ ultrasound imaging, particularly ultrasound imaging with the Synthetic Aperture Focusing Technique (SAFT), is one of the most accurate (EDWARDS; BELL, 2016). The accuracy of ultrasound imaging for that purpose has been assessed by Bittner et al. (2018), Edwards and Bell (2016), and Hoegh et al. (2011). Still, uncertainties on the accuracy of ultrasound imaging for that purpose remain.

Firstly, the aforementioned works reported that ultrasound imaging is fairly inaccurate for the measurement of the thickness of concrete elements, but they failed to report the variability in their accuracy measures. If the errors in the nondestructive thickness measures have significantly low variability, those measures could be rectified with certainty independently of the degree of their inaccuracy. It is uncertain, therefore, if such rectification is possible.

Secondly, the aforementioned works reported accuracy measures with no regard for the implications of either the range of the thickness of the concrete elements or the central frequency of the transmitted pulses in them. Yet, both factors could affect the accuracy of ultrasound imaging for that task, since the characteristics of the sensed pulses are affected by them (SCHICKERT et al., 2003).

In this work, the accuracy of an ultrasound imaging system for the measurement of the thickness of the surface layer of concrete pavements is assessed. The significance of changes in

¹ For a list of the nondestructive methods available for that purpose, see McCann and Forde (2001) or Edwards and Bell (2016).

its accuracy in consequence to changes in the central frequency and the thickness range are also assessed.

The ultrasound imaging system evaluated in this work comprised the MIRA device and an implementation of the SAFT. Similar systems were used in the aforementioned works and have been used by the transportation engineering industry in the last years.

Similar systems have also been used for the nondestructive evaluation of the characteristics of the rebars of, and defects in, concrete elements (CHOI; POPOVICS, 2015; HOEGH et al., 2011; HOEGH et al., 2013; SHOKOUHI et al., 2014). The relatively wide range of applications of such system, it should be mentioned, is one of the reasons why it has been selected for evaluation in this work.

1.1 OBJECTIVES:

The general objective of this work is to assess the accuracy of an ultrasound imaging system for the measurement of the surface layer of concrete pavements. The specific objectives of this work are then:

- To measure the thickness of the surface layer of concrete pavements with the ultrasound imaging system and then with the standard method for that coring;
- To assess the accuracy of the thickness measures that were determined with the ultrasound imaging system by objectively comparing them to the standard ones;
- To evaluate if changes in the transmitted pulses' central frequency or in the slabs' thickness range affected the accuracy of the ultrasound imaging system.

2 LITERATURE REVIEW

In this chapter, it is reviewed the implications of the inhomogeneous composition of concrete for the ultrasound imaging of concrete elements and then the fundamentals and the relevant applications of the SAFT for the structural evaluation of concrete elements.

2.1 BACKGROUND INFORMATION

First of all, it is presented in this section the background information for this chapter, namely the fundamentals of the phenomena of reflection, scattering, and attenuation of ultrasound and the fundamentals of the technology of ultrasound transducers.

2.1.1 Reflection

Reflection takes place when ultrasound impinges on the boundary between two media of different characteristic impedance.² The characteristic impedance of a medium, Z , is the product of the medium's density, ρ , and the speed of sound in the medium, c (BLITZ, 1967).

In Figure 2.1, the reflection of the impingent wave, I , gives rise to only a reflected wave, R , and a transmitted wave, T . So, it was assumed therein that the media were homogeneous, isotropic, and semi-infinite; that the boundary was perfectly smooth; and the angle of incidence, α , was smaller than the critical angle (CARLIN, 1960; KINSLER, 2000).

Figure 2.1 — Diagram of the reflection of ultrasound at a boundary.

Source: Adapted from Kinsler (2000).

² For the fundamentals of the wave motion and wave propagation in solids, see Kinsler (2000).

R is deflected towards the first medium and it propagates therein with the c that is characteristics of that medium, c_1 (Figure 2.1). The pressure amplitude of R , A_R , is given by Equation 2.1, where A_I is the pressure amplitude of I (BLITZ, 1967).

$$A_R = A_I \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right) \quad (2.1)$$

That is, A_R is proportional to the mismatch of characteristic impedance at the boundary (Equation 2.1) (BLITZ, 1967).

T is deflected by β towards the second medium and it propagates therein with the c that is characteristic of that medium, c_2 (Figure 2.1). The pressure amplitude of T is $A_T = A_I - A_R$. β is given by Snell's Law: $\sin \alpha / \sin \beta = c_1 / c_2$ (BLITZ, 1967).

Both R and T might impinge on further boundaries in their propagation paths and be reflected at them, and so forth (BLITZ, 1967).

2.1.2 Scattering

The solids of interest in engineering generally contain inhomogeneities whose dimensions are smaller than, or similar to, the wavelengths³ of the ultrasound and whose acoustical impedances are different to the acoustical impedances of the solid's matrix (KRAUTKRAMER; KRAUTKRAMER, 1990).

At the time ultrasound impinges on such inhomogeneities, several "reflections" take place at the same time, and multiple "reflected" and "transmitted" waves are scattered towards the solid's matrix. The scattered waves then impinge on further inhomogeneities and are themselves scattered at them, and so forth (KRAUTKRAMER; KRAUTKRAMER, 1990).

The waves that are scattered to the same direction of the impingent waves are termed forward-scattered waves. The waves that are scattered to the opposite direction are termed back-scattered waves (AGGELIS, 2013).

³ The wavelength, λ , of a plane wave is $\lambda = c/v$, where v is the wave's frequency (BLITZ, 1967).

2.1.3 Attenuation

The modulation of the pressure amplitude of a plane wave in consequence of attenuation is modelled by Equation 2.2, where A_0 is the wave's pressure amplitude at the origin, x is its position, and γ is the medium's coefficient of attenuation (BLITZ, 1967).

$$A(x) = A_0 e^{-\gamma x} \quad (2.2)$$

The attenuative characteristics of a solid are assessed experimentally by means of the estimate of its γ . To this purpose, the amplitude of a pulse is measured before and after it propagates through a path of length x in the solid and then used to solve Equation 2.2 for γ (KUTTRUFF, 1991).

The measured attenuation is, thus, the sum of the effects of several mechanism of attenuation, principally reflection, scattering, and absorption. Reflection and scattering result in attenuation because they result in the deviation of mechanical energy from the measured pulse. Absorption results in attenuation because it results in the conversion of the pulse's mechanical energy into heat (BLITZ, 1967; KUTTRUFF, 1991).

2.1.4 Ultrasound Transducers

In Figure 2.2, the possible arrangements of ultrasound transducers for the inspection of solids are presented. In the pulse-echo configuration, the same transducer is used for transmission and reception (Figure 2.2a). In the pitch-catch configuration, one transducer is used for transmission and another is placed alongside for reception (Figure 2.2b). In the through-transmission configuration, the transducer used for reception is placed on the opposite face of the solid (Figure 2.2c) (KUTTRUFF, 1991).

For the transmission of ultrasound into the solid, first electrical pulses are sent by the data acquisition system to the ultrasound transducer in transmission mode so that one of the dimensions of its piezoelectric element oscillates in consequence to the piezoelectric effect (KUTTRUFF, 1991). The oscillation of the piezoelectric element then excites the surface of the solid that the transducer is in contact with, resulting in the transmission of mechanical waves into the solid (KRAUTKRAMER; KRAUTRAMER, 1990).

Figure 2.2 — Diagram of the arrangements of ultrasound transducers in the (a) pulse-echo, (b) pitch-catch, and (c) through-transmission configuration and of the corresponding wavepaths in the solid.

Source: Adapted from Kuttruff (1991).

The transmitted ultrasound is eventually reflected, scattered, and attenuated in the solid. In time, either the reflected and the back-scattered or the transmitted and the forward-scattered waves impinge on the transducer in reception mode (Figure 2.2).

After that, electrical charges of magnitude proportional to the pressure amplitude of the impinging waves are produced in the ultrasound transducer in reception mode in consequence to the piezoelectric effect (SHUNG; ZIPPARO, 1996). The electrical charges are then converted in electrical pulses, which are in turn processed, sampled, quantized, and then digitized as a signal (KUTTRUFF, 1991).

In Figure 2.3, it is illustrated the pressure field of the transmitted ultrasound to show that the divergence angle, θ , represents the spread of the pressure field in the far field. The divergence angle is proportional to the ratio of wavelength to transducer's diameter (KUTTRUFF, 1991).

Figure 2.3 — Diagram of the pressure field of an ultrasound transducer.

Source: Adapted from Shung and Zipparo (1996).

2.2 IMPLICATIONS OF THE INHOMOGENEOUS COMPOSITION OF CONCRETE FOR THE ULTRASOUND IMAGING OF CONCRETE ELEMENTS

In this section, it is reviewed the characteristics of the phenomena of attenuation and scattering in cementitious materials and then their implications for the ultrasound imaging of concrete elements.

2.2.1 Attenuation and Scattering in Cementitious Materials

The characteristics of the phenomena of attenuation and scattering in the cement paste, mortar, and concrete are presented in this order next. The effects of the increasing compositeness of cementitious materials in the emergence and characteristics of the phenomena in question are thus presented. The complex characteristics of the phenomena in the concrete are then presented more simply and clearly.

The cement paste is the product of the mixture of the cement with water. It comprises the well-known hydration products and tiny air voids (MEHTA; MONTEIRO, 2006).

Punurai et al. (2006) investigated the attenuative characteristics of the cement paste. Namely, they assessed the coefficient of attenuation of the cement paste as a function of frequency for both shear and longitudinal waves.⁴

Punurai et al. (2006) demonstrated that the rates at which both shear and longitudinal waves are attenuated in the cement paste are proportional to the frequency (Figure 2.4) and, therefore, that the predominant mechanism of attenuation in the cement paste is absorption by hysteresis.

For this reason, the cement paste is assumed to be homogeneous and viscoelastic from the standpoint of ultrasonics (JACOBS; OWINO, 2000; SHIOTANI; AGGELIS, 2009; TREIBER et al., 2010).

⁴ In the bibliography of this section, the coefficient of attenuation was assessed using the through-transmission configuration. For the determination of the coefficient of attenuation as a function of the frequency, the amplitude of the pulses was measured as a function of frequency with the Fourier Transform (AGGELIS; PHILIPPIDS, 2004; PUNURAI et al., 2006). For information on the Fourier Transform, see Brigham (1974).

Figure 2.4 — Coefficient of attenuation of the cement paste as a function of frequency.

Note: $1\text{Np} \approx 8.686\text{dB}$.

Source: Punurai et al. (2006).

Punurai et al. (2006) demonstrated, too, that the coefficient of attenuation of the cement paste is higher for shear waves than for longitudinal waves for every frequency (Figure 2.4). The reason for this is that the shear waves propagate with smaller wavelengths (KUTTRUFF, 1991), and the coefficient of attenuation for absorption is proportional to the inverse of the wavelength (HARTMANN; JARZYŃKI, 1972).

Aggregates are granular materials added to the mortar and the concrete for strengthening (MEHTA; MONTEIRO, 2006). They are classified as either fine aggregates, if they are smaller than 4.75mm, or coarse aggregates (ABNT, 2011).

The product of the mixture of the cement paste with the fine aggregates is the mortar. The product of the mixture of the cement paste with both fine and coarse aggregates is the concrete. The cement paste binds the aggregates in both mortar and concrete, and the aggregates are distributed at random in both of them (MEHTA; MONTEIRO, 2006).

Therefore, the mortar and the concrete are modelled in ultrasonics as solids with a homogeneous matrix, namely the cement paste, and randomly-distributed inhomogeneities, namely the aggregates (JACOBS; OWINO, 2000; TREIBER et al., 2010). The attenuation in the mortar and the concrete is, thus, the undistinguishable sum of the effects of the absorption at the cement paste and of the scattering at the aggregates (BLITZ, 1967).

Aggelis and Philippidis (2004) investigated the attenuative characteristics of the mortar.

Firstly, they assessed and then compared the coefficient of attenuation of the cement paste and the mortar as function of the frequency. They demonstrated thus the emergence of, then the predominance of, scattering at the sand grains in the attenuative characteristics of the mortar (AGGELIS; PHILIPPIDIS, 2004). This is seen in Figure 2.5 if considered that, as previously mentioned, the response of the cement paste underlies the response of the mortar.

Figure 2.5 — Coefficients of attenuation of the cement paste and the mortar as function of the frequency.

Source: Adapted from Aggelis and Philippidis (2004).

They also demonstrated thus the rapid intensification of scattering as the wavelengths approach the dimensions of the inhomogeneities (BLITZ, 1967), the reason why the coefficient of attenuation of the mortar increases rapidly with increasing frequency in Figure 2.5 (AGGELIS; PHILIPPIDIS, 2004).

Secondly, they investigated the effects of the size of the sand grains in the attenuative characteristics of the mortar. They demonstrated thus the intensification of scattering with increasing cross-section of the inhomogeneities (KUTTRUFF, 1991), the reason why the coefficient of attenuation of the mortar produced with coarse sand was higher than that of the mortar produced with fine sand, particularly at the higher frequencies (Figure 2.6) (AGGELIS; PHILIPPIDIS, 2004).

Figure 2.6 — Coefficient of attenuation of mortar mixes produced with sand particles of varying size as function of the frequency.

Source: Adapted from Aggelis and Philippidis (2004).

Thirdly, they compared the spectra of the same pulse after it was through-transmitted in water, the cement paste, and mortar. After propagating through water and the cement paste, the pulse was not deformed. That is, the corresponding spectra are similar to the spectrum of the excitation. However, the pulse was attenuated to a great degree after propagating in the cement paste (Figure 2.7) (AGGELIS; PHILIPPIDIS, 2004).

Figure 2.7 — Spectra of the pulses through-transmitted in water (inset), the cement paste, and mortar mixes of varying sand content.

Source: Adapted from Aggelis and Philippidis (2004).

In contrast, the pulse was both deformed and attenuated to a great degree after propagating through the mortar mixes. In regard to the deformation, the central frequency of the pulse was reduced to roughly 400kHz from 500kHz after it propagated through the mortar with the lowest sand content. Furthermore, the whole spectrum of the pulse was shifted towards lower frequencies (Figure 2.7) (AGGELIS; PHILIPPIDIS, 2004).

The central frequency of the pulses that propagated through the mortar mixes with higher sand contents were deformed to a greater degree. Their central frequencies were reduced further to roughly 200kHz (Figure 2.7) (AGGELIS; PHILIPPIDIS, 2004).

This is the so-called frequency downshifting of a pulse and it presumably is another consequence of scattering (SHIOTANI; AGGELIS, 2009).⁵

Concrete elements also have small air voids and microcracks in their matrix due to, respectively, implications of the mixing stage (MEHTA; MONTEIRO, 2004) and the loading imposed on them during hardening and service life (BALBO, 2009). The air voids and the microcracks are additional scatterers in the concrete.

Figure 2.8 — Effects of the addition of vinyl inclusions mimicking damage to mortar in the energy-related parameters (left) and central frequency of the transmitted pulses (right).

Source: Adapted from Shiotani and Aggelis (2009).

⁵ Frequency downshifting is reported in several works in the bibliography (AGGELIS; PHILIPPIDIS, 2004; GAYDECKI et al., 1992; SCHICKERT, 2002; SCHICKERT et al., 2003; SELLECK et al., 1998) but none of them presented any information on the physical mechanisms behind it.

Shiotani and Aggelis (2009) investigated the effects of an increasing content of microcracks in the propagation of ultrasound pulses in concrete by adding vinyl inclusions of 15x15x0.5mm to mortar specimens to mimic damage in the concrete's matrix. They demonstrated thus that the “microcracks” intensified scattering, since the degree of attenuation and of frequency downshifting increased with increasing “damage content” (Figure 2.8). The central frequency at transmission was 300kHz (SHIOTANI; AGGELIS, 2009).

Selleck et al. (1998) demonstrated that the scattering at the aggregates and air voids of sound concrete results in the downshift of the central frequency of a through-transmitted pulse to about 250kHz from 500kHz. They demonstrated, too, that the additional scattering at microcracks due to simulation of freeze-thaw cycles results in further downshift of the through-transmitted pulses to about 175kHz (Figure 2.9).

Figure 2.9 — Comparison of the spectra of pulses transmitted through damaged and undamaged concrete elements.

Source: Adapted from Selleck et al. (1998).

The number of inhomogeneities interacting with an ultrasound pulse is not increased only with increasing damage content or aggregate content but also with increasing length of the wavepaths in the concrete element, that is, by increasing the dimensions of the concrete element.

Schickert et al. (2003) demonstrated the effects of this in the frequency downshift of a pulse, as seen in Figure 2.10.

Figure 2.10 — Effects of the length of concrete elements in the spectrum of pulses through-transmitted through them.

Source: Adapted from Schickert et al. (2003).

In conclusion, it was shown in this section that the characteristics of the phenomena of attenuation and scattering in cementitious materials depend on their constitution, porosity, structural condition, and dimensions as well as on the characteristics of the transmitted pulse. It was shown, too, that scattering is the predominant mechanism of attenuation in the mortar and concrete and that the frequency downshift is also present in both of them.

2.2.2 Implications of the Phenomena of Attenuation and Scattering for the Ultrasound Imaging of Concrete Elements

In this section, it is presented the implications of the phenomena of attenuation and scattering in the penetration depth, the vertical and lateral resolution, and the signal-to-noise ratio of ultrasound imaging systems aimed for the structural evaluation of concrete elements.⁶

The penetration depth is the depth in the solid of interest for which the ultrasound reflected a boundary thereat is totally attenuated on its way to the transducer in reception mode. Hence, there is no information on such boundary in the signals. The penetration depth should, thus, be larger than the thickness of the solid of interest.

⁶ According to McCann and Forde (2001), the penetration depth, the vertical and lateral resolution, and the signal-to-noise ratio are key factors in the evaluation of nondestructive systems for the structural evaluation of concrete elements.

The penetration depth in concrete elements is adequate for most structural evaluation purposes only if low-frequency pulses are used (SCHICKERT et al., 2003). The reason for this is the rapid increase of the coefficient of attenuation of cementitious materials with increasing frequency (Section 2.2.2). For example, the penetration depth of longitudinal waves in concrete elements is increased to 500mm from 50mm if the frequency is reduced to 50kHz from 200kHz (SCHICKERT, 2002).

The use of large wavelengths for the ultrasound imaging of concrete elements is, then, inevitable (SCHICKERT et al., 2003). For example, the wavelength of longitudinal waves at 50kHz in concrete is on the order of 90mm (SCHICKERT, 2002). Additionally, transducers of small diameters are preferred for the inspection of concrete elements. The reason for this is the difficulty in coupling large transducers to the rough surface of concrete elements. Consequently, the beams transmitted to concrete elements generally have large divergence angles (SCHICKERT et al., 2003).

The ultrasound imaging systems aimed for the structural evaluation of concrete elements generally have, thus, poor lateral resolution, since the lateral resolution is proportional to the width of the transmitted beam in the far field (KREMKAU; TAYLOR, 1986).

The poor lateral resolution hinders the capability of the imaging system in resolving two objects next to each other in the lateral direction (BOURNE, 2010). The reason for this is that two adjoining objects might be insonified at close time by the same beam and, thus, the waves reflected at them might interfere constructively or destructively in the propagation of each other. That is, the components of the independently reflected waves might be partially superimposed in the signals (SCHMITZ et al., 2000). In the images, the two objects would, then, be represented as one of new shape, preventing their recognition (KREMKARU; TAYLOR, 1986) and the assessment of their dimensions (BUYUKOZTURK, 1998).

The large divergence angle also hinders the capability of an imaging system in assessing the lateral position of objects. The reason for this is that the presence of an object instead of being registered only in the signal acquired at the point it is might be registered in the signals acquired at a number of neighbouring points, too (SCHICKERT et al., 2003).

The vertical resolution of an ultrasound imaging system is the measure of the capability of the system in resolving two objects that are next to each other in the vertical direction (BOURNE, 2010). It is in the order of half the pulse length (KREMKAU; TAYLOR, 1986), that is, in the order of $(n\lambda)/2$, where n is the number of cycles in the transmitted wave train. The vertical lateral resolution is improved, thus, with the use of shorter pulses, that is, pulses with high-frequency content (KUTTRUFF, 1991). The use of low-frequency pulses to meet the generally

required penetration depth affects, then, the vertical resolution of imaging systems (SCHICKERT et al., 2003).

The vertical and lateral resolution are both deteriorated further by the effects of the frequency downshifting as the pulse propagates in concrete elements (SCHICKERT et al., 2003). Consequently, the capability of an imaging system in resolving and localizing objects that are deep in the concrete elements is hindered further by the phenomenon.

The ultrasound reflected at deep objects is also attenuated to a great degree by the concrete before impinging on the transducer. The recognition of such reflection in the signals and then in the images is, then, hindered further by the noise, particularly the structural noise (SCHICKERT et al., 2003).

The ultrasound is continuously scattered at the inhomogeneities of the concrete. The back-scattered waves are, then, continuously sensed at the transducer. Hence, there are components throughout the entire signal corresponding to the back-scattered waves, which are termed structural noise. The structural noise increases with the same factors that intensify the scattering in cementitious materials, namely aggregate size, aggregate content, damage content, and frequency (Section 2.2.1) (SCHICKERT et al., 2003).

In conclusion, it was shown in this section that the use of high-frequency pulses in concrete is prevented by the implications of the use of such frequencies in the penetration depth and signal-to-noise ratio of ultrasound imaging systems. It was shown, too, that the use of low-frequency pulses to tackle those issues result in issues with the vertical and lateral resolution of the ultrasound imaging systems.

Furthermore, it was shown in this section that this is consequence of the characteristics of the phenomena of attenuation and scattering of ultrasound in cementitious materials. It was shown in the previous section that the aforementioned phenomena are characteristic of the response of a highly inhomogeneous material such as concrete. Consequently, the aforementioned issues are characteristic of the ultrasound imaging of concrete elements.

2.3 ULTRASOUND IMAGING BY MEANS OF THE SYNTHETIC APERTURE FOCUSING TECHNIQUE

In this section, it is reviewed the fundamentals of the SAFT and then its applications for the ultrasound imaging of concrete elements aiming the measurement of the thickness of the concrete elements.

2.3.1 The Synthetic Aperture Focusing Technique

The SAFT is presented next as an ultrasound imaging algorithm that comprises the processes of mapping and summation (GUAN et al., 2015).

It is assumed next the use of the same data acquisition technology that is used by the ultrasound imaging system under evaluation. The data acquisition system comprises, then, an ultrasound array of 1-by- M transducers.⁷ The array is operated in the pitch-catch configuration and in such a manner that while the transducer of index $m = 1, \dots, M - 1$ is in transmission, the $M - m$ transducers to its right are in reception (Figure 2.12).

Figure 2.12 — Diagram of the mode of operation of ultrasound arrays assumed in this work.

Source: Author.

The entire image plane is, then, insonified by $M - 1$ beams of width smaller than the width of the image plane (Figure 2.12). In total, $N = \sum(M - m)$ signals are acquired thus. Each signal, $g_i(t)$, $i = 1, \dots, N$, has a known pair of transducers associated with it, one in transmission, T_i , and another in reception, R_i .

In the mapping process, an ultrasound image $f_i(x, y)$ is generated for each signal by means of the assignment of the amplitude of the signal at t^* , $g_i(t^*)$, to the corresponding pixel $P(x, y)$ of $f_i(x, y)$ with Equations 2.3 (JENSEN et al., 2006) and 2.4 (HOEGH; KHAZANOVICH, 2015).

$$f_i(x, y) = g_i(t^*) \quad (2.3)$$

$$t^*(x, y) = t_d + \frac{1}{c} \left(\sqrt{(x_{T_i} - x)^2 + (y_{T_i} - y)^2} + \sqrt{(x_{R_i} - x)^2 + (y_{R_i} - y)^2} \right) \quad (2.4)$$

⁷ For information on the technology of ultrasound arrays, see Drinkwater and Wilcox (2006).

In Equation 2.4, t^* is the system's delay, t_d , plus the interval of the time the wave propagating at the velocity c would take to traverse the shortest path between $T_i(x_{T_i}, y_{T_i})$, $P(x, y)$, and $R_i(x_{R_i}, y_{R_i})$ (Figure 2.13) (CHOI et al., 2016).

Figure 2.13 — Geometry of the system for the SAFT algorithm.

Source: Author.

That is, in the mapping process it was assumed that the entire image plane was insonified by every beam (SPIES et al., 2012) and that reflection occurred everywhere in the image plane (SCHICKERT et al., 2003). The components of the signals were then “mapped” (GUAN et al., 2015), “migrated” (UPDAHAYAY, 2004), or “focused” (JENSEN et al., 2006) to the pixel representing the region of the image plane where reflection would have occurred if the waves which originated those components were reflected waves.

In the summation process, the images $f_i(x, y)$, ..., $f_N(x, y)$ are summed, after they are weighted by their weighting function, $w_i(x, y)$, to obtain the “final” ultrasound image $f(x, y)$ (Equation 2.5) (JENSEN et al., 2006).

$$f(x, y) = \sum_{i=1}^N f_i(x, y) w_i(x, y) \quad (2.5)$$

The weighting function takes into consideration the region of the image plane that was actually insonified by each transmitted beam (SPIES et al., 2012). The weighting function proposed for the data acquisition system assumed in this section is presented in Equation 2.6 (HOEGH; KHAZANOVICH, 2015).

$$w_i(x, y) = \frac{y - y_{T_i}}{\sqrt{(x - x_{T_i})^2 + (y - y_{T_i})^2}} \frac{y - y_{R_i}}{\sqrt{(x - x_{R_i})^2 + (y - y_{R_i})^2}} \quad (2.6)$$

That is, in the summation process the components of the signals that were mapped to the same region are superimposed (SPIES et al., 2012). If reflection took place in a region, the components of the signals mapped to the region will be in phase (PRAGER et al., 2013) and, thus, their superimposition should result in constructive interference between them (SPIES; RIEDER, 2010). If reflection did not take place in a region, the components of the signals mapped to that region will not be in phase and, thus, their superimposition should result in destructive interference between them (DOCTOR et al., 1986).

The summation process enhances then the regions of $f(x, y)$ corresponding to where there were reflecting surfaces while reducing the background noise, including the structural noise (SCHICKERT et al., 2003). Furthermore, since the summation process is carried out along the whole image plane, the best achievable resolution is achieved everywhere in the image plane (JENSEN et al., 2006).

In other words, the SAFT enhances the signal-to-noise ratio (DOCTOR et al., 1986) and the lateral resolution (SCHMITZ et al., 2000) of ultrasound images. This is the main reason why the SAFT is preferred for the ultrasound imaging of concrete elements (SCHICKERT et al., 2003) (Section 2.2.2).

Some consideration on the implementation and limitations of the SAFT are presented next.

The full waveform of every $g_i(t)$, that is, the full time-domain signal, must be used for imaging then, since the phase information is used in the summation process (KRAMER, 1989).

The accuracy of the information in the $f(x, y)$ is a function of the accuracy of a number of variables, principally R_i , T_i , c , and t_d (SCHICKERT et al., 2003).

In pitch-catch systems, the estimate of c is generally determined with the indirect transmission method. That is, it is determined from the regression line fitted to the distance between each pair of T_i and R_i in relation to the time-of-flight of the surface wave between T_i and R_i (BITTNER et al., 2018; STERGIPOLOU et al., 2007).⁸

⁸ For information on surface waves, see Krautkrämer and Krautkrämer (1990) and Gulyaev (1998).

The estimate of c determined therewith, and used for imaging, is, then, representative of the c in the superficial concrete only. It is, thus, 5-20% different to the c which would be determined with the through-transmission method (KARAIKOS et al., 2015). The reasons for this are the differences in the macrostructure, e.g. porosity and damage content, and characteristics, e.g. moisture content, of the superficial concrete in relation to the bulk concrete (POPOVICS et al., 1998; QIXIA; BUNGEY, 1996; STERGIPOLOU et al., 2007; YAMAN et al., 2001).

The SAFT assumes that the c is constant throughout the imaged volume, which is not true if the imaged volume is reinforced concrete. Consequently, the shape and size of rebars could be distorted because of the assumptions that their c is the same as the c of concrete (ORTIZ et al., 2012).

The SAFT assumes, too, that only bulk waves are sensed. Consequently, artefacts arise in consequence of the sensing of surface waves and their computation as bulk waves (BITTNER; POPOVICS, 2017; SHOKOUHI et al., 2014).

Furthermore, the SAFT does not tackle the strong attenuation of the signals and, hence, its artefacts (BITTNER; POPOVICS, 2017; ORTIZ et al., 2012) nor the effects of the frequency downshifting.

2.3.2 Applications of Ultrasound Imaging by means of the SAFT for the Measurement of the Thickness of Concrete Elements

In this section, it is reviewed the applications of ultrasound imaging by means of the SAFT for the measurement of the thickness of concrete elements.

Hoegh et al. (2011) assessed the accuracy of an ultrasound imaging system for the measurement of the surface layer of Continuously Reinforced Concrete Pavements (CRCP). Their ultrasound imaging system comprised a model of the MIRA and an undetailed implementation of the SAFT. The transmitted pulses comprised shear-horizontal waves, and their v_c was 55kHz. Furthermore, the thickness measures were determined from the images by taking the vertical position of the backwall's brightest pixel as the thickness (HOEGH et al., 2011).

Hoegh et al. (2011) measured the thickness of the slabs of a CRCP at seven points with their ultrasound imaging system and then with coring. The thickness of the slabs varied from roughly 280mm up to 380mm. The only measure of accuracy they reported was a " R^2 " of 0.967

between the nondestructive thickness measures and the destructive thickness measures.⁹ Regarding this result, they only stated that there was thus “good agreement” between the data sets (HOEGH et al., 2011).

They did not analyse their data further. They did not present any information on the age or structural condition of the CRCP either.

Edwards and Bell (2016) assessed the accuracy of an ultrasound imaging system for the measurement of plain slabs of concrete pavements. Their ultrasound imaging system comprised an “ultrasonic tomography” (sic) device and an undetailed implementation of the SAFT. The device was an ultrasound array containing dry-point contact transducers and forty-five transmitter-receiver pairs. The v_c was 50kHz (EDWARDS; BELL, 2016).

Edwards and Bell (2016) measures the thickness of plain concrete slabs at nineteen points on several concrete pavement sections with their ultrasound imaging system and then coring. They acquired three samples of the thickness at each point with their imaging system. The concrete pavements’ age varied from less than four months up to nine months old. The slabs’ thickness as measured by the cores varied from 192mm up to 634mm. The base layer of every slab was granular (EDWARDS; BELL, 2016).

Edwards and Bell (2016) determined three accuracy measures: the absolute error, e_a , the relative error, e_r , and the square of the coefficient of correlation between the nondestructive and the destructive data, R^2 . The e_a was the absolute difference between each corresponding pair of nondestructive and destructive thickness measures. The e_r was the ratio of the e_a to the destructive thickness measure (EDWARDS; BELL, 2016).

Edwards and Bell (2016) reported a mean e_a of 10.90mm., a mean e_r of 4.28%, and a R^2 of 0.99.

They did not present the standard deviation of the mean errors. The mean e_a and the mean e_r were determined from the full sample, that is, considering all point together despite the large difference between the thickness. Furthermore, they did not present how they determined the thickness of the slabs from the information in the images.

Bittner et al. (2018) assessed the accuracy of an ultrasound imaging system for the measurement of the thickness of concrete slabs in laboratory conditions. Their ultrasound

⁹ Hoegh et al. (2011) did not state what their R^2 stands for.

imaging system comprised a model of the MIRA and an undetailed implementation of the SAFT. Nonetheless, they mentioned that they used the estimate of c that was determined by the MIRA with the indirect transmission method and also that they used the vertical position of the brightest pixel of the backwall as the thickness (BITTNER et al., 2018). The v_c was not reported.

Bittner et al. (2018) measured the thickness of 228mm-thick plain concrete slabs at 36 points. They reported the error of the nondestructive thickness measures, not the e_a . They reported a mean error of 2.60mm and a confidence interval for the population mean of that error of negative 16.50 to positive 21.80mm (BITTNER et al., 2018). They did not report the standard deviation of that mean error.

Bittner et al. (2018) also stated that they measured thus the accuracy of the system in ideal conditions and that the accuracy of the system could be different, namely worse, in field conditions. Indeed, since this would be consistent with the reported by Maser et al. (2006) for impact-echo, another mechanical wave-based nondestructive method for the measurement of the thickness of concrete slabs.

The aforementioned works assessed, then, the accuracy of ultrasound imaging systems for the measurement of thickness of concrete elements by objectively comparing the thickness measures they determined with their ultrasound imaging system with those determined with coring, except for Bittner et al. (2018) which measure the thickness of the slabs directly with a calliper because they were in laboratory conditions. The accuracy measures they reported was not the same, hence it is not possible to compare them.

The vertical position of the brightest pixel of the backwall was taken by both Hoegh et al. (2011) and Bittner et al. (2018) as the thickness of the concrete element.

It should be noted that the works that reported the mean values of errors failed to report the standard deviation of the errors. For this reason, it is unknown if the mean errors could be used for the rectification of the nondestructive thickness measures. The rectification of such measures would be necessary since the mean errors were very large from the standpoint of engineering.

Furthermore, Edwards and Bell (2016) computed the mean errors with the data they acquired at slabs with very different thickness together. They did not mention if the errors were similar for the slabs of different thickness. In Section 2.2.1 it was shown that the thickness of a concrete element affect the characteristics of the pulse that propagated in concrete to a considerable degree.

3 METHODS AND MATERIALS

In this chapter, it is presented the ultrasound imaging system that was evaluated in this work and then the methods and materials of this work for the assessment of the accuracy of that ultrasound imaging system for the measurement of the thickness of the surface layer of concrete pavements.

3.1 THE ULTRASOUND IMAGING SYSTEM

The ultrasound imaging system that was evaluated in this work comprised the data acquisition device presented next and the signal processing program presented subsequently.

3.1.1 The Data Acquisition Device

The A1040 MIRA (Acoustical Control Systems, Moscow, Russia) was selected as the data acquisition device.

The device contained an ultrasound array of 48 transducers in a 04-by-12 grid which were operated as an array of 12 transducers in a 01-by-12 grid. The elements of the latter were 30mm apart and they were operated as assumed in Section 2.3.1 only and by default.

The transmitted pulses comprised shear-horizontal waves. The central frequency of the transmitted pulses, ν_c , could be selected from the range of 25 to 85kHz in steps of 5kHz.

The data that was acquired for each volume of interest were 66 signals, $g_1(t), \dots, g_{66}(t)$, and the estimates of the system's delay, t_d , and of the pulse velocity in the volume of interest, c_s .

The estimate of c_s was determined with the indirect transmission method (BITTNER et al., 2018). The device's sampling frequency, ν_s , was 1.0MHz (CHOI et al., 2016).

Further information on the device was neither disclosed by its manufacturer nor presented in the bibliography, with the exception of the information on its operation in filed that is presented in Section 3.2.2.

3.1.2 The Signal Processing Program

The signal processing program was developed for this work in MATLAB (MathWorks, Natick, USA). It executed the ultrasound imaging routine and then the thickness estimation routine. The routines are presented in this section.

3.1.2.1 The Ultrasound Imaging Routine

The pseudocode of the ultrasound imaging routine is presented in Figure 3.1. As shown therein, the input of the routine in question were the data that was acquired with the data acquisition device for the volume of interest, and its output was the ultrasound image $f^*(x, y)$ of the volume of interest.

Figure 3.1 — Pseudocode of the ultrasound imaging routine.

```

Input:  $g_1(t), \dots, g_{66}(t), t_d$ , and  $c_s$ .
Output:  $f^*(x, y)$ .
for  $i = 1$  to 66 do
    for all pixels  $P(x_p, y_p)$  in  $f_i(x, y)$  do
        Determine  $t^*(x_p, y_p)$  with Eq. 2.4.
         $t^* = \lfloor t^* \rfloor$ .
         $f_i(x_p, y_p) = g_i(t^*)$  (Eq. 2.3).
        Determine  $w_i(x_p, y_p)$  (Eq. 2.6).
    end
     $f_i(x, y) = f_i(x, y)w_i(x, y)$  (Eq. 2.5).
end
 $f(x, y) = f_1(x, y) + \dots + f_{66}(x, y)$  (Eq. 2.4).
Construct  $f^*(x, y)$  with the upper envelopes of the columns of  $f(x, y)$ .
Convert  $f^*(x, y)$  into grayscale.

```

Note: The variables were presented in the text. $\lfloor x \rfloor$ is the floor function applied to x .

Source: Author.

The first step of the ultrasound imaging routine was the processing of the signals with the SAFT for the acquisition of the ultrasound image $f(x, y)$ of the volume of interest. As seen in Figure 3.1, the SAFT was implemented for that purpose in accordance with Section 2.3.1 and thus with the bibliography.

The implementation in question assumed that the estimates of t_d and c_s that were determined by the data acquisition device were correct and that the data acquisition device was centred on

top of the image plane. Furthermore, the implementation used the floor function to determine the sample of the signals that would be taken as their values at t^* (Figure 3.1).

The second step of the ultrasound imaging routine was the processing of the ultrasound image $f(x, y)$ for display. First, the upper envelope of every column of $f(x, y)$ was determined and then used to construct the ultrasound images $f^*(x, y)$ of the volume of interest (JENSEN et al., 2006). Next, the image $f^*(x, y)$ was converted to grayscale (Figure 3.1).

The size of both $f(x, y)$ and $f^*(x, y)$ was 500 by 500 pixels, and the size of their pixels was 1 by 1mm.

The grayscale ultrasound image $f^*(x, y)$ of the volume of interest was, thus, the first output of the signal processing program.

A typical example of the ultrasound images acquired therewith for sample volumes of plain and sound concrete elements is presented in Figure 3.2. The characteristics of that image are discussed next.

The backwall was, as expected, the only object in Figure 3.2. The reason for this obviously was the plainness and soundness of the imaged concrete volume. The backwall was represented as expected too, if considered the characteristics of the ultrasound imaging system and of the imaged concrete volume. The backwall was a bright, namely the brightest, and oblong object that extended itself laterally considerably and presumably from the centreline of the image (Figure 3.2).

The noise¹⁰ and the sub-superficial artefacts¹¹ in Figure 3.2 were also expected, though intensified by the fact that the signals were not processed before the ultrasound imaging routine for the suppression of either of them. The reason for this was the observation that neither of the artefacts would hinder the recognition of the backwall if the backwall had the aforementioned characteristics, namely if the concrete volume was plain and sound, as seen in Figure 3.2.

¹⁰ The noise in that image was consequence of both the random and the structural noise in the signals. For further examples of such noise, see Schickert et al. (2003).

¹¹ The sub-superficial artefact in that image was consequence of the mis-mapping of the surface waves. For further examples of such artefact, see Shokouhi et al. (2014).

Figure 3.2 — Typical example of the ultrasound images acquired with the ultrasound imaging system evaluated in this work for sample volumes of plain and sound concrete elements.

Source: Author.

3.1.2.2 The Thickness Estimation Routine

The pseudocode of the thickness estimation routine is presented in Figure 3.3. As shown therein, the input of the routine in question was the ultrasound image $f^*(x, y)$ of the volume of interest, and its output was the estimate of the thickness of the concrete element which contained the volume of interest at the position of the volume of interest, h .

The vertical position of the brightest pixel of every column of $f^*(x, y)$, h_{x^*} , where x^* denoted the column, was determined and then registered. The median of the h_{x^*} was subsequently determined and then taken as h (Figure 3.3).

The h estimated was, thus, the second and last output of the signal processing program.

Figure 3.3 — Pseudocode of the thickness estimation routine.

```

Input:  $f^*(x, y)$ .
Output:  $h$ .
for  $x^* = 1$  to 500 do
   $h_{x^*} = \arg_y \max f^*(x^*, y)$ .
  Register  $h_{x^*}$ .
end
 $h$  is the median value of the set  $\{h_1, \dots, h_{500}\}$ .

```

Note: The variables were presented in the text. 500 is the number of columns in $f^*(x, y)$.

Source: Author.

The h_{x^*} pixels of the ultrasound image in Figure 3.2 are shown in Figure 3.4. As seen therein, most of the h_{x^*} pixels were in the backwall. The reason for this were the aforementioned characteristics of the backwall, namely its brightness and its length. Additionally, the h_{x^*} pixels which were in the backwall were at similar depths (Figure 3.4). The reason for this presumably was the migration process.

Figure 3.4 — Image showing only the brightest pixel of every column of the ultrasound image in Figure 3.2.

Source: Author.

Furthermore, one of the h_{x^*} pixels in the backwall was by construction the brightest pixel of the backwall. Therefore, most of the h_{x^*} were approximately the vertical position of the brightest pixel of the backwall. The median h_{x^*} was then approximately that value too.

The vertical position of the brightest pixel of the backwall was taken as h in the bibliography (Section 2.3.2). The thickness estimation routine determined thus an h which was approximately the value which would be acquired with the method of the bibliography but without the segmentation of the backwall.

The segmentation of the backwall would be prerequisite for the determination of the position of its brightest pixel automatically. It would also require some input from the operator, whom would have to first recognize the backwall in each and every image. This would hinder the efficiency of the imaging system for the task of interest in this work, for which large amounts of data are generally acquired.

In contrast to that, the method of the thickness estimation routine was fully automatic and did not require any input from the operator. Its disadvantage was that it assumed that the ultrasound images had the characteristics mentioned in the previous section.

3.2 METHODS AND MATERIALS OF THE ACCURACY ASSESSMENT

The methods and materials of this work for the assessment of the accuracy of that ultrasound imaging system for the measurement of the thickness of plain slabs of concrete pavements are presented in brief next and in detail subsequently.

First the as-built thickness of slabs of concrete pavements were measured at several points with the ultrasound imaging system and then with the standard method for that coring. The thickness measures that were determined with the ultrasound imaging system were then compared to the standard thickness measures for the determination of a number of accuracy measures. The accuracy of the ultrasound imaging system for that task was thereupon inferred from those results.

The methods of this work hitherto were in accordance with the bibliography (Section 2.3.2).

In addition to that, it was assessed the statistical and engineering significance of the differences in the accuracy of the ultrasound imaging system in consequence to, firstly, changes in one of its key operational characteristics, namely v_c , and, secondly, changes in one of the key characteristics of the imaged concrete volumes, namely the range of the thickness of the slabs.

3.2.1 The Concrete Pavement Test Sections

In this section, it is presented the four concrete pavement test sections on which the thickness measures that were posteriorly processed for the accuracy assessment were acquired.

The test sections in question were built in 1999 for distinct research purposes. They were built alongside each other within the grounds of the Escola Politécnica of the University of São Paulo (São Paulo, Brazil) (SEVERI, 2002).

The characteristics of the test sections in design are presented in Figure 3.5.¹² As seen therein, the test sections comprised three plain slabs each. The slabs of sections A and B were 150mm thick in design. The slabs of sections C and D were 250mm thick in design (Figure 3.5) (BALBO; SEVERI, 2002)

All slabs consisted of conventional concrete mixes, which were produced in plant and then laid by hand on top of plastic canvas. The base layers of sections A and D consisted of crushed stone. The base layers of sections B and C consisted of roller-compacted concrete (Figure 3.5) (BALBO; SEVERI, 2002; SEVERI, 2002).

Based on visual analyses,¹³ most of the slabs were in sound condition at the time of this work, whereas a few of the slabs either presented transversal cracks or were damaged in consequence to alkali-silica reaction. The defects were mapped for this work.

Furthermore, devices were inserted in every slab at the time of construction for the monitoring of strain and temperature (BALBO; SEVERI, 2002). The device were also mapped for this work.

At the time of this work the test sections were used only for the storage of containers with research material on them. For this reason, some areas of the test sections were inaccessible.

¹² The full design of the concrete pavement test sections is presented in Severi (2002).

¹³ For information on the evaluation of the structural condition of the surface layer of concrete pavements based on visual analysis, see Balbo (2009).

Figure 3.5 — Characteristics of the concrete pavement test sections in design.

Source: Adapted from Balbo and Severi (2002).

3.2.2 Acquisition of the Thickness Measures

In this section, it is presented the methods and materials of this work for the acquisition of the thickness measures that were posteriorly processed for the accuracy assessment.

3.2.2.1 The Sample Points

The thickness measures were acquired at 32 sample points evenly distributed among the four concrete pavement test sections. That is, there were eight points in each test section, and thus there were 16 points associated with each thickness range.

The number of points was limited mainly by the inefficiency of coring.

The position of the points in the test sections was determined before the acquisition of the thickness measures. It was determined at random and at the same time to circumvent the defects, insertions, and inaccessible areas that had been mapped as well as the extremities of the slabs.¹⁴ Thus, the sampled concrete volumes were all plain and sound. The position of the points in the test sections is presented schematically in Figure 3.6.

The points were labelled in accordance to the order the thickness measures were acquired at them. The only data on them that was registered for the ensuing tasks was the test section in which they were. The thickness in design would then be known.

3.2.2.2 Acquisition of the Evaluated Thickness Measures

The thickness of the slabs of the test sections at each point was first measured with the ultrasound imaging system. The thickness measures that were acquired therewith were termed evaluated thickness measures and they were denoted by h .

Nine h were acquired for each point, being three h for each v_c . The v_c that were selected for this work were 30, 50, and 80kHz. For a c_s of 2,500m/s, the λ were approximately 83, 50, and 31mm, respectively. Those v_c were selected because they were either the value generally reported in the bibliography (Section 2.3.2) or close to the upper or lower end of the range of possible v_c (Section 3.1.1).

It was acquired thus three sets of h in this work, one for each v_c . Each set of h comprised 96 h , three h for each point.

¹⁴ The extremities of the slabs were avoided because of the artefacts that arise from reflection at them, as shown in Shokouhi et al. (2014).

Figure 3.6 — Diagram of the position of the sample points in the concrete pavement test sections.

Note: The points were not labelled above for the sake of clarity.

Source: Author.

The first step in the acquisition of the h was the acquisition in field of the data eventually imputed to the signal processing program. To this purpose, first the area of the surface of the slab on which the data acquisition device would be placed on was free of dirt and debris. The device was subsequently positioned centred on a sample point and then configured to transmit pulses with one of the selected v_c (Figure 3.7a). The transducers of the device were dry-point contact ones; so, no coupling liquid was necessary.

The buttons on the device's handlers were then pressed and kept pressed for the data acquisition to occur. At the same time the device was pushed by the operator against the surface of the slab by its handlers so that the spring system attached to the transducers would work to ensure that all transducers were in contact with the rough surface of the slab. The start and end of the data acquisition were signalled by beeps and it took roughly 4s.

The data that was acquired thereby were then labelled according to the label of the point, the sample index, and the v_c and then saved in the device's hard disk.

The steps above were executed three times for each v_c at each point. Furthermore, they were in accordance with the recommendations of the device's manufacturer.

Afterwards, in laboratory the data that was acquired in field were transferred to a computer, inputted to the signal processing program, and then processed therewith in bulk. The output of this was a spreadsheet with the 288 h . The determination of each h with the program took roughly 4s.

Figure 3.7 — Photos of (a) the data acquisition device placed next to a point, (b) the drilling of a slab at a point, and (c) a core after extraction.

(a)

(b)

(c)

Source: Author.

3.2.2.3 Acquisition of the Standard Thickness Measures

The thickness of the slabs of the test sections at each sample point was then measured with the standard method for that coring. The thickness measures that were acquired therewith were termed standard thickness measures and they were denoted by h_s .

A core was extracted at a point right after the data acquisition device was moved away from that point.

The slabs were drilled by Egis Engineering and Consulting (São Paulo, Brazil) under the supervision of the author of this work. Special care was taken to ensure that the main axis of the driller was perpendicular to the surface of the slab at all times (Figure 3.7b). The heights of the cores would thus be the most accurate measures of the thickness of the slabs.

The diameter of the cores was 70mm. The cores were identified with paint right after they were extracted. The extraction of the 32 cores took two full work days.

In laboratory first three random samples of the height of each core were acquired with a calliper. The mean of those samples was subsequently determined and then taken as the h_s at the point the core was extracted.

It was acquired thus one set of h_s , which comprised 32 h_s , one for each point.

3.2.3 Determination and Analysis of the Accuracy Measures

In this section, it is presented the methods and materials of this work for the determination and analysis of the accuracy measures.

3.2.3.1 Analysis and Processing of the Evaluated Thickness Measures

The evaluated thickness measures, the h and the h_e , were processed and analysed before the h_e were processed for the determination of the accuracy measures. The h_e are presented in this section.

The h for each v_c were, first of all, processed for the removal of their outliers. The outliers were determined with the Tukey's fences with a k of 1.50. Each set of h was first separated in two groups for that purpose. The 150mm and the 250mm h comprised the h which were acquired at slabs which were, respectively, 150mm and 250mm thick in design. The reason for this was

that the statistics that were determined for that purpose would be unintelligible otherwise. The h are henceforth termed raw evaluated thickness measures.

The apparent causes of the outliers were investigated for the sake of completeness. The method for this was the analysis of the ultrasound images from which the outliers were determined.

The remaining h were then processed for the determination of the h_e . The h_e for each point and each v_c was the mean of the remaining h for each point and each v_c . The h_e are henceforth termed evaluated thickness measures, since they were the ones that were processed for the determination of the accuracy measures.

It was acquired, then, three sets of h_e , one for each v_c . Each set of h_e comprised 32 h_e , one for each point.

The h_e for each v_c were then analysed for the acquirement of information for the analysis of the accuracy measures. To this purpose, the h_e for each v_c were separated in the 150mm and the 250mm h_e . The reason for this was that the statistics that were determined for that purpose would be unintelligible otherwise.

The 150mm and the 250mm h_e for distinct v_c were first compared among them for the analysis of the implications of the changes in the v_c in the h_e for each thickness range. The 150mm and the 250mm h_e for each v_c were then compared to the 150mm and the 250mm h_s for the analysis of the differences between the h_e and the h_s . The analyses were carried out from the standpoints that every h_e and the h_s were measures of the same physical characteristic of the same objects.

Traditional methods of data summarization and description were used for that purpose. The confidence intervals for the population means of the 150mm and the 250mm h_e and h_s were also determined for that purpose. They were determined for the confidence level of 95% only if the distribution of a group was not markedly skewed and at least approximately normal (MONTGOMERY; RUNGER, 2002).

Hypothesis tests, namely t-tests, were carried out for the population means of the 150mm and the 250mm h_e and h_s too. They were carried out for the significance level of 5% only if the distribution of a group was not markedly skewed and at least approximately normal (MONTGOMERY; RUNGER, 2002). The null hypothesis, H_0 , was $H_0: \mu_\alpha = \mu_\beta$, where μ is the population mean and α and β are the indexes of the groups. The alternative hypothesis, H_1 , was $H_1: \mu_\alpha \neq \mu_\beta$.

The skewness and normality of each group of h_e or h_s was assessed with, respectively, the median skewness and normal probability plots (MONTGOMERY; RUNGER, 2002). The median skewness of each group is presented in Section 4.1. The normal probability plots of each group is presented in Figure A.1 in Appendix A. The conclusions from the assessment of the skewness and normality of each group are presented in Table 3.1.

Table 3.1 — Data on the skewness and normality of the 150mm and the 250mm h_e and h_s .

Group of h_e or h_s	Is the distribution markedly skewed?	Is the distribution at least approximately normal?
150mm h_s	No	Yes
150mm h_e for 30khz	No	Yes
150mm h_e for 50khz	No	Yes
150mm h_e for 80khz	No	Yes
250mm h_s	No	Yes
250mm h_e for 30khz	No	Yes
250mm h_e for 50khz	No	Yes
250mm h_e for 80khz	No	Yes

Source: Author.

3.2.3.2 Determination of the Accuracy Measures

The accuracy measures determined in this work were the ones reported by Edwards and Bell (2016): the absolute error, e_a , the relative error, e_r , and the square of the coefficient of correlation, R^2 .

As shown in Equation 3.1, the e_a was the absolute difference between each h_s and the corresponding h_e for each v_c (EDWARDS; BELL, 2016). It was acquired, thus, three sets of e_a , one for each v_c . Each set of e_a comprised 32 e_a , one for each point.

$$e_a = |h_s - h_e| \quad (3.1)$$

As shown in Equation 3.2, the e_r was the ratio of the e_a to the corresponding h_s (EDWARDS; BELL, 2016). It was acquired, thus, three sets of e_r , one for each v_c . Each set of e_r comprised 32 e_r , one for each point.

$$e_r = e_a/h_s \quad (3.2)$$

The R^2 was determined for the h_e for each v_c in relation to the h_s .¹⁵ It was acquired, thus, three R^2 , one for each v_c .

3.2.3.3 Analysis of the Accuracy Measures

The e_a and the e_r for each v_c were first analysed for the evaluation of the degree of inaccuracy of the h_e for each v_c and then for the evaluation of the certainty of the means of the e_a and e_r for each v_c for the rectification of the h_e for each v_c . The e_a and the e_r for distinct v_c were subsequently analysed for the evaluation of the engineering and statistical significance of the differences among the e_a and the e_r for distinct v_c .

The 150mm and the 250mm e_a and e_r for each v_c were then analysed for the evaluation for the engineering and statistical significance of the differences among the 150mm and the 250mm e_a and e_r for each v_c .

In accordance with Balbo (2009), differences in the e_a for distinct v_c or distinct thickness ranges of more than 5mm were considered significant from the standpoint of engineering; and, accordingly, differences in the e_r for distinct v_c or distinct thickness ranges of more than 2.25pp for 150mm slabs and 4.75pp for 250mm slabs were considered significant from the standpoint of engineering.

The analysis were carried out with traditional data description and summarization approaches, confidence intervals, and hypothesis tests. The last two were carried out as mentioned in Section 3.2.3.1 for the h_e and the h_s .

The median skewness of each group of e_a and e_r is presented in Section 4.2, and the normal probability plots of each group of e_a and e_r is presented in Figures B.1 to B.4 in Appendix B. The conclusions from the assessment of the skewness and normality of each group of e_a and e_r are presented in Table 3.2.

¹⁵ The formula of the R^2 is presented in, for example, Montgomery and Runger (2002).

Table 3.2 — Data on the skewness and normality of the e_a and e_r for each v_c and the 150mm and the 250mm e_a and e_r for each v_c

Group of e_a and e_r	Is the distribution markedly skewed?	Is the distribution at least approximately normal?
e_a for 30kHz	No	Yes
e_a for 50kHz	No	Yes
e_a for 80kHz	No	Yes
e_r for 30kHz	No	Yes
e_r for 50kHz	Yes	-
e_r for 80kHz	No	Yes
150mm e_a for 30kHz	No	Yes
250mm e_a for 30kHz	Yes	-
150mm e_a for 50kHz	No	Yes
250mm e_a for 50kHz	Yes	-
150mm e_a for 80kHz	No	Yes
250mm e_a for 80kHz	No	Yes
150mm e_r for 30kHz	No	Yes
250mm e_r for 30kHz	Yes	-
150mm e_r for 50kHz	No	Yes
250mm e_r for 50kHz	Yes	-
150mm e_r for 80kHz	No	Yes
250mm e_r for 80kHz	No	Yes

Source: Author.

The R^2 for each v_c were subsequently analysed.

Lastly, accuracy measures of the ultrasound imaging system that was evaluated in this work were compared to the accuracy measures of similar ultrasound imaging systems that were reported in the bibliography.

3.2.3.4 Analysis of the Ultrasound Images

A random sample of 18 ultrasound images were selected for the analysis of the apparent causes of the observed, or not, differences in the e_a and the e_r for distinct v_c or thickness ranges.

First, six sample points were selected at random.¹⁶ They were the points of indexes 3, 8, 14, 20, 29, and 31. Second, three ultrasound images for each point, one for each v_c , were selected at

¹⁶ The Random Integer Generation tool in the website www.random.org was used to that purpose.

random. They were the second, third, and second ultrasound image for each point for the v_c of 30, 50, and 80kHz, respectively.

The analysis of the ultrasound images aimed to answer the following questions for each point:

- Question A: Is there any unexpected artefact in the ultrasound images?
- Question B: Were the assumptions of the thickness estimation routine satisfied?
- Question C: Is the backwall thicker or thinner with increasing v_c ?
- Question D: Is the backwall shorter or longer with increasing v_c ?
- Question E: Was the backwall shifted vertically with changes in the v_c ?

The purpose of this was, firstly, to evaluate if the assumptions of the thickness estimation routine were satisfied for the sample images (Questions A and B). If they were, then the method of the thickness estimation routine presumably as not a cause for the differences in the e_a and the e_r for distinct v_c and distinct thickness ranges.

And, secondly, to evaluate if the characteristics of the backwall of the sample images changed with changes in the v_c (Questions C to E). If they did, and the assumptions of the thickness routine were satisfied, then changes in the response of the concrete volumes presumably were the causes for the differences in the e_a and the e_r for distinct v_c and distinct thickness ranges.

4 RESULTS AND DISCUSSION

In this chapter, the results of this work are presented and analysed and then discussed.

4.1 ANALYSIS OF THE EVALUATED THICKNESS MEASURES

In this section, the evaluated thickness measures, h_e , are presented and analysed.

4.1.1 On the Outliers of the Raw Evaluated Thickness Measures

First of all, it is presented some data on the outliers of the raw evaluated thickness measures, h . The h for each v_c are presented in Table A.2 in Appendix A. The summary statistics of the 150mm and the 250mm h for each v_c are presented in Table 4.1.

Table 4.1 — Summary of the 150mm and the 250mm h for each v_c .

Statistic	Group/ v_c					
	150mm			250mm		
	30kHz	50kHz	80kHz	30kHz	50kHz	80kHz
Mean (mm)	152.28	152.65	148.60	207.63	218.46	227.06
Median (mm)	148.00	147.00	146.00	217.00	226.00	232.50
Median Skewness (1)	-0.24	0.51	-0.31	-0.67	-0.58	-0.31
Standard Deviation (mm)	34.032	40.685	26.188	42.159	39.211	52.193
Coefficient of Variation (%)	22.35	26.65	17.62	20.31	17.95	22.99
Minimum Value (mm)	123.00	83.50	128.50	51.00	49.00	67.00
Maximum Value (mm)	350.00	350.50	312.50	304.00	310.00	455.00
Range (mm)	227.00	267.00	184.00	253.00	261.00	388.00
First Quartile (mm)	138.75	138.00	138.75	202.25	219.00	222.00
Third Quartile (mm)	155.25	151.25	151.00	225.25	231.00	239.25
Interquartile Range (mm)	16.50	13.25	12.25	23.00	12.00	17.25
Sample Size (1)	48	48	48	48	48	48

Source: Author.

The Tukey's fences of, and the number of outliers in, the 150mm and the 250mm h for each v_c are presented in Table 4.2.

The analysis of the ultrasound images from which the outliers were determined showed that the apparent causes of the outliers were either the incoherence of the images, or the presence of odd artefacts in the images, or odd values of c_s .

Table 4.2 — Data on the outliers of the 150mm and the 250mm h for each v_c .

Statistic	Group/ v_c					
	150mm			250mm		
	30kHz	50kHz	80kHz	30kHz	50kHz	80kHz
Tukey's Lower Fence (mm)	114.00	118.13	120.38	167.75	201.00	196.13
Tukey's Upper Fence (mm)	180.00	171.13	169.38	259.75	249.00	265.13
Number of Outliers (1)	2	4	2	4	7	7

Source: Author.

4.1.2 Analysis of the Evaluated Thickness Measures

The h_e for each v_c are presented in Table A.3 in Appendix A. The summary statistics of the 150mm and the 250mm h_e for each v_c are presented in Table 4.3. The summary statistics of the 150mm and the 250mm standard thickness measures, h_s , are also presented therein.¹⁷

The confidence intervals for the population means of the 150mm and the 250mm h_s and h_e are presented in Table 4.4.

Table 4.4 — Confidence intervals for the population means of the 150mm and the 250mm h_s and h_e .

Thickness Measure	Group	
	150mm	250mm
h_s	154.10-163.55mm	241.86-252.90mm
h_e for 30kHz	139.00-152.15mm	207.67-223.01mm
h_e for 50kHz	138.09-149.94mm	219.35-230.31mm
h_e for 80kHz	139.90-151.03mm	222.74-235.41mm

Note: Confidence Level: 95%. For the assessment of the normality of the data, see Table 3.1.

Source: Author.

The results of the hypothesis tests on the population means of the 150mm and the 250mm h_s and h_e are presented in Table 4.5.

¹⁷ The h_s are presented in Table A.1 in Appendix A.

Table 4.3 — Summary of the 150mm and the 250mm h_s and h_e .

Statistic	Group of h_s		Group of h_e/v_c					
	150mm	250mm	150mm			250mm		
			30kHz	50kHz	80kHz	30kHz	50kHz	80kHz
Mean (mm)	158.83	247.38	145.57	144.02	145.47	215.34	224.83	229.07
Median (mm)	159.18	244.08	146.83	146.17	147.00	217.00	225.17	231.00
Median Skewness (1)	-0.12	0.96	-0.31	-0.58	-0.44	-0.34	-0.10	-0.51
Standard Deviation (mm)	8.87	10.36	12.344	11.119	10.442	14.396	10.284	11.436
Coefficient of Variation (%)	5.58	4.19	8.48	7.72	7.18	6.69	4.57	4.99
Minimum Value (mm)	143.92	232.25	125.50	124.00	129.67	188.67	203.50	206.00
Maximum Value (mm)	174.63	270.78	165.50	165.33	166.00	239.50	242.50	251.33
Range (mm)	30.71	28.53	40.00	41.33	36.33	50.83	39.00	45.33
First Quartile (mm)	152.93	241.54	137.71	137.83	139.00	206.42	221.00	223.67
Third Quartile (mm)	164.50	250.90	153.67	150.00	150.50	225.17	231.08	235.71
Interquartile Range (mm)	11.57	9.36	15.96	12.17	11.50	18.75	10.08	12.04
Sample Size (1)	32	32	32	32	32	32	32	31

Source: Author.

Table 4.5 — Results of the hypothesis tests on the population means of the 150mm and the 250mm h_s and h_e .

Case	Group		P-Value	Reject H_0 ?
	α	β		
A	150mm h_e for 30khz	150mm h_e for 50khz	0.710	No
B	150mm h_e for 30khz	150mm h_e for 80khz	0.980	No
C	150mm h_e for 50khz	150mm h_e for 80khz	0.706	No
D	150mm h_s	150mm h_e for 30khz	7.63E-04	Yes
E	150mm h_s	150mm h_e for 50khz	2.42E-04	Yes
F	150mm h_s	150mm h_e for 80khz	5.02E-04	Yes
G	250mm h_e for 30khz	250mm h_e for 50khz	0.040	Yes
H	250mm h_e for 30khz	250mm h_e for 80khz	6.58E-03	Yes
I	250mm h_e for 50khz	250mm h_e for 80khz	0.286	No
J	250mm h_s	250mm h_e for 30khz	4.83E-08	Yes
K	250mm h_s	250mm h_e for 50khz	8.46E-07	Yes
L	250mm h_s	250mm h_e for 80khz	6.23E-05	Yes

Note: $H_0: \mu_\alpha = \mu_\beta$, $H_1: \mu_\alpha \neq \mu_\beta$. Significance Level: 5%. For the assessment of the normality of the data, see Table 3.1

Source: Author.

The means of the 150mm h_e for distinct v_c are, from the standpoint of engineering, significantly similar. The standard deviations of the 150mm h_e for distinct v_c are fairly similar. The extreme values of the 150mm h_e for distinct v_c are also fairly similar, particularly the maxima (Table 4.3 and Figure 4.1a). The 150mm h_e for distinct v_c presumably are, then, on average, significantly similar.

The confidence intervals show that the 150mm h_e for distinct v_c are, from the standpoint of engineering, on average, significantly similar indeed (Table 4.4).

The conclusions from the hypothesis tests are consistent with the above too. That is, the differences among the population means of the 150mm h_e for distinct v_c are not statistically significant for the selected significance level (Cases A to C, Table 4.5).

The mean of the 150mm h_s is, from the standpoint of engineering, significantly larger than the one of each 150mm h_e . The coefficient of variation of the 150mm h_s is fairly smaller than the one of each 150mm h_e . The extreme values of the 150mm h_s are significantly larger than the ones of each 150mm h_e (Table 4.3 and Figure 4.1a). The 150mm h_s presumably are, then, on average, significantly larger than the 150mm h_e for each v_c .

Figure 4.1 — Box-and-whisker plots of (a) the 150mm h_s and h_e and (b) the 250mm h_s and h_e .

Source: Author.

The confidence intervals show that the 150mm h_s are, from the standpoint of engineering, on average, significantly larger than the 150mm h_e for each v_c indeed (Table 4.4).

The conclusions from the hypothesis tests are consistent with the above too. That is, the difference between the population mean of the 150mm h_s and the one of each 150mm h_e is statistically significant for the selected significance level (Cases D to F, Table 4.5).

The degree of similarity among the 150mm h_e for distinct v_c suggests that the ultrasound imaging system measured the thickness of the 150mm slabs uniformly despite the changes in the v_c . At the same time, the degree of difference between the 150mm h_s and the 150mm h_e for each v_c suggests that the ultrasound imaging system was fairly inaccurate for every v_c .

The means of the 250mm h_e for distinct v_c are, from the standpoint of engineering, significantly different. The coefficients of variation of the 250mm h_e for distinct v_c are fairly different. The extreme values of the 250mm h_e for distinct v_c are very different (Table 4.3 and Figure 4.1b). The 250mm h_e for distinct v_c presumably are, then, on average, significantly different.

The confidence intervals show that the 250mm h_e for distinct v_c are, from the standpoint of engineering, on average, significantly different indeed (Table 4.4).

The conclusions from the hypothesis tests are not totally consistent with the above. That is, only the differences between the population mean of the 250mm h_e for 30kHz and the ones of the 250mm h_e for 50 and 80kHz separately are statistically significant for the selected significance level (Cases G to I, Table 4.5).

The mean of the 250mm h_s is, from the standpoint of engineering, significantly larger than the one of each 250mm h_e . The coefficient of variation of the 250mm h_s is fairly smaller than the one of each 250mm h_e . The extreme values of the 250mm h_s are significantly larger than the ones of each 250mm h_e (Table 4.3 and Figure 4.1b). The 250mm h_e presumably are, then, on average, significantly larger than the 250mm h_e for each v_c .

The confidence intervals show that the 250mm h_s are, from the standpoint of engineering, on average, significantly larger than the 250mm h_e for each v_c indeed (Table 4.4).

The conclusions from the hypothesis tests are consistent with the above too. That is, the difference between the population mean of the 250mm h_s and the one of each 250mm h_e is statistically significant for the selected significance level (Cases J to L, Table 4.5).

The degree of dissimilarity of the 250mm h_e for distinct v_c suggests that the ultrasound imaging system measured the thickness of the 250mm slabs differently with changes in the v_c , particularly when the v_c was 30kHz. At the same time, the degree of difference between the 250mm h_s and the 250mm h_e for each v_c suggests, once again, that the ultrasound imaging system was fairly inaccurate for every v_c .

The first observation above was not observed for the 150mm h_e for distinct v_c . The ultrasound imaging system, then, presumably measured the thickness of the 150mm and the 250mm slabs differently.

Furthermore, the 250mm h_e are, on average, more similar to the 250mm h_s with increasing v_c . As previously mentioned, the 150mm h_e for distinct v_c are, though, on average, similarly (dis)similar to the 150mm h_s (Table 4.3 and Figure 4.1). Hence, the accuracy of the 250mm h_e presumably is dependent on the v_c , but the one of the 150mm h_e presumably is not dependent on the v_c .

Lastly, every h_s is larger than the respective h_e for each v_c (Figure 4.2), except for a single observation for the v_c of 30kHz (Figure 4.2a). Therefore, the ultrasound imaging system systematically underestimated the thickness of the slabs, independently of the thickness range and of the v_c .

Figure 4.2 — Graphical comparison of the h_s with the h_e for the v_c of (a) 30, (b) 50, and (c) 80kHz.

(a)

(b)

(c)

Note: The line in the graphs is the equality line.

Source: Author.

4.2 ANALYSIS OF THE ACCURACY MEASURES

In this section, the accuracy measures, namely the absolute errors, the relative errors, and the R^2 , are presented and analysed separately.

4.2.1 Analysis of the Absolute Errors

The absolute errors, e_a , for each v_c are presented and analysed next. The significance of the differences among the e_a for distinct v_c are thereby analysed. The 150mm and the 250mm e_a for each v_c are presented and analysed subsequently. The significance of the differences among the e_a for distinct thickness ranges are thereby analysed.

4.2.1.1 Absolute Errors and the Central Frequency at Transmission

The e_a for each v_c are presented in Table B.1 in Appendix B and in Figure 4.3. The summary statistics of the e_a for each v_c are presented in Table 4.6.

Figure 4.3 — Histogram of the e_a for the v_c of (a) 30, (b) 50, and (c) 80kHz.

Source: Author.

Table 4.6 – Summary of the e_a for each v_c .

Statistic	Central Frequency at Transmission		
	30kHz	50kHz	80kHz
Mean (mm)	22.66	18.68	15.92
Median (mm)	22.03	17.93	15.42
Median Skewness (1)	0.13	0.23	0.16
Standard Deviation (mm)	14.403	9.571	9.616
Coefficient of Variation (%)	63.57	51.23	60.38
Minimum Value (mm)	0.13	3.67	1.72
Maximum Value (mm)	63.78	46.78	45.12
Range (mm)	63.67	43.12	43.40
First Quartile (mm)	12.66	11.90	9.06
Third Quartile (mm)	28.48	24.41	21.78
Interquartile Range (mm)	15.82	12.51	12.72
Sample Size (1)	32	32	31

Source: Author.

The confidence intervals for the population mean of the e_a for each v_c are presented in Table 4.7.

Table 4.7 – Confidence intervals for the population means of the e_a for each v_c .

v_c	30khz	50khz	80khz
Confidence Interval	17.46-27.85mm	15.23-22.13mm	12.40-19.45mm

Note: Confidence Level: 95%. For the assessment of the normality of the data, see Table 3.2.

Source: Author.

The results of the hypothesis tests on the population means of the e_a are presented in Table 4.8.

Table 4.8 – Results of the hypothesis tests on the population means of the e_a .

Case	Group α	Group β	P-value	Reject H_0 ?
A	e_a for 30kHz	e_a for 50kHz	0.199	No.
B	e_a for 30kHz	e_a for 80kHz	0.033	Yes.
C	e_a for 50kHz	e_a for 80kHz	0.258	No.

Note: $H_0: \mu_\alpha = \mu_\beta$, $H_1: \mu_\alpha \neq \mu_\beta$. Significance Level: 5%. For the assessment of the normality of the data, see Table 3.2

Source: Author.

The mean e_a for each v_c is, from the standpoint of engineering, very high. The standard deviation of the e_a for each v_c is also very high (Table 4.6). The mean e_a for each v_c is, then, very high yet uncertain.

That is, the h_e for each v_c were, on average, inaccurate measures of the thickness of the slabs of the test sections indeed (Section 4.1.2). At the same time, the rectification of the h_e for each v_c based on the mean e_a for that v_c is uncertain because of the high degree of dispersion in the e_a .

The uncertainty on the mean e_a for each v_c is evident in, for instance, the engineering significance of the range of their confidence intervals (Table 4.7).

The conclusions from the analysis of the h_e are consistent with the above. Firstly, the h_e for each v_c were, on average, significantly smaller than the h_s , hence the high mean e_a for each v_c . Secondly, the variability in the h_e for each v_c was larger than the variability in the h_s , hence the high variability in the e_a for each v_c (Section 4.1.2).

The mean e_a decreases with increasing v_c . Nonetheless, only the difference between the mean e_a for 30kHz and the one for 80kHz is significant from the standpoint of engineering. The coefficient of variation of the e_a neither increase nor decrease with increasing v_c . The first and third quartiles of the e_a decrease with increasing v_c (Figure 4.4) (Table 4.6). The e_a presumably are, then, on average, smaller with increasing v_c , though only the e_a for 30kHz and the e_a for 80kHz presumably are, on average, significantly different.

Figure 4.4 — Box-and-whisker plots of the e_a for each v_c .

Source: Author.

The analysis of the confidence intervals of the e_a for the validation of the above was inconclusive (Table 4.7). The conclusions from the hypothesis tests are consistent with the above. That is, only the difference between the population mean of the e_a for 30kHz and the one of the e_a for 80kHz is statistically significant for the selected significance level (Cases A to C, Table 4.8).

The conclusions from the analysis of the h_e , though, are not totally consistent with the above. For one thing, only the 250mm h_e were, on average, more similar to the corresponding h_s with increasing v_c , and thus more accurate with increasing v_c (Section 4.1.2).

Therefore, based on the e_a , the h_e for every v_c are, on average, inaccurate measures of the thickness of the slabs of the test sections. At the same time, the rectification of the h_e for each v_c with the e_a for that v_c would be uncertain because of the high dispersion on the e_a for each v_c .

Additionally, based on the e_a , the h_e are, on average, more accurate with increasing v_c , though only significantly more accurate when the v_c was changed from 30kHz to 80kHz.

Furthermore, the uncertainty in the rectification of the h_e with the e_a would be increased by the fact that such trend is not totally consistent with the observed for the h_e , namely the 150mm h_e .

4.2.1.2 Absolute Errors and the Thickness Range

The 150mm and the 250mm e_a for each v_c are presented in Figure 4.5. The summary statistics of the 150mm and the 250mm e_a for each v_c are presented in Table 4.9.

The confidence intervals for the population mean of the 150mm and the 250mm e_a for each v_c are presented in Table 4.10.

The results of the hypothesis tests on the population means of the 150mm and the 250mm e_a are presented in Table 4.11.

Figure 4.5 — Box-and-whisker plots of the 150mm and the 250mm e_a for the v_c of (a) 30, (b) 50, and (c) 80kHz.

Source: Author.

Table 4.9 — Summary of the 150mm and the 250mm e_a for each v_c .

Statistic	Group/ v_c					
	150mm			250mm		
	30kHz	50kHz	80kHz	30kHz	50kHz	80kHz
Mean (mm)	13.27	14.81	13.36	32.04	22.55	18.66
Median (mm)	12.63	12.62	13.56	27.17	18.82	17.78
Median Skewness (1)	0.22	0.88	-0.08	1.15	1.11	0.24
Standard Deviation (mm)	8.848	7.451	7.447	12.745	10.090	11.097
Coefficient of Variation (%)	66.68	50.31	55.75	39.77	44.74	59.46
Minimum Value (mm)	0.12	3.67	1.72	15.90	9.57	4.93
Maximum Value (mm)	30.73	27.73	24.40	63.78	46.78	45.12
Range (mm)	30.62	24.07	22.68	47.88	37.22	40.18
First Quartile (mm)	8.33	9.62	8.08	22.94	16.86	9.79
Third Quartile (mm)	17.80	19.43	19.30	40.21	27.10	24.94
Interquartile Range (mm)	9.54	9.81	11.21	17.27	10.24	15.15
Sample Size (1)	16	16	16	16	16	15

Source: Author.

Table 4.10 — Confidence intervals for the population means of the 150mm and the 250mm e_a for each v_c .

v_c	Group	
	150mm	250mm
30kHz	8.55-17.98	-
50kHz	10.84-18.78	-
80kHz	9.39-17.33	12.52-24.81

Note: Confidence Level: 95%. For the assessment of the normality of the data, see Table 3.2.

Source: Author.

Table 4.11 — Results of the hypothesis tests on the population means of the 150mm and the 250mm e_a .

Case	Group α	Group β	P-Value	Reject H_0 ?
A	150mm e_a for 30kHz	250mm e_a for 30kHz	-	-
B	150mm e_a for 50kHz	250mm e_a for 50kHz	-	-
C	150mm e_a for 80kHz	250mm e_a for 80kHz	0.127	No.
D	150mm e_a for 30kHz	150mm e_a for 50kHz	0.598	No.
E	150mm e_a for 30kHz	150mm e_a for 80kHz	0.975	No.
F	150mm e_a for 50kHz	150mm e_a for 80kHz	0.585	No.
G	250mm e_a for 30kHz	250mm e_a for 50kHz	-	-
H	250mm e_a for 30kHz	250mm e_a for 80kHz	-	-
I	250mm e_a for 50kHz	250mm e_a for 80kHz	-	-

Note: $H_0: \mu_\alpha = \mu_\beta$, $H_1: \mu_\alpha \neq \mu_\beta$. Significance Level: 5%. For the assessment of the normality of the data, see Table 3.2

Source: Author.

The median of the 150mm e_a for 30kHz is, from the standpoint of engineering, significantly smaller than the one of the corresponding 250mm e_a . The interquartile range of the 150mm e_a for 30kHz is considerably smaller than the one of the corresponding 250mm e_a . Furthermore, the first and the third quartiles of the 150mm e_a are significantly smaller than the ones of the corresponding 250mm e_a (Figure 4.5a) (Table 4.9). The 150mm e_a for 30kHz presumably are, then, on average, significantly smaller than the 250mm e_a for the same v_c .

The median of the 150mm e_a for 50kHz is, from the standpoint of engineering, significantly smaller than the one of the corresponding 250mm e_a . The interquartile range of the 150mm e_a for 50kHz is fairly similar to the one of the corresponding 250mm e_a . Furthermore, the first and third quartiles of the 150mm e_a for 50kHz are significantly smaller than the ones of the corresponding 250mm e_a (Figure 4.5b) (Table 4.9). The 150mm e_a for 50kHz presumably are, then, on average, significantly smaller than the 250mm e_a for the same v_c .

The mean of the 150mm e_a for 80kHz is, from the standpoint of engineering, significantly smaller than the one of the corresponding 250mm e_a . The coefficient of variation of the 150mm e_a for 80kHz is fairly similar to the one of the corresponding 250mm e_a . The first and third quartiles of the 150mm e_a for 80kHz are, respectively, fairly similar and significantly smaller than the ones of the corresponding 250mm e_a (Figure 4.5c) (Table 4.9). The 150mm e_a for 80kHz presumably are, then, on average, significantly smaller than the 250mm e_a for the same v_c .

The analysis of the confidence intervals for the validation of the above was inconclusive (Table 4.10). The conclusion from the hypothesis tests is not consistent with the above. That is, the difference between the population mean of the 150mm e_a for 80kHz and the one of the 250mm e_a for the same v_c is not statistically significant for the selected significance level (Case C, Table 4.11).

Furthermore, the difference between the average of the 150mm e_a and the average of the corresponding 250mm e_a decreases with increasing v_c .

Therefore, based on the 150mm and the 250mm e_a , the ultrasound imaging system measured the thickness of the 150mm and the 250mm slabs differently indeed (Section 4.1.2). Namely, the 150mm h_e for each v_c were, on average, significantly more accurate measures of the thickness of the slabs of the test sections than the 250mm h_e for the same v_c .

The means of the 150mm e_a for distinct v_c are, from the standpoint of engineering, very similar. The standard deviations of the 150mm e_a for distinct v_c are fairly similar. The extreme values of the 150mm e_a for distinct v_c are considerably different. The first and third quartiles of the 150mm e_a for distinct v_c are, though, very similar (Figure 4.6a) (Table 4.9). The 150mm e_a for distinct v_c presumably are, then, on average, very similar).

The confidence intervals show that the 150mm e_a for distinct v_c are, on average, very similar from the standpoint of engineering indeed (Table 4.10). The hypothesis tests are consistent with the above. That is, the differences among the population means of the 150mm e_a for distinct v_c are not statistically significant for the selected significance level (Cases D to F, Table 4.11).

Figure 4.6 — Box-and-whisker plots of (a) the 150mm e_a and (b) the 250mm e_a for each v_c .

Source: Author.

Therefore, based on the 150mm e_a , the ultrasound imaging system measured the thickness of the 150mm slabs uniformly despite the changes in the v_c indeed (Section 4.1.2). That is, the accuracy of the 150mm h_e were, on average, approximately the same despite the changes in the v_c . Furthermore, the observations for the general e_a (Section 4.2.1.1) are not consistent with the observed for the 150mm e_a then.

The median of the 250mm e_a decreases with increasing v_c . The interquartile range of the 250mm e_a neither increase nor decrease with increasing v_c . The first and third quartiles of the 250mm e_a decrease with increasing v_c too (Figure 4.6b) (Table 4.9). The 250mm e_a are, then, on average, smaller with increasing v_c .

Therefore, based on the 250mm e_a , the ultrasound imaging system measured the thickness of the 250mm slabs differently with changes in the v_c indeed (Section 4.1.2). Namely, the 250mm h_e were, on average, more accurate with increasing v_c . The same was not observed for the 150mm e_a for distinct v_c (above). Furthermore, the observations for the general e_a (Section 4.2.1.1) are consistent with the observed for the 250mm e_a .

Nonetheless, the averages of every 150mm and 250mm e_a are very high yet uncertain. Hence, the rectification of the 150mm and the 250mm h_e with the respective mean e_a is uncertain.

The implications of the above on the general e_a for each v_c is discussed in Section 4.4.

4.2.2 Analysis of the Relative Errors

The relative errors, e_r , for each v_c are presented and analysed next. The significance of the differences among the e_r for distinct v_c are thereby analysed. The 150mm and the 250mm e_r for each v_c are presented and analysed subsequently. The significance of the differences among the e_r for distinct thickness ranges are thereby analysed.

4.2.2.1 Relative Errors and the Central Frequency at Transmission

The e_r for each v_c are presented in Table B.2 in Appendix B and in Figures 4.7 and 4.8. The summary statistics of the e_r for each v_c are presented in Table 4.12.

Figure 4.7 — Histogram of the e_r for the v_c of (a) 30, (b) 50, and (c) 80KHz.

Source: Author.

Figure 4.8 — Box-and-whisker plots of the e_r for each v_c .

Source: Author.

Table 4.12 — Summary of the e_r for each v_c .

Statistic	Central Frequency at Transmission		
	30kHz	50kHz	80kHz
Mean (%)	10.65	9.19	7.94
Median (%)	9.63	7.79	7.25
Median Skewness (1)	0.54	1.00	0.45
Standard Deviation (pp)	5.683	4.218	4.400
Coefficient of Variation (%)	53.35	45.88	55.39
Minimum Value (%)	0.07	2.39	1.04
Maximum Value (%)	23.56	17.72	16.66
Range (pp)	23.48	15.33	15.62
First Quartile (%)	7.48	6.56	4.29
Third Quartile (%)	15.55	11.95	10.82
Interquartile Range (pp)	8.07	5.39	6.54
Sample Size (1)	32	32	31

Source: Author.

The confidence intervals for the populations means of the e_r for each v_c are presented in Table 4.13.

Table 4.13 — Confidence intervals for the population means of the e_r for each v_c .

v_c	30khz	50khz	80khz
Confidence Interval	8.60-12.70%	-	6.33-9.56%

Note: Confidence Level: 95%. For the assessment of the normality of the data, see Table 3.2.

Source: Author.

The results of the hypothesis tests on the populations means of the e_r are presented in Table 4.14.

Table 4.14 — Results of the hypothesis tests on the populations means of the e_r .

Case	Group α	Group β	P-value	Reject H_0 ?
A	e_a for 30kHz	e_a for 50kHz	-	-
B	e_a for 30kHz	e_a for 80kHz	0.039	Yes.
C	e_a for 50kHz	e_a for 80kHz	-	-

Note: $H_0: \mu_\alpha = \mu_\beta$, $H_1: \mu_\alpha \neq \mu_\beta$. Significance Level: 5%. For the assessment of the normality of the data, see Table 3.2

Source: Author.

The means of the e_r for 30 and 80kHz are, from the standpoint of engineering, very high. The standard deviations of the e_r for 30 and 80kHz are also very high (Table 4.12). The means of the e_r for 30 and 80kHz are, then, very high yet uncertain. The uncertainty on the means of the e_r for 30 and 80kHz is evident in the engineering significance of the range of their confidence intervals (Table 4.13).

The rectification of the h_e for each v_c with the respective mean e_r would, therefore, be as uncertain as the rectification of the h_e for each v_c with the respective mean e_a (Section 4.2.1.1). The reasons for this are, firstly, the high degree of dispersion in the e_r for 30 and 80kHz and, secondly, the markedly skewness of the e_r for 50kHz (Table 4.12).

The mean of the e_r for 30kHz is, from the standpoint of engineering, significantly larger than the one of the e_r for 80kHz. The coefficient of variation of the e_r for 30kHz is fairly similar to the one of the e_r for 80kHz. The first and third quartiles of the e_r for 30kHz are significantly larger than the ones of the e_r for 80kHz (Figure 4.8) (Table 4.12). The e_r for 30kHz presumably are, then, on average, significantly larger than the e_r for 80kHz.

The confidence intervals show that the e_r for 30kHz are, from the standpoint of engineering, on average, significantly larger than the e_r for 80kHz indeed (Table 4.13). The conclusion from the hypothesis test is consistent with the above. That is, the difference between the population mean of the e_r for 30kHz and the one of the e_r for 80kHz is statistically significant for the selected significance level (Case B, Table 4.14).

The median of the e_r for 30kHz is, from the standpoint of engineering, larger, though not significantly larger, than the one of the e_r for 50kHz. The first and third quartiles of the e_r for 30kHz are, respectively, fairly larger and significantly larger than the ones of the e_r for 50kHz

(Table 4.12). The e_r for 30kHz presumably are, then, on average, larger, though not significantly larger, than the e_r for 50kHz.

The median of the e_r for 50kHz is, from the standpoint of engineering, very similar to the one of the e_r for 80kHz. The first and the third quartiles of the e_r for 50kHz are, respectively, fairly larger and very similar to the ones of the e_r for 80kHz (Table 4.12). The e_r for 50kHz presumably are, then, on average, fairly similar to the e_r for 80kHz.

Therefore, based on the e_r , the h_e for every v_c are, on average, inaccurate measures of the thickness of the slabs of the test sections. At the same time, the rectification of the h_e for each v_c with the e_r for that v_c would be uncertain because of the high dispersion on the e_r for the v_c of 30 and 80kHz and the markedly skewness of the e_r for the v_c of 50kHz.

Furthermore, based on the e_r , the h_e are, on average, significantly more accurate if the v_c is increased from 30kHz to 80kHz, fairly more accurate if the v_c is increased from 30kHz to 50kHz, and similarly accurate if the v_c is increased from 50kHz to 80kHz.

The observations above are consistent with the observed for the general e_a . Firstly, the e_a were also, on average, smaller with increasing v_c . Secondly, the difference between the e_a for distinct v_c was also significant only when the v_c was increased from 30kHz to 80kHz (Section 4.2.1.1).

4.2.2.2 Relative Errors and the Thickness Range

The 150mm and the 250mm e_r for each v_c are presented in Figure 4.9. The summary statistics of the 150mm and the 250mm e_r for each v_c are presented in Table 4.15.

The confidence intervals for the populations means of the e_r for each v_c are presented in Table 4.16.

Table 4.16 — Confidence intervals for the population means of the 150mm and the 250mm e_r for each v_c .

v_c	Group	
	150mm	250mm
30kHz	5.39-11.35%	-
50kHz	6.81-11.85%	-
80kHz	5.91-10.86%	5.13-9.82%

Note: Confidence Level: 95%. For the assessment of the normality of the data, see Table 3.2.

Source: Author.

Figure 4.9 — Box-and-whisker plots of the 150mm and the 250mm e_r for the v_c of (a) 30, (b) 50, and (c) 80kHz.

Source: Author.

Table 4.15 — Summary of the 150mm and the 250mm e_a for each v_c .

Statistic	Group/ v_c					
	150mm			250mm		
	30kHz	50kHz	80kHz	30kHz	50kHz	80kHz
Mean (%)	8.37	9.33	8.38	12.93	9.06	7.47
Median (%)	7.87	7.79	8.57	10.86	7.72	7.14
Median Skewness (1)	0.27	0.98	-0.12	1.26	1.06	0.24
Standard Deviation (pp)	5.587	4.732	4.644	4.941	3.788	4.233
Coefficient of Variation (%)	66.77	50.71	55.39	38.20	41.81	56.64
Minimum Value (%)	0.07	2.39	1.04	6.41	3.86	1.93
Maximum Value (%)	19.48	17.72	15.47	23.56	17.28	16.66
Range (pp)	19.41	15.33	14.43	17.14	13.42	14.74
First Quartile (%)	5.61	5.92	4.80	9.23	7.03	4.04
Third Quartile (%)	11.95	12.84	12.01	16.22	11.32	10.22
Interquartile Range (pp)	6.34	6.92	7.22	6.99	4.29	6.18
Sample Size (1)	16	16	16	16	16	15

Source: Author.

The results of the hypothesis tests on the populations means of the 150mm and the 250mm e_r are presented in Table 4.17.

Table 4.17 — Results of the hypothesis tests on the population means of the 150mm and the 250mm e_r .

Case	Group α	Group β	P-Value	Reject H_0 ?
A	150mm e_r for 30kHz	250mm e_r for 30kHz	-	-
B	150mm e_r for 50kHz	250mm e_r for 50kHz	-	-
C	150mm e_r for 80kHz	250mm e_r for 80kHz	0.573	No.

Note: $H_0: \mu_\alpha = \mu_\beta$, $H_1: \mu_\alpha \neq \mu_\beta$. Significance Level: 5%. For the assessment of the normality of the data, see Table 3.2

Source: Author.

The median of the 150mm e_r for 30kHz is, from the standpoint of engineering, significantly smaller than the one of the corresponding 250mm e_r . The interquartile range of the 150mm and the 250mm e_r for 30kHz are very similar. The first and third quartiles of the 150mm e_r for 30kHz are considerably smaller than the ones of the corresponding 250mm e_r (Figure 4.9) (Table 4.15). The 150mm e_r for 30kHz presumably are, then, on average, considerably smaller than the 250mm e_r for the same v_c .

The median of the 150mm e_r for 50kHz is, from the standpoint of engineering, very similar to the one of the corresponding 250mm e_r . The interquartile range of the 150mm e_r for 50kHz is considerably larger than the one of the corresponding 250mm e_r . The first and third quartiles of the 150mm e_r for 50kHz are, respectively, considerably smaller and larger, though not significantly larger, than the ones of the corresponding 250mm e_r (Figure 4.9) (Table 4.15). The 150mm e_r for 50kHz presumably are, then, on average, fairly similar to the 250mm e_r for the same v_c .

The mean of the 150mm e_r for 80kHz is, from the standpoint of engineering, larger, though not significantly larger, than the one of the corresponding 250mm e_r . The standard deviations of the 150mm and the 250mm e_r for 80kHz are very similar. The extreme values of the 150mm and the 250mm e_r for 80kHz are also very similar (Table 4.15). The 150mm e_r for 80kHz presumably are, then, on average, fairly similar to the 250mm e_r for the same v_c .

The confidence intervals show that the 150mm e_r for 80kHz are, on average, fairly similar to the 250mm e_r for the same v_c from the standpoint of engineering indeed (Table 4.16). The conclusion from the hypothesis test is consistent with the above. That is, the difference between the population mean of the 150mm e_r for 80kHz and the one of the 250mm e_r for the same v_c is not statistically significant for the selected significance level (Case C, Table 4.17).

Therefore, based on the e_r , the ultrasound imaging system measured the thickness of the 150mm and the 250mm slabs with different accuracy only when the v_c was 30kHz.

The observations above for the v_c of 50 and 80kHz are actually consistent with the previously observed for the 150mm and the 250mm e_a (Section 4.2.1.2), since the 150mm e_a for 50 and 80kHz should be smaller than the corresponding 250mm e_a the 150mm and the 250mm e_r to be similar.

4.2.3 Analysis of the R^2

The R^2 between the h_e for each v_c and the h_s are presented in Table 4.18.

Table 4.18 — R^2 for each v_c .

v_c	30kHz	50kHz	80kHz
R^2	0.920	0.960	0.958

Source: Author.

The R^2 show that in linear regression models 92.0, 96.0, and 95.8% of the variability in the h_e for 30, 50, and 80kHz is explained by the variability in the h_s .

4.3 ANALYSIS OF THE SAMPLE ULTRASOUND IMAGES

The sample ultrasound images are presented in Appendix C according to Table 4.19. The images of only the h^* pixels of the sample ultrasound images are also presented in Appendix C. The h , h_e , and h_s correspondent to each sample ultrasound image are presented in Table 4.19. As seen therein, the average characteristics of the h_e in relation to the h_s are represented by the sample ultrasound images.

The results of the analysis of the sample ultrasound images are presented in Table 4.20.

The assumptions of the thickness estimation routine were satisfied for every sample ultrasound image. At the same time, there were unexpected artefacts, namely multiple reflections, in some of the sample ultrasound images (Table 4.20). Nonetheless, they did not affect the method of the thickness estimation routine, since, as seen in Appendix C, the pixels of the backwall were brighter and, thus, they were the h^* pixels.

Table 4.19 — Data on the sample ultrasound images.

Point Index	h_s (mm)	v_c /Evaluated Thickness Measure (mm)						Figures
		30kHz		50Khz		80Khz		
		h_e	h	h_e	h	h_e	h	
3	242.42	219.67	215.00	232.33	233.00	236.67	236.00	C.1-3
8	237.02	199.00	200.00	220.00	216.00	227.00	222.00	C.4-6
14	232.25	188.67	186.00	204.00	200.00	209.33	215.00	C.7-9
20	165.38	165.50	165.00	158.33	160.00	163.67	163.00	C.10-12
29	169.65	154.67	155.00	147.67	149.00	151.33	153.00	C.13-15
31	143.92	135.33	136.00	138.33	138.00	139.67	142.00	C.16-18

Source: Author.

Table 4.20 — Results of the analysis of the sample ultrasound images.

Point Index	Question				
	A	B	C	D	E
3	Yes, MR	Yes	Thinner	Longer	Yes
8	No	Yes	Neither	Longer	Yes
14	No	Yes	Neither	Longer	Yes
20	Yes, MR	Yes	Neither	Longer	Yes
29	Yes, MR	Yes	Thinner	Longer	Yes
31	Yes, MR	Yes	Neither	Longer	Yes

Note: The questions were presented in Section 3.2.3.4.

Source: Author.

The backwall of the sample ultrasound images was generally neither thinner nor thicker “with increasing v_c ”. The backwall of every sample ultrasound image was longer “with increasing v_c ”. And the backwall of every sample ultrasound image was also shifted vertically with changes in the v_c (Table 4.20).

The changes in the width or length of the backwall with changes in the v_c presumably were not the main reasons for the changes in the h with changes in the v_c . As seen in Appendix C, the vertical position of the h^* pixels of the backwall still were approximately h despite that.

The changes in vertical position of the backwall with changes in the v_c obviously were the main reasons for the changes in the h with changes in the v_c .

Therefore, the method of the thickness estimation routine presumably was not the main reason for the characteristics of the h_e with changes in the thickness range or the v_c . The reason presumably was changes in the response of the concrete volume, which were represented by

changes in the characteristics of the backwall reflection and, then, in the vertical position of the backwall. No data was determined in this work for further analysis of this.

4.4 DISCUSSION

The h_e are, therefore, inaccurate measures of the thickness of the surface layer of concrete pavements, as shown by the averages of the e_a and the e_r for every v_c and thickness range. Furthermore, the rectification of the h_e would be uncertain because of the high degree of dispersion in the e_a and the e_r for every v_c and thickness range.

The data that was acquired in this work prevented the evaluation of the sources of the dispersion in the e_a and the e_r . Nonetheless, it showed that the cause of the dispersion presumably was neither the v_c nor the thickness range, since the degree of dispersion in the errors was high independently of those factors.

The accuracy of the ultrasound imaging system as measured by the general e_a , the general e_r , and the R^2 changed with changes in the v_c . The general e_a and e_r were, on average, smaller with increasing v_c . At the same time, the general e_a and e_r were, on average, significantly reduced only when the v_c was increased to 80kHz from 30kHz.

The ultrasound imaging system evaluated in this work was significantly less accurate than the imaging systems evaluated in the bibliography. For example, Edwards and Bell (2016) reported a mean e_a of 10.90mm and a mean e_r of 4.28% for a v_c of 50kHz. The mean e_a and the mean e_r determined in this work for the same v_c were, respectively, 18.8mm and 7.79%.¹⁸

The reasons for this are uncertain. A presumable reason for that is the age of the concrete slabs inspected in this work and, thus, the implications of the increased damage content in the characteristics of the sensed ultrasound (Section 2.2.1). Nonetheless, no data was determined in this work for the validation of this hypothesis.

The results of this work showed, too, that the accuracy of the ultrasound imaging system as measured by the e_a is dependent in the thickness range of the concrete slabs and, furthermore, that the aforementioned dependency on the v_c is true only for the 250mm thick slabs. That is,

¹⁸ The comparison of the results of this work to those of Bittner et al. (2018) is not possible, because they did not report absolute errors. The comparison of the R^2 of this work to those of Edwards and Bell (2016) and Hoegh et al. (2011) were inconclusive.

based on the e_a , the ultrasound imaging system measured the thickness of the 150mm and the 250mm slabs differently. The rectification of the h_e with the e_a should, therefore, consider the thickness range of the slabs and the v_c .

The accuracy of the ultrasound imaging system as measured by the e_r was dependent on the thickness range only when the v_c was 30kHz. This is, however, consistent with the aforementioned for the e_a if considered the formulae of the accuracy measures. The rectification of the h_e with the e_r should, therefore, consider the thickness range of the slabs only when the v_c is 30kHz.

Nonetheless, the rectification of the 150mm and the 250mm h_e separately with the mean 150mm and 250mm e_a or e_r would also be uncertain, because of the high degree of the dispersion in those mean values.

The analysis of the sample ultrasound images showed that the characteristics of the signal processing program were not the main causes of the aforementioned changes in the accuracy of the ultrasound imaging with changes in the v_c and the thickness range. Rather, it presumably was changes in the response of the inspected volume as represented by changes in the characteristics of the pulse reflected at the backwall.

5 CONCLUSIONS

The accuracy of an ultrasound imaging system for the measurement of the thickness of the surface layer of plain concrete pavements was assessed in this work. The significance of changes in the accuracy measures with changes in the thickness range of the slabs and the central frequency of the transmitted pulses was assessed.

The results of this work showed that if the thickness range of the slabs is disregarded, the accuracy of the ultrasound imaging system as measured by the e_a and e_r is dependent on the v_c . At the same time, the system's accuracy is changed to a significant degree only when the v_c is changed to 80kHz from 30kHz.

The results of this work showed, too, that the accuracy of the ultrasound imaging system as measured by the e_a is dependent on the thickness range. The ultrasound imaging system was significantly less accurate for the 250mm thick slabs than for the 150mm thick slabs for every central frequency.

The implications of changes in the v_c were dependent on the thickness range too. The accuracy of the 150mm h_e was not dependent on the v_c , but the 250mm h_e were, on average, more accurate with increasing v_c .

The results for the 150mm and the 250mm e_r were consistent with the above. Nonetheless, the accuracy of the imaging system as measured by the e_r were dependent on the thickness range only when the v_c was 30kHz.

The rectification of the h_e with the means e_a should, therefore, consider the thickness range and the v_c . At the same time, the rectification of the h_e with the means e_r should consider the thickness range only when the v_c is 30kHz. Nonetheless, the rectification of the h_e with the means e_a or means e_r would be uncertain due to the considerable degree of dispersion in the e_a and e_r for every case.

The results of this work are limited, firstly, by the characteristics of the concrete pavement test sections and by the characteristics of the ultrasound imaging system. It is not possible to extrapolate the results of this work for different ultrasound imaging systems or for slabs that are approximately neither 150mm thick nor 250mm thick.

The results of this work are also limited by the methods used to analyse the e_a and the e_r . Future works should analyse the data with other methods, particularly methods that account for the skewness of the data, and that thus would permit a more robust analysis of the

significance of the changes in the accuracy measures with changes in the v_c and the thickness range.

Future works should first study the reasons for the high dispersion in the e_a and the e_r and then methods to improve the accuracy of the h_e . Improvements in the accuracy of the ultrasound imaging system without improvements in the precision of the accuracy measures would be irrelevant. Improvements in the accuracy of the h_e could be achieved by improvements in the method to estimate the c_s .

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APPENDIX A

Table A.1 – The standard thickness measures, h_s , at each point.

Point Index	Section	h_s (mm)
1	D	238.11
2	A	157.73
3	D	242.42
4	C	240.50
5	B	158.22
6	A	159.12
7	B	147.77
8	C	237.02
9	D	243.75
10	D	260.67
11	D	270.78
12	C	244.40
13	C	242.08
14	C	232.25
15	B	153.67
16	B	160.70
17	B	145.25
18	A	169.00
19	A	159.23
20	A	165.38
21	A	164.20
22	B	162.05
23	C	241.88
24	D	249.12
25	D	247.90
26	D	262.50
27	C	248.47
28	C	256.27
29	B	169.65
30	B	174.63
31	A	143.92
32	A	150.70

Source: Author.

Table A.2 – The raw evaluated thickness measures, h , for each v_c at each point.

Point Index	Section	v_c/h (mm)								
		30kHz			50kHz			80kHz		
1	D	194.00	189.50	55.00	180.00	203.50	66.00	206.00	116.00	67.00
2	A	128.00	128.00	125.00	129.00	131.00	350.50	131.00	132.00	137.00
3	D	227.00	215.00	217.00	235.00	229.00	233.00	235.00	236.00	239.00
4	C	225.00	217.00	223.00	223.00	221.00	220.00	227.00	216.00	222.00
5	B	144.00	145.00	148.00	140.50	296.00	139.00	137.00	140.00	134.00
6	A	158.00	151.00	156.00	143.00	145.00	144.00	148.00	146.00	150.00
7	B	139.00	350.00	138.00	134.00	137.00	138.00	141.00	140.00	143.00
8	C	199.00	200.00	198.00	221.00	223.00	216.00	225.00	222.00	234.00
9	D	203.00	204.00	207.00	216.00	225.00	223.00	225.00	239.00	229.00
10	D	223.00	217.00	211.00	252.00	231.00	231.00	247.00	235.00	233.00
11	D	210.00	197.00	214.00	165.00	223.00	225.00	212.00	229.00	236.00
12	C	214.00	217.00	219.00	230.00	227.00	227.00	226.00	232.00	233.50
13	C	221.00	219.00	211.00	227.00	220.00	225.00	300.00	455.00	88.00
14	C	186.00	186.00	194.00	208.00	204.00	200.00	203.00	215.00	210.00
15	B	152.00	157.00	151.00	147.00	151.00	152.00	152.00	151.00	150.00
16	B	148.00	149.00	147.00	148.00	150.00	147.00	151.00	150.00	146.00
17	B	125.00	126.00	133.00	128.00	127.00	125.00	132.00	129.00	128.50
18	A	144.00	144.00	141.00	147.00	145.00	142.00	146.00	144.00	148.00
19	A	151.00	151.00	153.00	150.00	227.50	149.00	154.00	151.00	146.00
20	A	166.00	165.00	165.50	158.00	157.00	160.00	164.00	163.00	164.00
21	A	153.00	148.00	153.00	149.00	152.00	153.00	148.00	149.00	147.00
22	B	144.00	139.00	144.00	150.00	150.00	150.00	144.00	141.00	145.00
23	C	203.00	51.00	216.00	208.50	226.00	49.00	226.00	224.00	248.00
24	D	226.00	223.00	85.00	234.00	231.00	229.00	228.00	233.00	233.00
25	D	233.00	235.00	228.00	237.00	239.00	239.00	240.00	241.00	234.00
26	D	242.00	304.00	237.00	226.00	212.00	241.00	225.00	244.50	162.00
27	C	227.50	229.00	225.00	230.00	230.00	230.00	199.00	271.00	244.00
28	C	236.00	220.00	233.00	248.00	310.00	237.00	249.00	263.00	242.00
29	B	153.00	155.00	156.00	147.00	147.00	149.00	151.00	153.00	150.00
30	B	159.00	167.00	167.00	166.00	166.00	164.00	166.00	170.00	312.50
31	A	138.00	136.00	132.00	138.00	139.00	138.00	139.00	142.00	138.00
32	A	123.00	128.00	236.00	83.50	121.00	127.00	129.00	130.00	130.00

Source: Author.

Table A.3 – The evaluated thickness measures, h_e , for each v_c at each point.

Point Index	Section	v_c/h_e (mm)		
		30kHz	50kHz	80kHz
1	D	191.75	203.50	206.00
2	A	127.00	130.00	133.33
3	D	219.67	232.33	236.67
4	C	221.67	221.33	221.67
5	B	145.67	139.75	137.00
6	A	155.00	144.00	148.00
7	B	138.50	136.33	141.33
8	C	199.00	220.00	227.00
9	D	204.67	221.33	231.00
10	D	217.00	231.00	238.33
11	D	207.00	224.00	225.67
12	C	216.67	228.00	230.50
13	C	217.00	224.00	-
14	C	188.67	206.00	209.33
15	B	153.33	150.00	151.00
16	B	148.00	148.33	149.00
17	B	128.00	126.67	129.83
18	A	143.00	144.67	146.00
19	A	151.67	149.50	150.33
20	A	165.50	158.33	163.67
21	A	151.33	151.33	148.00
22	B	142.33	150.00	143.33
23	C	209.50	217.25	232.67
24	D	224.50	231.33	231.33
25	D	232.00	238.33	238.33
26	D	239.50	226.33	234.75
27	C	227.17	230.00	221.50
28	C	229.67	242.50	251.33
29	B	154.67	147.67	151.33
30	B	164.33	165.33	166.00
31	A	135.33	138.33	139.67
32	A	125.50	124.00	129.67

Source: Author.

Figure A.1 – Normal probability plots of the 150mm (a) h_s and h_e for (b) 30, (c) 50, and (d) 80kHz and of the 250mm (e) h_s and h_e for (f) 30, (g) 50, and (h) 80 kHz.

Source: Author.

APPENDIX B

Table B.1 — Absolute errors, e_a , for each v_c .

Point Index	Section	v_c/e_a (mm)		
		30kHz	50kHz	80kHz
1	D	46.36	34.61	32.11
2	A	30.73	27.73	24.40
3	D	22.75	10.08	5.75
4	C	18.83	19.17	18.83
5	B	12.55	18.47	21.22
6	A	4.12	15.12	11.12
7	B	9.27	11.43	6.43
8	C	38.02	17.02	10.02
9	D	39.08	22.42	12.75
10	D	43.67	29.67	22.33
11	D	63.78	46.78	45.12
12	C	27.73	16.40	13.90
13	C	25.08	18.08	-
14	C	43.58	26.25	22.92
15	B	0.33	3.67	2.67
16	B	12.70	12.37	11.70
17	B	17.25	18.58	15.42
18	A	26.00	24.33	23.00
19	A	7.57	9.73	8.90
20	A	0.12	7.05	1.72
21	A	12.87	12.87	16.20
22	B	19.72	12.05	18.72
23	C	32.38	24.63	9.22
24	D	24.62	17.78	17.78
25	D	15.90	9.57	9.57
26	D	23.00	36.17	27.75
27	C	21.30	18.47	26.97
28	C	26.60	13.77	4.93
29	B	14.98	21.98	18.32
30	B	10.30	9.30	8.63
31	A	8.58	5.58	4.25
32	A	25.20	26.70	21.03

Source: Author.

Table B.2 — Relative errors, e_r , for each v_c .

Point Index	Section	v_c/e_r (%)		
		30kHz	50kHz	80kHz
1	D	19.47	14.54	13.49
2	A	19.48	17.58	15.47
3	D	9.38	4.16	2.37
4	C	7.83	7.97	7.83
5	B	7.93	11.67	13.41
6	A	2.59	9.50	6.99
7	B	6.27	7.74	4.35
8	C	16.04	7.18	4.23
9	D	16.03	9.20	5.23
10	D	16.75	11.38	8.57
11	D	23.56	17.28	16.66
12	C	11.35	6.71	5.69
13	C	10.36	7.47	
14	C	18.77	11.30	9.87
15	B	0.22	2.39	1.74
16	B	7.90	7.70	7.28
17	B	11.88	12.79	10.61
18	A	15.38	14.40	13.61
19	A	4.75	6.11	5.59
20	A	0.07	4.26	1.04
21	A	7.84	7.84	9.87
22	B	12.17	7.44	11.55
23	C	13.39	10.18	3.81
24	D	9.88	7.14	7.14
25	D	6.41	3.86	3.86
26	D	8.76	13.78	10.57
27	C	8.57	7.43	10.85
28	C	10.38	5.37	1.93
29	B	8.83	12.96	10.80
30	B	5.90	5.33	4.94
31	A	5.96	3.88	2.95
32	A	16.72	17.72	13.96

Source: Author.

Figure B.1 – Normal probability plots of the e_a for the v_c of (a) 30, (b) 50, and (c) 80kHz.

(a)

(b)

(c)

Source: Author.

Figure B.2 – Normal probability plots of the e_r for the ν_c of (a) 30, (b) 50, and (c) 80kHz.

(a)

(b)

(c)

Source: Author.

Figure B.3 – Normal probability plots of the 150mm e_r for the v_c of (a) 30, (b) 50, and (c) 80kHz and the 250mm e_r for the v_c of (d) 30, (e) 50, and (f) 80kHz.

(a)

(d)

(b)

(e)

(c)

(f)

Source: Author.

Figure B.4 – Normal probability plots of the 150mm e_a for the v_c of (a) 30, (b) 50, and (c) 80kHz and the 250mm e_a for the v_c of (d) 30, (e) 50, and (f) 80kHz.

Source: Author.

APPENDIX C

Figure C.1. (a) The second ultrasound image of the point of index #3 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.2. (a) The third ultrasound image of the point of index #3 for the ν_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.3. (a) The second ultrasound image of the point of index #3 for the ν_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.4. (a) The second ultrasound image of the point of index #8 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.5. (a) The third ultrasound image of the point of index #8 for the ν_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.6. (a) The second ultrasound image of the point of index #8 for the ν_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.7. (a) The second ultrasound image of the point of index #14 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.8. (a) The third ultrasound image of the point of index #14 for the v_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.9. (a) The second ultrasound image of the point of index #14 for the v_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.10. (a) The second ultrasound image of the point of index #20 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.11. (a) The third ultrasound image of the point of index #20 for the v_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.12. (a) The second ultrasound image of the point of index #20 for the v_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.13. (a) The second ultrasound image of the point of index #29 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.14. (a) The third ultrasound image of the point of index #29 for the ν_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.15. (a) The second ultrasound image of the point of index #29 for the v_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.16. (a) The second ultrasound image of the point of index #31 for the v_c of 30kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.17. (a) The third ultrasound image of the point of index #31 for the ν_c of 50kHz and (b) the image of the h^* pixels of (a).

Source: Author.

Figure C.18. (a) The second ultrasound image of the point of index #31 for the v_c of 80kHz and (b) the image of the h^* pixels of (a).

Source: Author.