The Use of Impact-Echo in Concrete Plates with Very Small Thicknesses

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Abstract
The impact-echo has been proved to be a reliable non destructive test to evaluate the quality of concrete structures. One of its applications is to measure the thickness of concrete plates by the frequency pattern of the reflected stress waves generated by the impact. In usual applications, frequencies up to 20 kHz are obtained. This range of frequencies can be easily excited with the use of small hollow steel balls. The challenge lies at plates with very small thickness which is associated to much higher frequencies. This study presents an experimental investigation in which the impact-echo method was used to estimate thickness in concrete plates with values ranging from 120 down to 30 mm. Massive steel balls and a mechanical impact device were seen to be needed to be able to estimate such small frequencies.

Keywords: nondestructive testing, concrete, thickness, impact-echo, device, metal balls and frequency.

1. Introduction
The use of nondestructive testing in the evaluation of concrete structures has recently been systematically increasing. Non-destructive tests have become a quite attractive alternative to conventional destructive tests, due to their modernization and improvement in the precision of result analysis. These tests give information of the concrete structure without causing any possible damage to the structure; they can be used even when the structure is in service enabling a rapid diagnosis especially in the initial stage of possible problems. Non-destructive tests generally use easy-to-operate equipment, providing data quickly and reliably, as long as the operator knows how to interpret the presented results correctly.

The impact-echo method allows information on different geometric shapes of concrete structures based on the interpretation of the stress waves acquired, mainly from the frequency spectrum of the reflected stress waves. These parameters allow the identification and location of internal faults in the structure, cross section dimensions, thickness of plates, among other applications [1]. Since the impact-echo methodology was developed in the 80’s, several studies with great results have been performed to estimate the thickness of pavement, bridge decks, walls or slabs, generally with a relatively low frequency range. This study covers the higher frequency bands, which in turn are associated to lower thicknesses, being the main objective of this research.

The research is being conducted in the Research Group on Nondestructive Testing (GPEND) of the Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Apart from the use of hollow metal balls provided by the manufacturer of the impact-echo equipment used in the research, new balls were developed with the same diameter, but using massive tempered steel. In order to standardize the force applied and to eliminate the influence of the operator in the results, a mechanical impact device was built. This device also helped to maintain fixed the exact impact point.

2. Impact-echo for thickness evaluation
The nondestructive test method of impact-echo can be used to determine the thickness of concrete structures through multiple reflections of the P-wave (longitudinal or compression...
stress wave), generated by the impact of a small ball on the surface of the structure [2]. As a result of these multiple reflections, a frequency spectrum arises containing only one well-defined peak amplitude which is often called thickness frequency [3]. The use of frequency analysis instead of time domain analysis of the resulting waveforms is what ensures the success of this methodology. Since each time of arrival of the P-wave on the surface of the concrete structure causes a characteristic shift, the waveform has a periodic pattern that is dependent on the frequency \( f \) of arrival of the P-wave. In order to apply the frequency analysis, the results of the waveforms are transformed into frequency domain using the fast Fourier transforms (FFT). The thickness of the concrete plate is given by the dominant frequency peak in the frequency spectrum [4]. The frequency \( f \) is related to the thickness \( h \) according to Equation 1, with the known P-wave velocity \( V_p \).

\[
f = \frac{\beta \cdot V_p}{n \cdot h}
\]

Where \( f \) is the frequency of the thickness mode, \( \beta \) considers the geometry of the concrete member (0.96 for plates) and \( V_p \) is the P-wave velocity. The parameter \( n \) depends on the acoustic impedance \( Z \) of the materials and can be 2 if the structure is in contact with a layer of air or if there is delamination; or it can be 4 if in contact with a layer of steel [3,4-5]. In this study the value of \( n \) equals 2. The P-wave velocity can be obtained by adopting the Procedure A of the ASTM 1383 regulation, using the ultrasound test or simply arbitrating values between 3,500 and 5,000 m/s, which represent the average velocity of the ultrasonic wave in concrete [1]. The impact-echo technique is carried out quite rapidly, with each reading performed in less than 20 seconds, between acquisition and data processing [6]. The interpretation of the stress waves, however, is not easy depending primarily on the experience of the operator [7].

When conducting an impact-echo test, one should be attentive to the choice of parameters that define the conditions under which the analog signal received by the transducer is digitalized and transferred to computer memory. For tests on plates with thicknesses of less than 1000 mm, the number of samples \( N \) can be defined between 1024 and 2048. On the other hand, when measuring velocity and the depth of surface cracks, a smaller value of 440 is suggested. Usually, the time interval \( \Delta t \) between data points is between 1 and 4 \( \mu \)s. Another important factor is the frequency resolution \( \Delta f \), which represents the difference between successive points in the frequency spectrum. It can be calculated by Equation (2). It should be observed that the record length \( N \times \Delta t \) should be both long enough, offering a reasonable level of frequency resolution, but also at the same time short, to avoid multiple reflections of P and R-waves from the boundaries of the concrete member, which may add frequency peaks in the spectrum making it difficult to identify the desired amplitudes.

\[
\Delta f = \frac{1}{N \cdot \Delta t}
\]

Frequency resolution is a key parameter in determining the accuracy of thickness measurements in impact-echo tests, introducing an uncertainty of approximately half of the interval \( \pm \Delta f/2 \) for each frequency. This can be incorporated in Equation (1) as shown in Equation (3).

\[
h = \frac{\beta \cdot V_p}{2 \cdot \left( f \pm \frac{\Delta f}{2} \right)}
\]
The three parameters that characterize the impact are contact time \((t_c)\), ball diameter \((D)\) and kinetic energy of the impact. The relation between these parameters is given by the impact theory of Hertz, which becomes appropriate for this situation when the kinetic energy associated to the relative motion of the colliding bodies is much lower than the elastic energy content of these bodies. This condition is found when the relative velocity of the colliding bodies is significant lower than the p-wave of the concrete and the mechanical properties of the colliding materials are considered, such as the Poisson ratio \((\mu)\), the modulus of elasticity \((E)\) and the specific masses \((\rho)\) of the ball and the concrete plate \([9]\). During the impact, the kinetic energy of the ball is transformed into elastic energy of the wave in the concrete. The maximum force is proportional to the kinetic energy of the ball movement and the shift of the stress wave is proportional to this force. The contact time \((t_c)\) is a linear function of the diameter of the ball \((D)\) and has little dependence on the kinetic energy and drop height, which can be disregarded. To choose the appropriate ball diameter, it is necessary to know which maximum frequency can be excited by it. The amplitudes of stress waves are sufficient for impact-echo tests at frequencies below the ratio of \(1.25/t_c\). The contact time \((t_c)\) can be obtained by Equation (4) where \((\alpha_m)\) is the maximum compression and \((V_0)\) represents the initial relative velocity \([10]\) and \([1]\).

\[
t_c = \frac{\pi \cdot \alpha_m}{1.068 \cdot V_0} \tag{4}
\]

In the use of the impact-echo test to determine thicknesses of concrete plates, thickness frequencies of up to 10 kHz are usually excited, associated to plate thickness of at least of 200 mm. For concrete plates of lower thicknesses, the challenge lies in the ability to excite higher frequencies, which demands the use of smaller balls with little impact energy. In this situation, it is essential to obtain clear waveforms in order to obtain success in performing the FFT. The impact-echo equipment used in this work generates impacts through the use of manually operated impact devices, which often makes it difficult to immediately obtain good waveforms and thus accuracy and repeatability, as already reported by other authors. Given these difficulties, a mechanical device that would allow the improvement of the performance of the test was developed for this study. This device ensures that the impact occurs at the same position, allowing for acquisition of reliable readings. Two types of balls were also used to carry out the impacts: hollow metal balls provided by the manufacturer and massive metal balls in tempered steel.

3. Experimental Program

For the analysis of higher frequencies that are associated to elements of small thicknesses, four self compacting concrete plates were cast. The choice of this type of concrete was due to the reduced thicknesses which required the need for coarse aggregate with a nominal diameter of 9.5 mm, combined with high fluidity, facilitating the molding process with no vibration. To ensure that the surfaces of the plates were smooth, a 4 mm thick glass plate was inserted inside the molds. The surface in contact with the glass plate was used for the realization of the impact tests.

The concrete used in this study was produced with materials available in the region: a Brazilian type CPV-ARI-RS cement, similar to ASTM type III cement, with specific mass of 2.96 kg/m³, coarse aggregate with a maximum diameter of 9.5 mm, natural fine sand with a maximum diameter of 0.3 mm and artificial medium sand with a maximum diameter of 4.8 mm. A superplasticizer water-reducer admixture was also used, in the dosage recommended by the manufacturer. The spreading of the self-compacting concrete was of 780 mm. All plates were air-cured in the laboratory.
All four concrete plates were of 600 x 600 mm, with thicknesses of 120, 63, 43 and 30 mm. The 600 mm lateral dimensions are at least 5 times higher than the thickness, a ratio proved suitable for laboratory testing [13]. The equipment used to perform the readings was manufactured by LLC of Ithaca, USA. ASTM C 1383 procedure B was adopted for the tests. It was necessary to previously determine the p-wave velocity in the material. Since Procedure A did not provide reliable results in this study, the p-wave velocity was determined using conventional ultrasonic method, performed in the thickest plate of 120 mm. The average measured velocity was 4,450 m/s. To excite higher frequencies, associated to low thicknesses, it was necessary to use smaller or heavier balls, to be able to reduce the contact time. These requirements were met with new impact balls developed with massive tempered steel from bearings (Figure 1), with the same dimensions of the balls provided by the manufacturer of the impact-echo equipment. However, for this work only 3.2 mm balls were used, which have proven to excite higher frequencies and showed the best results for the thicknesses studied. All tests were performed at the center of the concrete plates to mitigate the edge effect, considering the results of three impacts applied at the same point. According to the impact law of Hertz from Equation (4), the maximum frequency of excitation for a 3.2 mm ball was of 92 kHz for the hollow metal ball and 96 kHz for the massive tempered steel ball.

The impact-echo tests were performed after 28 days of curing. The resistance to axial compression of the concrete mixture evaluated by four cylindrical specimens of 100 x 200 mm was 32 MPa at 28 days. In actual tests using manual impact it was noticed that it was very difficult to use a ball so small and of relatively light-weight, which required several attempts to get a good waveform. Apart from that, it was not possible to ensure a good repeatability at the point of impact application. Since the plates studied have low thicknesses, keeping the same location as the point of impact was crucial for the analysis of the results. In addition to finding new impact devices with massive tempered steel balls (Figure 1), a mechanical device was also designed to improve these aspects. The designed device made it possible to choose the time of impact and the length of the lever arm of the metal stem of the ball. The device also allows the exchange of balls, due to the stiffness of the spring. With the development of this device, it became possible to apply impact always at the same point and with the same intensity, regardless of who performed the test, providing more accuracy in the results. The device is shown in Figure 2.

Some data acquisition parameters were defined to guarantee the reliability of results, such as the number of samples (N) as 1024 points, the time between the samples of 1µs, the frequency resolution of 0.98, the voltage of ±1.0 volts and the trigger voltage (in the transducer), which ranged between -0.45 and -0.80 volts. Some of these parameters needed to be changed during the analysis of results, because the high frequencies demanded greater care on these initial data. These data have proved to be reliable for lower frequencies.
Since the thicknesses of the plates were very small, the distance between the transducer and the point of impact did not follow the required distance of not more than 0.4 of the thickness of the plate [2]. However, the outer diameter of the transducer was 64 mm and, therefore, only the 120 mm thick plate could meet the standard recommendation. Thus, a single value of 10 mm between the point of impact and the transducer was adopted for all tests, which did not affect the quality of the results.

4. Presentation and Discussion of Results
In the data analysis, it was decided to use 880 sample points (N) due to the smaller thicknesses evaluated, which proved to be well suited for this study. The change in the number of points after the test resulted in the change of the record length (N x Δt) and frequency range (Δf) applied to Equation (3) to ensure the accuracy of the results. In all tests the amplitude frequencies below 20 kHz were considered as noise in the analysis of results, with the exception of the 120 mm thick plate, whose noise was considered below 15 kHz. The P-wave velocity was kept constant at 4,450 m/s. The results obtained in each concrete plate are discussed below.

4.1. 120 mm thick plate:
In the test of the 120 mm thick plate, an amplitude frequency of 17.9 kHz and an estimated thickness of 119 mm were found. Figure 3 shows the amplitude spectra when using the hollow and the massive 3.2 diameter metal ball, with manual and with mechanical impact. Although the frequency found is not high, the values of this plate served as reference for the other plates. One can notice from Figures 3a to 3d that the use of higher mass balls and of the mechanical device did not bring great benefits for the identification of the thickness frequency.

![3a) Hollow metal ball with manual impact.](image)

![3b) Hollow metal ball with impact device.](image)

![3c) Massive metal ball with manual impact.](image)

![3d) Massive metal ball with impact device.](image)

Figure 3. Performance of the massive and hollow metal balls with manual and mechanical impact in the 120 mm thick plate.

4.2. 63 mm thick plate:
For this plate a thickness of 62 mm associated to a frequency of 34.5 kHz were found. The use of balls of higher mass helped in the identification of the thickness frequency, as shown in Figures 4c and 4d.
(4a) Hollow metal ball with manual impact.  (4b) Hollow metal ball with impact device.  
(4c) Massive metal ball with manual impact.  (4d) Massive metal ball with impact device.  
Figure 4. Performance of the massive and hollow metal balls with manual and mechanical 
impact in the 63 mm thick plate.

4.3. 43 mm thick plate:  
Test on this plate resulted in an estimated thickness of 46 mm and frequency of 46.6 kHz. The impact performed with the device and the massive ball shows clearest frequency peak, as shown in Figure 5d.

(5a) Hollow metal ball with manual impact.  (5b) Hollow metal ball with impact device.  
(5c) Massive metal ball with manual impact.  (5d) Massive metal ball with impact device.  
Figure 5. Performance of the massive and hollow metal balls with manual and mechanical 
impact in the 43 mm thick plate.
4.4. 30 mm thick plate:
In this case, the manual impact with the two kinds of balls yielded a very high frequency of 65.8 kHz, resulting in a thickness of 32 mm. For the impact achieved through the device, a frequency of 63.5 kHz and a thickness of 34 mm were found for both balls. Although with the manual impact, the thickness seen in this case was closer to the actual thickness of the plate, it was necessary several impact tests to be able to obtain three good readings at the same point. With the impact made through the device, however, only three tests were necessary, making the test much faster. For this low thickness plate, the advantage of using the ball of larger mass and the impact device is clear, as shown in Figure 6d. Without the use of the impact device, as seen in Figures 6a and 6c, there are several amplitude peaks at low frequencies, which make it difficult to interpret the results.

5. Conclusion
The results indicated that the non-destructive test method of impact-echo can be successfully used to determine small thicknesses associated to high frequencies, especially if a mechanical device of impact application and higher mass balls are used. In these cases, the same impact force together with the better accuracy in the impact location facilitated the achievement of better waveforms, ensuring the repeatability of the test. The highest mass balls enabled a greater impact force, which also facilitated the obtainment of clearer frequency spectra.

The metal balls, usually used in impact-echo tests, may limit the results when used to measure even smaller thicknesses than the ones studied here because they are not capable to excite such high frequency peaks. For this reason, impact devices are already being developed with new materials that can excite even higher frequencies, thus improving the visualization of frequency spectra of impact-echo tests.

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