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NON-DESTRUCTIVE, ACOUSTIC EVALUATION OF MASONRY COMPRESSIVE STRENGTH

Booth, James[1,2], Bown, Katherine[1], Nguyen, Brandon[1], Zhang, Chi[1], Song, Bowen[1], Mendoza, Mark[1], Talukdar, Sudip[1], and Cox, Neil[1].

[1] British Columbia Institute of Technology, Canada

[2] James_Booth@bcit.ca

Abstract: In developing economies, the ability to implement and to maintain standard quality assurance programs for the masonry blocks used in residential and commercial construction may be beyond their current capacity. One consequence of this is that seismic events have a disproportionate cost in lives and in infrastructure damage. For example, in 2010 Haiti suffered a magnitude 7.0 earthquake while Chile weathered a magnitude 8.8 event, but the resulting loss of life was far greater in Haiti than in Chile. To address the need for introducing some type of quality assurance, a cross-disciplinary team at BCIT is investigating a non-destructive testing (NDT) protocol for assessing the compressive strength of masonry units from the airborne acoustic signals generated by striking the masonry unit. The sound is recorded and the measured characteristic vibrational frequencies, f, are correlated with the compressional strength of the units, f_c'. Testing on 64 concrete cylinders (length, L, diameter, L/2), ranging in compressive strength from 3 MPa to 30 MPa, has shown that $\ln \mathrm{f}_c' = \mathrm{a} + \mathrm{b}(2\mathrm{Lf})$ with a Pearson r- squared value of 0.95. A similar trend has been observed on testing of concrete blocks. The proposed NDT technique is very attractive as it can be implemented using low-cost technology that is found ubiquitously throughout the world, it can be quickly and easily applied by non-technical personnel, and the tested specimen is not damaged. This paper will provide an overview of the testing methods and the results that have been realized to date.

1 INTRODUCTION

Quality assurance (QA) is one of the cornerstones of good construction practices in developed economies. One important component is the measurement of the compressive strength of masonry units to insure that they adhere to well-defined performance targets (Zachar and Naik 1996) (ACI 318R-95 1995) (AS 3600 1988) (CSA A23.1 2004) (BSA 8110 1985) (CEB-FIP 1990) (MacGregor 1976) (CSA A165-04 2004). Standard testing procedures for concrete samples mandate the use of destructive testing on a statistically-selected fraction of fabricated units to verify their compressive strength directly (CSA A23.1 2004) (ASTM C140 1999) (ASTM C1716/1716M 2010). While this testing reliably verifies the quality of the concrete, it results in the destruction of a fixed percentage of the units. As well, the cost of the destructive testing infrastructure and the training of the personnel are important considerations when implementing a QA program. These costs are usually too high for many developing economies, which can leave them with little to no regulation on the testing of blocks used for private and public structures. The consequences of this vacuum contribute to a significant loss of life and infrastructure in the event of seismic episodes. The contrast between the 2010 magnitude 7.0 earthquake in Haiti and the 8.8 earthquake in Chile the same year is striking. In Haiti, an estimated 200,000 people lost their lives compared to fewer than 500 in Chile. While certainly not the complete story, the lack of compressive strength standards in Haiti contributed significantly to the disproportionate size of the catastrophe (Lovett 2010).

The need for some form of QA methodology provided the motivation for the formation of a multi-disciplinary team of engineers and physicists at BCIT to investigate alternative methods for estimating the strength of masonry units. The main criteria selected to meet the demands of limited resource environments were that the method should be: i) reliable, ii) low-cost, iii) easily integrated into existing fabrication methods, iv) readily carried out by local workers without the need for extensive training, and v) non-destructive. Using these guiding principles, the team focused on measuring the airborne sound generated by striking a masonry unit with a short duration, mechanical impulse. The idea was inspired by the behaviour of masons who evaluate the "sound" of bricks by clapping two together and recognizing whether they sound "right" or not (McEwan 2010). This observation supports the hypothesis that experienced masonry workers are performing a sophisticated frequency analysis of the airborne signal generated by striking two blocks together. The work described in this paper details our work which aims to investigate systematically this anecdotal evidence.

1.1 Background and Hypothesis

The hypothesis being tested is that the characteristic frequencies, f, associated with the normal vibrations of the masonry unit are correlated to the compressive strength of the sample, f_c'. Mathematically,

[1] $\mathrm{f}_\mathrm{c}' = \mathrm{g}(\mathrm{f}).$

This simple ansatz, while not an obvious connection, is a very general mathematical statement of the experience of masonry workers. There are significant challenges in establishing the form of the functional relationship. Namely, the compressive strength is an intrinsic property of the material. By contrast the normal mode frequencies observed will be influenced by both intrinsic factors (the material properties, including type of material used to create the concrete, the water content, age, and void fraction, to name a few) and extrinsic properties (the shape of the test object). The exact functional relationship between f_c' and f will be determined empirically.

There is a great deal of literature which describes acoustic testing of concrete based on attaching accelerometers to the sample and measuring the dynamic elastic modulus and Poisson's ratio from the modes of vibration of the sample, for example (Powers 1938) (ASTM C215 2002). In addition, the propagation speed of ultrasonic pulses (for example, (Parker 1953) (ASTM C597 2009) (ACI 228.2R-13 2013)) has been investigated as a means of estimating compressive strength of concrete. However, this technique has encountered limitations in the accuracies and reproducibility that can be achieved. Finally, acoustic pulse propagation through concrete slabs is used to estimate sample thickness and for locating defects (ASTM C1383 2004).

The technique applied in this work involves striking the masonry sample with a short duration, mechanical impulse (Cox, et al. 2016). The sample is isolated mechanically from the environment and from the support apparatus to minimize confounding effects of sounds generated by spurious sources, not related to the sample under test. The acoustic signals are digitized and subjected to a spectral analysis to reveal their frequency content. This data can be correlated to the normal modes of vibration of the masonry unit through tractable physical analysis for simple shapes such as cylindrical samples, compared to predictions of finite element analysis (FEA) for the expected vibrational modes for more complex shapes, or may be applied completely empirically to standardized shapes of masonry for strength calibration.

1.2 Cylindrical Concrete Units

As a first proof of principle, concrete cylinders were studied. Cylinders provided a simple shape for which the normal modes of vibration are readily visualized. One expects to find longitudinal vibrations, torsional modes of oscillation and transverse vibrations in these structures. The speed of the acoustic waves for each mode can be described (Rayleigh 1945) (Powers 1938) (Graff 1975) as: The longitudinal mode is expressed as,

[2] $v_{long} = \sqrt{\frac{E}{\rho}}$

where E is the elastic modulus of the material, and ρ is its density. The speed of the torsional mode is expressed as,

[3] $v_{tor} = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{1}{2(1+\nu)}\frac{E}{\rho}} < 0.71\ v_{long}.$

The speed of the transverse waves in a cylinder, as expressed below, is more complex,

[4] $v_{trans} = \frac{mk}{L}\sqrt{\frac{E}{\rho}} < 0.59\ v_{long}$

as it depends on both intrinsic properties of the material and on its shape. Here, $k = D/4$, is the radius of gyration of the cylinder around its transverse axis, D, is the diameter of the cylinder, L, is its length, and m is a numerical factor which is derived from the solution to the transcendental equation governing the motion of the cylinder. The value of m can also account for the coupling between the transverse and longitudinal motion (Powers 1938) of the cylinder. The cylinders conformed to standard geometry ($L = 2D$) in this work.

For a resonating cylinder, longitudinal and torsional standing waves will be set up in the material when the length of the cylinder satisfies,

[5] $L = \left(\frac{n}{2}\right)\lambda$

where $n = 1, 2, \ldots$ and λ is the wavelength of the resonant wave. The speed of these acoustic waves can be deduced experimentally from,

[6] $v = \lambda f = \frac{2L}{n} f$

For the lowest order mode, $n = 1$, we see that the speed of the wave can be measured from the length of the cylinder, L, and the measured resonant frequency, f, as $v = 2Lf$. The transverse mode is more complicated, following $v = 2\,\pi/m\,Lf$. From Equations 2 - 6 one observes that the longitudinal and torsional wave speeds can be expressed in terms of intrinsic material properties (an elastic modulus and a density of the material). This makes the speed a good candidate to relate to the compressive strength of the material, another intrinsic material property. Namely, the hypothesis Equation 1 can be refined as,

[7] $f_c' = h(v = 2Lf).$

To deduce the form of the functional relationship, a series of concrete cylinders were fabricated and tested as described below.

2 EXPERIMENTAL DESIGN

A schematic of the experimental arrangement used for the testing described in this paper is shown in Figure 1. The apparatus was constructed to ensure that the airborne acoustic signal detected is produced primarily by the vibrations of the masonry sample when it is stimulated. Any sound generated by the stimulation device or by the support frame will lead to confounding effects for the measurements. Further, the support system must not constrain the motion of the sample nor be mechanically coupled to the test specimen in a way that will alter the specimen’s natural resonant frequencies, as this would invalidate the assumptions underlying the signal analysis. To achieve these goals, an apparatus was built which consists of a metal frame onto which two cables, with adjustable separation, are attached. The flexible spacing is used to accommodate the size and shape of the masonry unit (either a concrete cylinder or a concrete block), placed on top of the two cables. While this apparatus performs exceptionally well, a simpler arrangement of supporting the masonry unit on top of a foam or rubber pad is also adequate for these measurements.

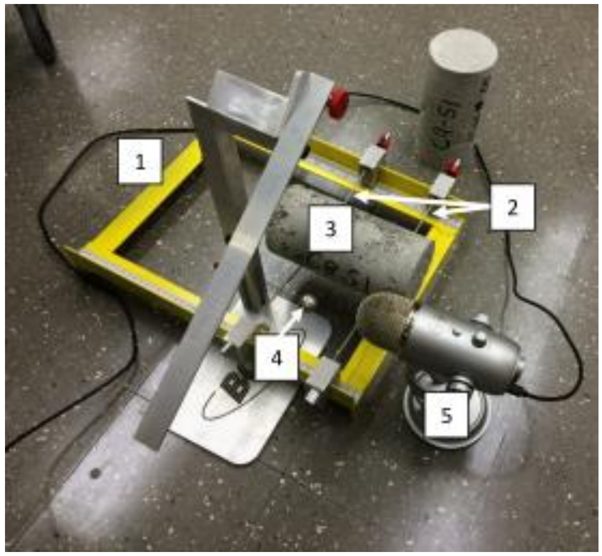

Figure 1: Custom apparatus used to test concrete samples: (1) Support frame, (2) Adjustable cables isolating the (3) sample, (4) ball-bearing/striker, and (5) Microphone to collect the acoustic signals.

A short duration, mechanical impulse is delivered using either a small ball-bearing arranged as a pendulum to strike the sample, or using a spring-loaded striker. Using a hammer for this purpose can produce undesirable vibrations of the head and/or of the handle. Further, the larger mass of a hammer will lead to longer duration strikes, limiting the range of sample natural frequencies that can be stimulated efficiently.

The ball-bearing pendulum was centered at the selected strike location, then the ball-bearing was drawn back so that the attached string was taut and parallel to the horizontal. The ball-bearing was released and allowed to swing freely into the sample, producing the strike. This technique provided a constant impulse being delivered, but had the disadvantage that the ball-bearing tended to bounce from the sample surface several times, delivering a series of impulses. Since these were separated sufficiently in time, the responses from each impulse could be isolated and analyzed.

The spring-loaded striker was constructed by modifying a pen-sized, hand-held flare apparatus commonly carried by hikers and others working outdoors where there is a risk of encounters with large animals such as bears. These devices are made of a cylindrical housing which contains a spring-loaded metal firing pin. The pin is drawn back in the housing to engage the spring, and then released by depressing a button, propelling it forward. In this work, the firing pin, which has a pointed end facing outward and a flattened end in contact with the spring, was rotated so that the flat end faced out to strike the test sample. The best results were obtained by ensuring that the firing pin moved clear of the spring, and was moving freely under its own momentum, clearing the edge of the housing as it struck the sample. The pin could then rebound cleanly after the strike, imparting a single impulse. This provided improved control over delivering a single impulse, but did contribute a small amount of noise to the measurements attributed to vibrations of the spring and the housing.

The masonry unit responded to the impulse by vibrating in some combination of its normal modes of vibration. The resonant frequencies were contained in the acoustic signals produced. The airborne sound was recorded using a microphone (Blue Yeti Studio USB microphone, 16 bit, 48 kHz sampling rate) attached to a digital computer. The signals were captured using an open-source, cross-platform software package (Audacity) and the frequency content was extracted using Fourier analysis. The acoustic spectrum was produced using a custom-written computer code in Python 2.7, based on the open-source Python scipy.fftpack module which has built-in fast Fourier transform (FFT) functions. Frequency components below 400 Hz were ignored in the analysis since these were, generally, produced via instrumental or environmental noise.

3 RESULTS

3.1 Cylindrical Concrete Units

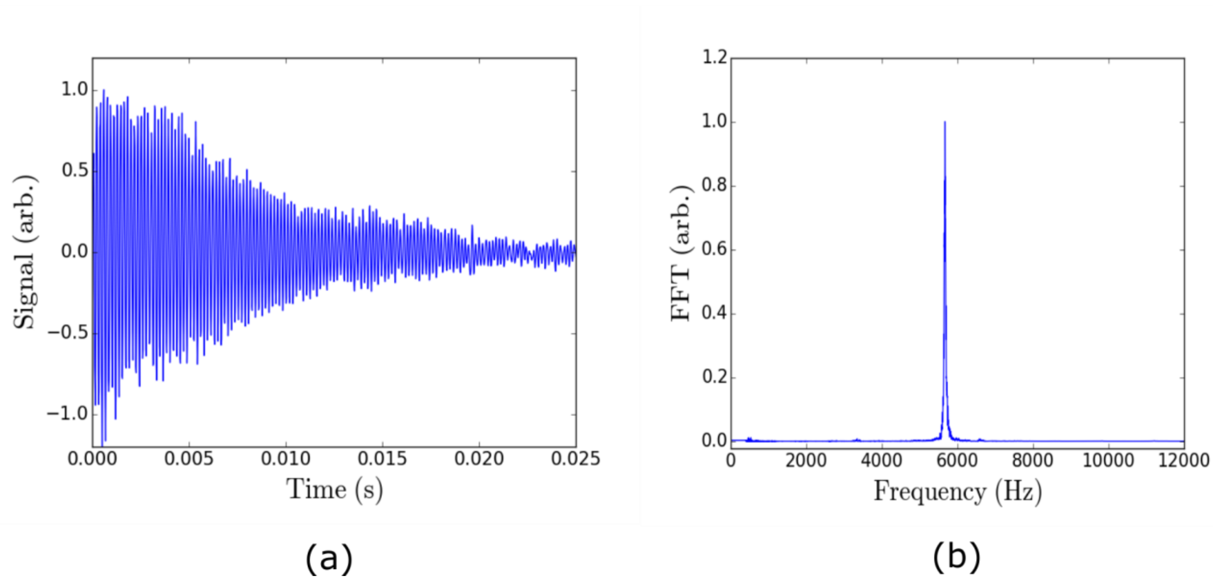

Figure 2: The airborne acoustic signal (a) and the frequency spectrum (b) of the sound produced by striking the end of a concrete cylinder.

One example of the acoustic signal and its frequency spectrum for a cylindrical concrete sample (15 cm diameter, 30 cm long) is shown in Figures 2(a) and 2(b). In this example, the stimulating impulse was delivered in the center of one of the flat faces of the cylinder, efficiently coupling the energy into the longitudinal mode of vibration. In this figure one observes that the airborne signal is dominated by a single (longitudinal mode) frequency at 5671 Hz, with a small contribution from a transverse mode (3448 Hz).

The strike location plays an important role in defining which oscillation modes are stimulated, and, therefore, the frequency content of the airborne signals. This is illustrated for a concrete cylinder in Figure 3, which shows the frequency spectrum associated with striking the cylinder in the center of the end face (longitudinal mode) and on the side (transverse mode). It is important to define the strike location so that the acoustic signals are interpreted correctly.

This acoustic testing was performed on 64 concrete cylinders (either 15 cm diameter x 30 cm long or 10 cm diameter x 20 cm long) fabricated at BCIT. The composition of the concrete was varied for each mix to yield a wide range of compressive strengths (Bown, et al. 2017) (K. Bown 2015). The compressive strength of these samples was then determined using standard destructive measurements with a Test Mark TM-6000-DB masonry testing machine. The compressive strengths of these samples ranged from 3 MPa to 30 MPa. The acoustic velocities for the longitudinal and torsional modes of oscillation were determined according to Equation 6, $v = 2Lf$. The data revealed a very strong correlation between the compressive strengths, f_c', and v for each mode of vibration. In particular, f_c' was exponentially dependent on the acoustic velocities. This is illustrated in Figure 4 which is a plot of $\ln f_c'$ versus v for both modes of oscillation. Linearizing the plots more clearly exposes the functional relationship and allows the data to be analyzed using straightforward linear regression techniques.

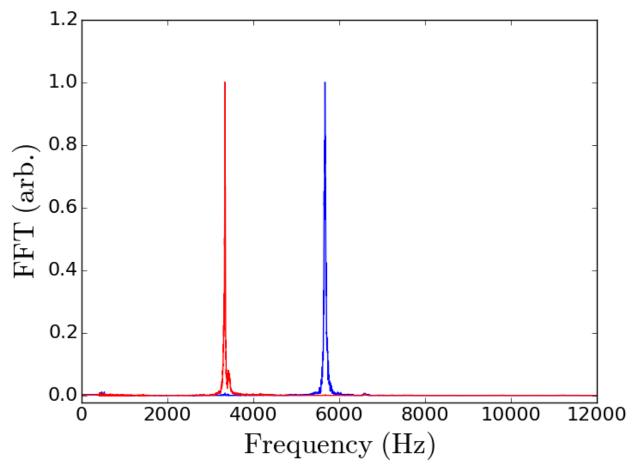

Figure 3: Plot of the frequency spectra produced by striking one cylinder at the center of its flat end face (blue trace) compared to striking it on its side (red trace).

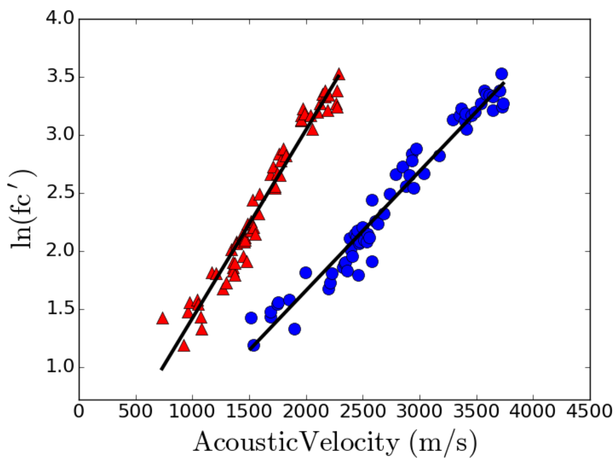

Figure 4: Plot of $\ln f_c'$ versus the measured acoustic velocities ($v = 2Lf$) of the longitudinal mode of vibration (blue circles) and of the transverse oscillation (red triangles).

[8] $\ln f_c' = -0.40(8) + 0.00103(3)\frac{s}{m} \cdot (2Lf)$

[9] $\ln f_c' = -0.20(7) + 0.00162(4)\frac{s}{m} \cdot (2Lf)$

The regression analysis found Equation 8 for the longitudinal oscillations and Equation 9 for the transverse mode. Both regressions had a Pearson r-squared correlation of 0.95. In other words, 95% of the variation in $\ln f_c'$ was explained by the variation in the acoustic velocities. The difference in the slopes reflects the fact that the acoustic speeds are different for the two different normal modes. If Poisson's ratio were known these samples, allowing one to relate the transverse speed from the longitudinal speed, as per Equations 2 and 4, one could combine the two data sets and perform a single regression analysis for improved precision. However, in this case, with the already strong correlation, this added complexity is not necessary.

3.2 Concrete Blocks: Demonstration of Empirical Calibration

For simple shapes, such as cylinders, an analytical description of the modes of vibration is possible. For more complex shapes Finite Element Analysis (FEA) can be applied to the masonry unit to extract relationships between oscillation modes and acoustic velocities. However, a purely empirical approach, which relates the compressive strength directly to the frequencies that are extracted from the spectral analysis treatment of the airborne acoustic signals, is also possible. Equations 8 and 9 show that the relationship can be expressed as,

[10] $\ln f_c' = a + k \cdot (v) = a + k \cdot (2Lf)$

where k depends on the mode of vibration, and L is the characteristic resonant length. For a complex shape, such as a block, these factors can be absorbed into an effective slope,

[11] $\ln f_c' = a + b \cdot (f)$

Thus, an empirical calibration is possible provided the shape of the masonry units being compared remains constant (maintaining a constant characteristic length, "L") and they are struck at a pre-determined, "standard" location (measuring the same mode(s) of oscillation). The calibration procedure described above for concrete cylinders can then be employed. Such an empirical calibration has previously been suggested for ultrasonic pulse velocity testing in concrete (Malhotra and Carino 2004).

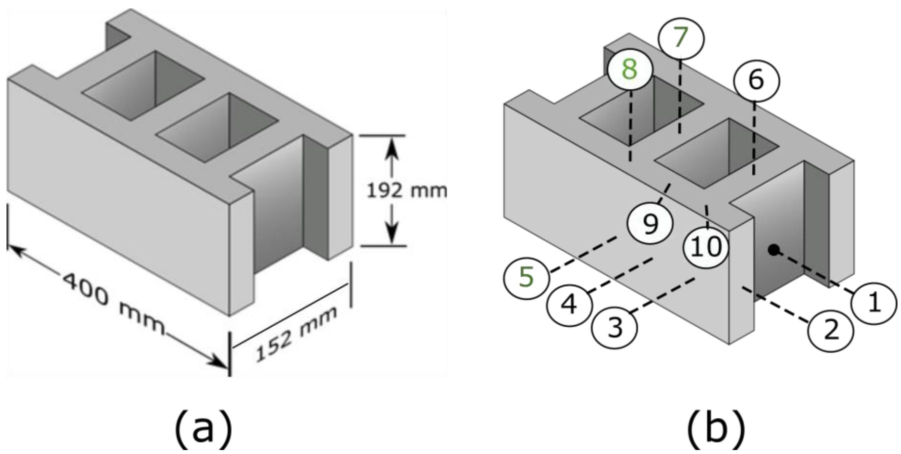

Figure 5: (a) Nominal dimensions of the 2 cell, concrete blocks used in this work. (b) Strike locations used to survey the acoustic responses of the blocks to an impulse stimulus.

Concrete blocks provide a test-bed for the empirical calibration procedure via Equation 10. These blocks have a complex shape and, as a result, will have much richer acoustic spectra than one observes in cylinders. A group of 31, two-cell concrete blocks of compressive strengths ranging from 3 – 30 MPa were fabricated at BCIT (K. Bown 2015). Each block had the nominal dimensions indicated in Figure 5 (a). A survey of the acoustic response of a single block was performed by striking it at the ten different locations indicated in Figure 5 (b). As expected, the spectral analysis revealed evidence of many modes of oscillation, shown in Figure 6 (a). However, the survey showed that striking the blocks along the center web at locations 5 and 7 produced spectra which are dominated by a single frequency. Striking location 8, also on the centre web, generated 3 main frequencies, two of which were identical to those from locations 5 and 7, plus a higher frequency component. (See Figure 6 (b).) These locations were adopted as the "standard" test locations for this calibration demonstration.

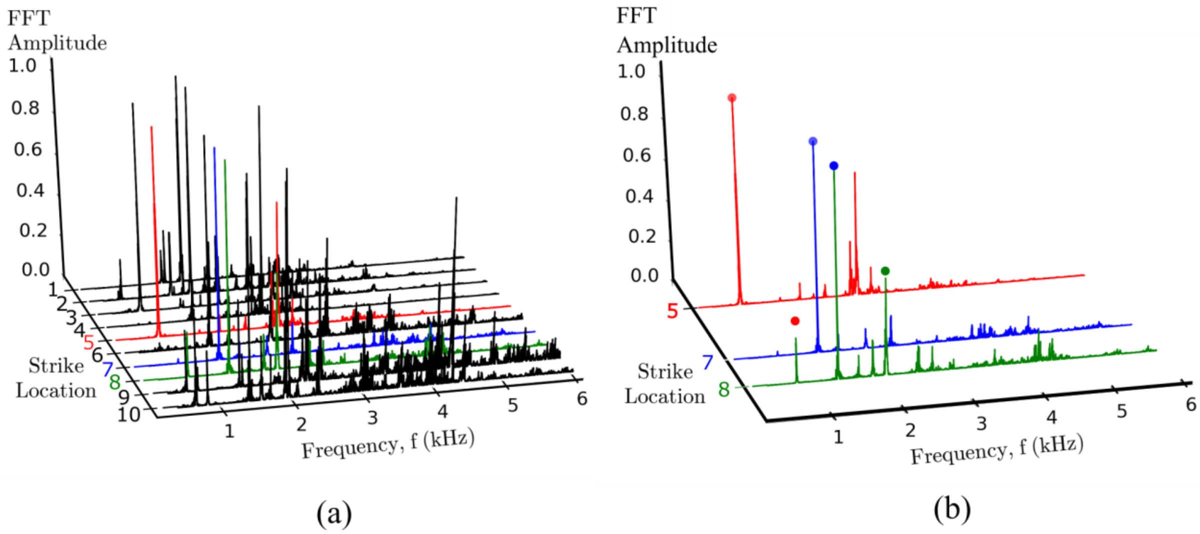

Figure 6: Plot of the frequency spectra derived from the airborne acoustic signals produced by striking the 10 different locations indicated in Figure 5(b).

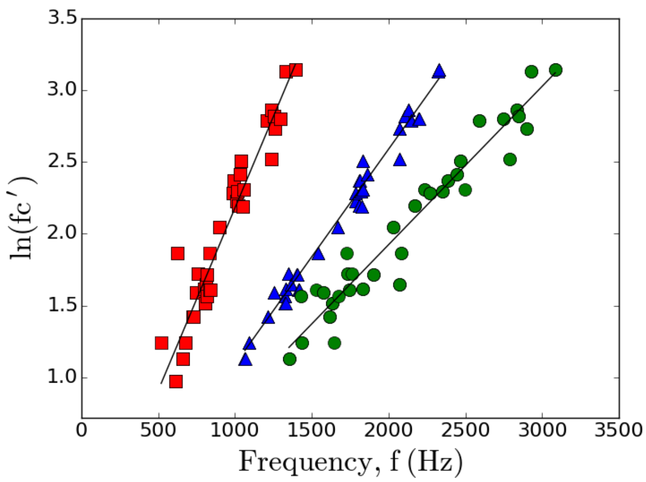

Figure 7: Plot of $\ln f_c'$ as a function of the dominant resonant frequency observed from strike location 5 (red squares), location 7 (blue triangles), and the higher frequency mode from location 8 (green circles). The data are correlated in accordance with Equation 10.

These blocks were subjected to acoustic testing followed by destructive testing to measure their compressive strengths. Plotting the $\ln f_c'$ as a function of the dominant resonant frequencies observed from strike locations 5, 7, and 8 yielded the behavior predicted by Equation 11, as indicated in Figure 7.

Table 1 lists the regression fits to the block data along with the Pearson r-squared correlation coefficient. The slopes of the different calibration curves vary from vibration mode to vibration mode, in agreement with Equation 10. The intercepts are expected to agree within their uncertainties, which they do for location 5 and 7 and for location 5 and 8. Location 7 and 8's intercepts lie slightly outside the 1 standard deviation uncertainties listed. No attempt to identify the different normal vibrations recorded was made for this empirical calibration. The strong correlations measured provide validation for the empirical calibration method for identically-shaped masonry units presented here.

Table 1: List of the linear regression fits for the acoustic frequencies, f, detected from impulse strikes at block locations 5, 7, and 8

Strike Location	Regression Fit Equations	Pearson r-squared coefficient
5	$\ln f_c' = -0.36(7) + 0.00254(7)s \cdot f$	0.93
7	$\ln f_c' = -0.41(4) + 0.00150(2)s \cdot f$	0.98
8	$\ln f_c' = -0.28(7) + 0.00110(3)s \cdot f$	0.94

4 CONCLUSION

A non-destructive method for estimating masonry unit compressive strength is presented in this work. Masonry units (concrete cylinders and blocks here) were stimulated with a short-duration, mechanical impulse at specific strike locations. The resulting airborne acoustic signals were recorded and subjected to spectral analysis to extract the frequencies of the dominant modes of oscillation of the samples. For cylinder test specimens, these frequencies were used to compute the speed of the acoustic waves, $v = 2Lf$. A strong, exponential correlation was observed between the compressive strength of these cylinders and the speeds. Linearized plots of $\ln f_c'$ versus v for longitudinal vibrations and transverse oscillations of the cylinders had a Pearson r-squared correlation coefficient of 0.95 for the data set composed of 64 samples with compressive strengths ranging from 3 MPa to 30 MPa. This result supports the hypothesis that the compressive strength can be deduced from the airborne acoustic signal, in accordance with the anecdotal evidence supplied by masons.

For complex shapes of masonry units which may not be amenable to theoretical analysis or to FEA methods, the technique described in this work can be adapted as an empirical calibration method. Namely, fixed shaped samples of varying compressive strengths can be tested by striking them at a pre-determined “standard” location and extracting the dominant resonant frequencies from the acoustic signals. These samples can be destructively tested and the compressive strengths fit to the acoustic frequencies as per Equation 10. This method was validated on a sample of 31, 2-cell concrete blocks ranging in strength from 3 MPa to 30 MPa. For these blocks, the standard strike locations were taken to be along the center web. Again, a strong correlation supporting an exponential dependence was demonstrated ($r^2 \geq 0.93$ for three resonant mode frequencies tested).

In conclusion, a novel, non-destructive, method to estimate the compressive strength of masonry units has been developed. The technique is low cost and simple to implement and use. A strong correlation between compressive strength and a small set of easy to access experimental parameters (masonry unit shape, resonant mode frequency, and strike location) has been demonstrated. These findings indicate that the technique is a promising candidate for compressive strength testing in both developing and developed economies.

Acknowledgements

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