Continuous Strength Measurements of Cement Pastes and Concretes by the Ultrasonic Wave Reflection Method

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Abstract

Concrete compressive strength is a critical design criterion for concrete elements and should, as a consequence, be carefully controlled to ensure structural integrity and intended functionality. As the cementitous binder of concrete hydrates, its strength and elastic modulus increase with time as concrete transitions from a fluid with suspended particles to a rigid but porous solid. Porosity of the material decreases as hydration products fill available space to create a densified structure. Ultrasonic instruments are able to continiously measure the material properites of cementitious materials. This is a significant advantage over destructive, quasi-static compression test of cylinders or cubes at discrete time intervals. Here, we estimate the elastic modulus and compressive strength of a cement paste or concrete from the amplitude of a reflected ultrasonic wave. A series of cement pastes and concretes are tested in quasi-static compression to establish a correlation between compressive strengths estimated from ultrasonic methods and classical compression test. The differences between the compressive strengths obtained by quasi-static compression tests and ultrasonic wave reflection differ by ± 20 % over a range of compressive strengths spanning more than 3 decades.

Keywords: Compressive Strength Measurements, Early-age hydration, Non-destructive Testing, Setting time

Introduction

Compressive strength testing is a commonly utilized early-age test to characterize cementitious materials [1]. Strength evolution is a key parameter in construction, and consequently, all product development or quality control operations make extensive use of destructive compression and tensile strength tests. Due

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to the random and heterogeneous nature of the cement-based pastes, mortars, and concretes, an average of at least 3 specimens at a given age is typically required to obtain an acceptable precision of compressive strength results, often cited as the multi-laboratory coefficient of variation of about 7 % for mortar cube testing according to the ASTM C109 standard test method [2]. The process of preparing specimens for testing by ASTM C109 requires mixing, casting, curing, and destructive testing. This process is labor intensive and cannot be easily automated. Replacing this method of testing with one that does not require this type of sample preparation, even on a partial basis, would represent a gain in material testing efficiency, as well as a reduction in material and labor costs.

Ultrasonic methods are used in industrial application to measure the evolution of the elastic modulus of a cementitious materials over time [3]. Three techniques are commonly used: (i) compression sound wave propagation through the concrete [3, 4, 5], (ii) speed of the surface wave at the interface between concrete and air [6], (iii) and wave reflection at the interface between the concrete and a wave guide [7, 8, 9, 10]. The three techniques measure the acoustic properties of the materials of interest, which are related to their mechanical properties. The attenuation of the ultrasonic wave through the material may be used to estimatethe evolution of the shear or bulk modulus of material, respectively G and K. Acoustic impedance measurements of shear waves have been successfully used to monitor the flocculation and setting times of cement paste [11, 12]. Akkaya et al. [8], estimated the compressive strengths of concretes with aggregate volume fractions from 50 % to 70 % using ultrasonic wave reflection techniques. Results indicate the reflection loss coefficient is sensitive to cement hydration and, after calibration, the reflection loss change may be used to predict concrete strength at early ages.

This study estimates the strength of concrete, with aggregate volume fractions ranging from 10 % to 70 %, using ultrasonic wave reflection techniques. Accelerating admixtures are added to the concrete assess the ability of this technique to estimate the strength of samples with a rapidly changing compressive strength. A custom-built ultrasonic device is used to measure the reflection loss coefficient of a reflected wave generated at the interface of a waveguide and a hydrating cementitious material. The shear modulus of the sample is estimated from this measurement, which is related to the elastic modulus and, ultimately, the strength. Compressive strengths estimated by this method are compared to traditional quasi-static compressive strength measurements to assess the suitability of replacing these measurements with non-destructive assessments of strength.

Materials and Methods

Mixture Proportions

Both samples of cement paste and concrete, containing aggregates up to 70 % by volume, are evaluated in this study. An ASTM C150 Type III ordinary portland cement (OPC) is used to limit the impact of the temperature increase during curing on the hydration kinetics of the samples [13]. Cement pastes were prepared using three non-commercial accelerators: two alkali-free sulfoaluminate suspensions, called accelerators A1 and A2, and a sodium silicate-based accelerator. The cement was mixed with a limestone powder, having a similar particle size distribution to the cement, and water with a Hobart[1] mixer at a speed setting of 2 (285 rev/min ± 10 rev/min) for 3 min. Samples were prepared for quasi-static compression testing by spraying the materials into the mold using the the device described in [14]. In the case of ultrasonic measurements, the paste was sprayed directly onto the instrument. The accelerator and cement paste are mixed before the material exits the nozzle. Both paste and accelerator are pumped at a constant flow rate to a mixing chamber. Compressed air at 200 kPa creates a homogeneous mixture of the two components. Quasi-static compression testing samples are prepared using 40 mm x 40 mm x 40 mm cube molds. Samples for ultrasonic measurements are cylinders with a diameter of 100 mm and a thickness of 20 mm. Samples for both test are shown in Figure 1. The samples were kept at a temperature in the range of 23 °C to 27 °C. The paste formulations are summarized in Table 1. Concrete mixtures were prepared per the formulations provided in Table 2 and cast into the same molds used for the paste specimens.

(a) Cylinder Specimens

(b) Cube Specimens

Figure 1: Samples of concrete for testing, including cylinder (100 mm diameter and 20 mm height) and cube (40 mm) geometries, shown after compression tests.

Table 1: Formulation of the sprayed cement paste.

	Cement (kg)	Limestone Powder (kg)	Water (kg)	Accelerator	Accelerator Concentration (by mass of cement)
Paste 1	1	1	0.46	Alkali-free A1	6 %
Paste 2	1	1	0.46	Sodium Silicate	10 %
Paste 3	1	1	0.36	Alkali-free A2	6 %
Paste 4	1	1	0.38	Sodium Silicate	10 %

[1]Certain commercial products are identified in this paper to specify the materials used and the procedures employed. In no case does such identification imply endorsement or recommendation by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.

Table 2: Concrete formulations used for quasi-static and ultrasonic testing.

Aggregates (vol. %)	Cement (kg)	Limestone Powder (kg)	Water (L)	Aggregates 4 mm - 8 mm (kg)	1 mm - 4 mm (kg)	$<$ 1 mm (kg)	Admixture $(SiO_2)_nO$ 2 %/kg-cement
10 %	3.15	3.15	1.48	0.14	0.35	0.21	0.12
30 %	2.45	2.45	1.24	0.42	1.05	0.63	0.09
50 %	1.75	1.75	1.01	0.70	1.75	1.05	0.06
70 %	1.05	1.05	0.77	0.98	2.45	1.47	0.04

Derivation of Equations

The ultrasonic wave speed of an isotropic material is a function of the Lamé coefficients and the density of the material. A sample may be considered homogenous with respect to the propagating ultrasonic wave when the largest heterogeneity of the material is smaller than the wavelength. A wave propagating at 1000 m/s with a frequency of 1 MHz will have a wavelength of 1 mm. The particle size for cement powder is approximately < 100 µm, indicating cement paste may be treated as a homogenous material for this particular propagating wave. For concrete or mortars containing aggregates (or other heterogeneities) larger than 1 mm, the heterogeneities will cause the propagating wave to scatter, further complicating the assessment of the concrete's elastic properties. To overcome this, the reflected wave generated at the wave guide-sample interface may be used to infer the changing elastic properties of the paste portion of the concrete. The amplitude of the reflected wave can be used to estimate the strength of the sample by recognizing that the amplitude of the reflected wave will decrease as the acoustic impedance of the binder portion of the sample increases. When the binder is composed of OPC, the increase in the acoustic impedance is a result of hydration reactions between the cement and water which create hydration products, such as calcium silicate hydrate (C-S-H), which create percolated network of particles.

Concrete may be considered a two phase composite material consisting of a paste phase (binder and water) and an aggregate phase. The volume fraction of the aggregates in concrete is spatially dependent near the surface of a mould or a form (the wall effect) [15]. Numerical simulation in three dimensions have shown the volume fraction of aggregates converges to the theoretical volume fraction (volume of aggregates/total volume) at approximately 10 mm from the wall [16]. This result holds for the range of volume fractions of interest to this study and indicates that, for the first few millimeters from a surface, the primary constituent of the material is cement paste. The shear modulus of the cement portion of a concrete sample may be estimated by generating a reflected wave at the interface between the waveguide and the sample. The reflected wave generated at the waveguide/sample interface is assumed to follow the theory outlined in [17] and is assumed to probe the cement paste portion of the sample due to the wall effect. A shear wave with amplitude, A_i, is generated within a waveguide with an acoustic impedance Z_{wg}. At an interface of the waveguide and the sample the medium experiences a sudden change in acoustic impedance. A portion of the incident wave is transmitted through the interface to the sample medium with impedance, Z_s, while the remaining portion is reflected from the interface to ultrasonic sensor. The reflection coefficient, r, is the ratio of the reflected wave amplitude, A_r, to the amplitude of the incident wave and is related to the impedance of the two mediums by relationship, $r(t) = A_r/A_i = (Z_{wg} - Z_s(t)) / (Z_{wg} + Z_s(t))$ [17], where t is the time after mixing. $Z_s(t)$ is assumed to represent the time-dependent impedance of the cement paste portion of the concrete. The increase in the portion of the incident wave which is transmitted through the samples and the decrease in the amplitude of the reflected wave generated at the waveguide-sample interface has been attributed to the formation of a percolated network of cement particles which is a result of the formation of hydration products within the cement paste. [18, 19, 20].

The reflection coefficient is estimated from amplitude measurements of the incident and 1$^{\text{st}}$ reflected wave as a function of time. The reflection coefficient is used to estimate the shear modulus of the paste portion of the concrete. The elastic modulus of the paste is calculated assuming the sample obeys linear elastic, isotropic theory and a Poisson's ratio, ν. The range of expected values of ν is 0.2 to 0.3 [21, 22]. Here a value of $\nu = 0.3$ is used in computing the elastic modulus. The effective elastic modulus of the concrete is estimated using the Hashin-Shtrikman model and the concrete strength is calculated assuming a power-law relationship between elastic modulus and compressive strength.

Relationship between ultrasound and mechanical properties

Ultrasonic waves propagate through solids in either compression or shear modes. Both the shear and elastic modulus capture the time-dependent evolution of the material. The shear modulus experiences an increase by more than 5 orders of magnitudes from the fresh state after mixing to the final setting of the paste which enables accurate study of the paste flocculation and its early age setting [23]. Thus, shear waves are preferred for recording the evolution of the mechanical properties at early ages [24].

In this study, a shear wave is generated by one of the transducers and propagates through the wave guide until a reflection is created at the wave guide-sample interface. The reflected wave, which is detected by the same transducer that generated the pulse, is the first signal received by the transducer (at time t_1 in Figure 2). The following reflected wave is a result of the sample-air interface (t_2). Figure 2 is a schematic representation of the ultrasonic test configuration.

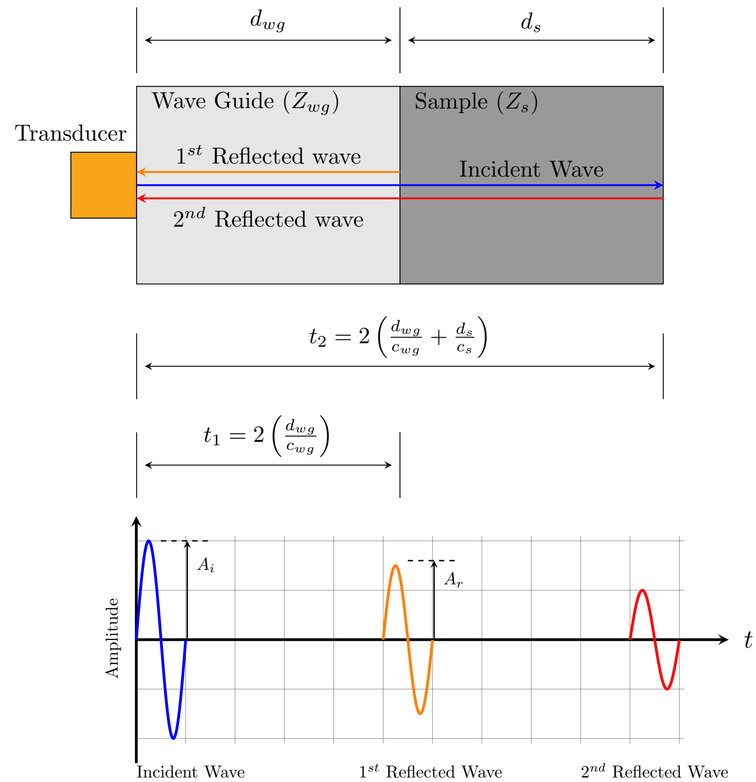


Figure 2: Echo mode measurement of ultrasonic wave propagation. A pulse generated from the transducer travels through the wave guide were a reflection wave is created. The arrival time of this wave at the transducer is t_1.

All the pulse energy is reflected when the wave guide is in contact with the air, as the acoustic impedance of air is much less than that of the wave guide ($Z_{air} \ll Z_{wg}$). In the case of cementitious materials, the amplitude of the reflected wave changes with time as hydration reactions create a hardened material [9]. The shear modulus, $G\left(t\right)$, of the sample is estimated using Equation 1, where $Z_s\left(t\right)$ is the acoustic impedance of the sample, ρ_s is the density of the sample, and $r\left(t\right)$ is the reflection coefficient, which is estimated from the ratio of the amplitude of the reflected wave to the amplitude of the incident wave.

$$G\left(t\right) = \rho_s^{-1} Z_s\left(t\right)^2 = \rho_s^{-1} Z_{wg}^2 \left(\frac{1 - r\left(t\right)}{1 + r\left(t\right)}\right)^2 \tag{1}$$

Under the assumption of a homogeneous and isotropic material, the shear modulus, G, is related to the elastic modulus, E, through Poisson's ratio, ν.

The relationship between the elastic modulus and the compressive strength, σ, of a cement paste or a mortar is obtained by a power law function as reported [25], and denoted in Equation 2, where k and n are the fitting parameters. Here, we assume $n = 0.5$ [26].

$$E = k\sigma^n \tag{2}$$

The relationship between compressive strength and elastic modulus, given in Figure 2, is acceptable over a broad range of compressive strengths and elastic moduli, even if concrete is not strictly a homogenous, linear elastic, isotropic material. The shear modulus may be expressed as a function of compressive strength as shown in Equation 3.

$$G = \frac{k\sigma^n}{2\left(1+\nu\right)} \tag{3}$$

Therefore, by measuring the shear modulus G with the ultrasonic device and using Poisson's ratio ν for a cement paste or concrete, one can use Equation 3 to calculate σ_u by Equation 4.

$$\sigma_u = \left(\frac{2G\left(1+\nu\right)}{k}\right)^{\frac{1}{n}} \tag{4}$$

When the sample undergoing test may be treated as homogenous with respect the the ultrasonic waves, e.g., cement paste, the compressive strength of a sample is related to the reflection coefficient, r, by introducing Equation 1 into Equation 4 to produce Equation 5.

$$\sigma_u\left(t\right) = \left(\frac{2\left(1+\nu\right)}{k}\frac{Z_{wg}^2}{\rho_s}\left(\frac{1-r\left(t\right)}{1+r\left(t\right)}\right)^2\right)^{\frac{1}{n}} \tag{5}$$

When the sample undergoing testing is heterogenous, e.g., concrete, the Hashin-Shtrikman lower bound model (see [27]) is used with Equation 1 to compute the composite shear modulus of the sample. The composite shear modulus is then used with Equation 4 to compute the compressive strength. The relationship between the compressive strength measurement by quasi-static compression test and shear modulus correlation is estimated using linear regression techniques. The uncertainty of the compressive strengths predicted by ultrasonic measurements is estimated at a 95 % confidence level.

The objective of this study is to compare measurements of compressive strengths of cement paste and concrete samples made by physical testing (σ_c) and estimated from Equation 5 (σ_u).

Equipment

The ultrasonic device used in this study is presented in Figure 3. It is a custom-built, non-commercial device for evaluating the material proprieties of cement-based materials. The device is composed of 8 cells which record and process data independent of each other. Each cell each contains three ultrasonic shear wave transducers bonded to the wave guide, operating at a frequency of 0.8 MHz. The three transducers operate sequentially. Each transducer will generate an incident wave and detect the 1$^{\text{st}}$ reflected wave to estimate the reflection coefficient at the wave guide/sample interface. The amplitude of the detected waves is calculated by taking the root mean square of the signal. The amplitudes from the three transducers are averaged to account for heterogeneities, such as air voids and inclusions, in the sample volume that may affect the acquired signal. Multiple independently operating cells are used to assess the sample variation for one mixture formulation or they can be used to test multiple mixture formulations simultaneously. The user can program the sampling interval, length, and test duration according to their needs. The signal is processed by a low noise amplifier, sampled at 75 MHz with 16-bit resolution, and saved for post processing. Full details of the ultrasonic device used in this study are reported in [28].

Figure 3: Ultrasonic device used in this study. Device consists of 8 cells, each with 3 transducers and one temperature sensor.

Results

Comparisons between quasi-static compressive strength measurements and compressive strengths estimated by Equation 5 are of interest to this study. The presented results first address the case of cement paste samples and then address the case of concrete samples with two aggregate shapes at four volume fractions.

Cement Paste

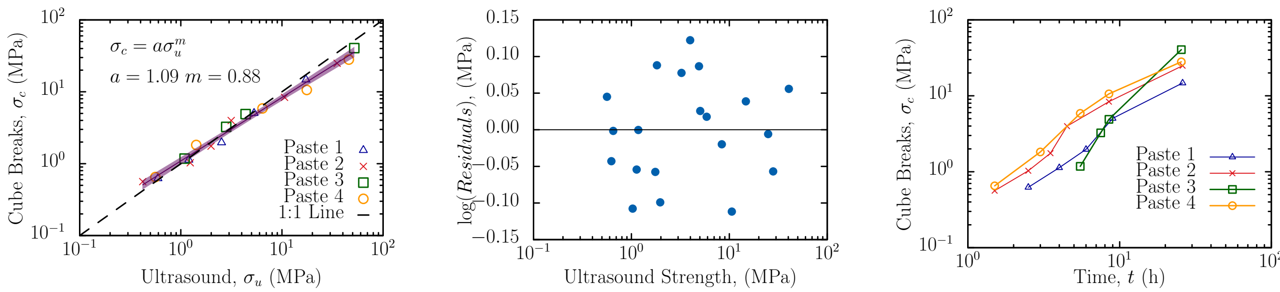
Figure 4 reports the relationship between compressive strengths estimated by Equation 5 and quasi-static compression testing of the four paste formulations reported in Table 1. The mean quasi-static compressive strengths and standard deviations for 10 replicate specimens, are reported in Table 3. The maximum coefficient of variation of the quasi-static compressive strengths is 10 % of the measured value. Figure 4c reports the quasi-static compressive strengths as a function of the curing time. Compressive strength measurements span a range of two orders of magnitude in an approximately 24 h period.

As can be observed in Figure 4a, there is a power-law relationship between the two methods of determination of the compressive strength. To assess the relationship between the compressive strength of the paste determined by quasi-static compression tests (σ_c) and ultrasonic measurements (σ_u), linear least squares regression was performed to determine the coefficients a and m of the power-law equation described in Equation 6.

$$\sigma_c = a\sigma_u^m \tag{6a}$$

$$\log(\sigma_c) = \log(a) + m\log(\sigma_u) \tag{6b}$$

Performing linear least squares regression on the linearized form of the data produces the estimates for $\log(a)$ and m given in Table 4. The expanded uncertainty of $\log(a)$ at a 95 % confidence level is computed by multiplying the standard error in Table 4 by the t-statistic, $t_{0.975,18} = 1.762$. The lower bound of the confidence interval for $\log(a)$ is -0.0008 and the upper bound is 0.077, corresponding to a confidence interval of 19.6 %. The plot of the residuals of the fitted values versus the quasi-static compressive strengths is shown in Figure 4b. Akaike Information Criterion (AIC) was used to assess the suitability of the model in Equation 6 compared to a linear model of the form $\sigma_c = \beta_1 \sigma_u + \beta_0$. The small sample AIC values for the model of Equation 6 and the linear model are -43.92 and 82.53, respectively, with a probability that the linear model minimizes information loss compared to power law model of 1.22×10^{-55}, indicating the model of Equation 6 is suitable for this data set.



(a) Relationship between ultrasonic computed and quasi-static compressive strength measurements

(b) Residuals of linear least squares regression of Equation 6

(c) Quasi-static Compressive Strengths

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Figure 4: (a) Relationship between the strength measured with ultrasound and with the compression of the cubes. The representations are all made in logarithmic scales. (b) Residuals plotted versus cube break strengths. (c) Evolution of paste strength as a function of time for the four pastes.

Table 3: Mean $(\bar{X})$ quasi-static compressive strengths and standard deviation $(\sigma_{\bar{X}})$ of 10 replicate samples for the paste mixtures described in Table 1. Units: MPa.

time	Paste 1		Paste 2		Paste 3		Paste 4	
(h)	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$
1.5	–	–	0.56	1.1×10^{-3}	–	–	0.65	1.3×10^{-3}
2.5	0.62	1.2×10^{-3}	1.03	2.1×10^{-3}	–	–	–	–
3.0	–	–	–	–	–	–	1.82	3.6×10^{-3}
3.5	–	–	1.76	3.5×10^{-3}	–	–	–	–
4.0	1.13	2.3×10^{-3}	–	–	–	–	–	–
4.5	–	–	3.98	1.6×10^{-2}	–	–	–	–
5.5	–	–	–	–	1.18	2.4×10^{-3}	5.87	2.9×10^{-2}
6.0	1.97	3.9×10^{-3}	–	–	–	–	–	–
7.5	–	–	–	–	3.25	9.7×10^{-3}	–	–
8.5	–	–	8.38	6.7×10^{-2}	4.90	2.5×10^{-2}	10.61	1.1×10^{-1}
9.0	5.05	2.5×10^{-2}	–	–	–	–	–	–
25.5	–	–	–	–	40.54	1.6	28.03	7.8×10^{-1}
26.0	14.75	2.2×10^{-1}	24.92	6.2×10^{-1}	–	–	–	–

Table 4: Parameter estimates determined by linear least squares regression. Experimental data was linearized by taking the base 10 logarithm of each observation.

	Estimate	Standard Error
$\log(a)$	0.038	0.022
m	0.883	0.025

It is possible to estimate the compressive strengths of cement paste with Equation 5 and then one can correct the measured values using the power-law relationship $\sigma_c = a\sigma_u^m$ determined previously with $a = 1.09$ and $m = 0.88$ which enables continuous and reproducible measurement of the compressive strength of a cement paste.

Concrete

In this section, we study the feasibility to use the ultrasonic device to measure the compressive strength of a concrete sample. As previously discussed, when the size of the aggregates are larger than the wavelength of the ultrasonic wave, scattering effects begin to dominate the acquired signal. The elastic properties of a concrete sample are estimated from the wave that is reflected at the sample-wave guide interface, i.e., the 1^{st} reflected wave in Figure 2.

Quasi-static Compression Test

The quasi-static compressive strength development of concretes created with crushed or rounded aggregate, at various volume fractions, is reported in Figure 5. The quasi-static compressive strengths range between 0.2 MPa and 20 MPa over a time period ranging from 4 h to 30 h. Tables 5 and 6 report the mean quasi-static compressive strength of the cubes composed of crushed aggregates and rounded aggregates, respectively.

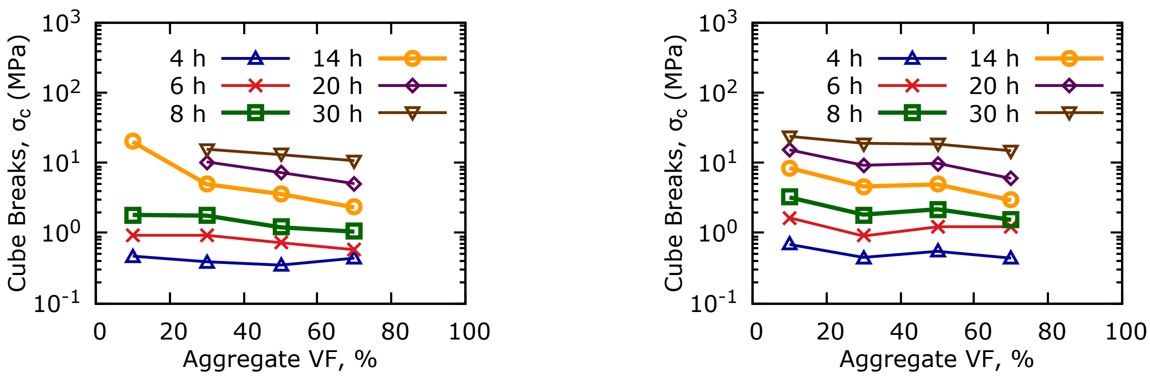
Table 5: Mean $(\bar{X})$ quasi-static compressive strengths and standard deviation $\sigma_{\bar{X}}$ of 10 replicate samples for the concrete mixtures with crushed aggregates described in Table 2. Units: MPa.

time	VF 10 %		VF 30 %		VF 50 %		VF 70 %	
(h)	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$
4	0.47	0.06	0.39	0.04	0.35	0.02	0.44	0.04
6	0.94	0.12	0.94	0.1	0.73	0.1	0.58	0.03
8	1.82	0.13	1.78	0.11	1.21	0.07	1.05	0.05
14	–	–	4.99	0.22	3.62	0.18	2.33	0.15
20	–	–	10.4	0.25	7.33	0.20	5.11	0.28
30	20.09	0.64	15.77	5.73	13.21	0.64	10.81	0.37

Table 6: Mean $(\bar{X})$ quasi-static compressive strengths and standard deviation $\sigma_{\bar{X}}$ of 10 replicate samples for the concrete mixtures with rounded aggregates described in Table 2. Units: MPa.

time	VF 10 %		VF 30 %		VF 50 %		VF 70 %	
(h)	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$	$\bar{X}$	$\sigma_{\bar{X}}$
4	0.69	0.06	0.39	0.06	0.54	0.05	0.44	0.03
6	1.66	0.09	0.89	0.07	1.26	0.1	0.94	0.06
8	3.24	0.2	1.83	0.09	2.16	0.12	1.55	0.17
14	8.51	0.26	4.63	0.34	4.63	0.34	2.95	0.2
20	15.45	0.6	9.29	0.78	9.92	0.63	6.03	0.19
30	24.06	0.98	17.15	1.06	18.6	0.59	14.97	0.98

The quasi-static compressive strength of the two concretes with crushed or rounded aggregates is reported in Figure 5 as a function of aggregate volume fraction and age of the specimen. For both the rounded and crushed aggregates, the strength is globally decreasing with an increasing volume fraction of aggregates, indicating a weak interface between cement paste and the aggregates. As the strength of the paste increases from approximately 0.2 MPa to 20 MPa, fracture begins to occurs preferentially at the interface between the paste and the aggregates, increasing the path length of the fracture, which increases the bulk fracture toughness of the material.



(a) Crushed Aggregate

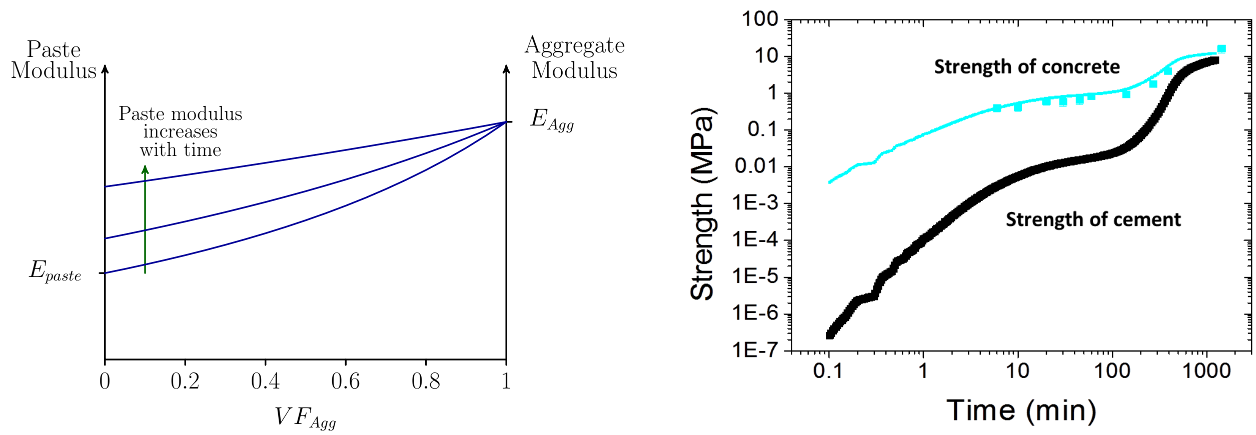
(b) Rounded Aggregate

Figure 5: Quasi-static compressive strength of concrete cubes with various volume fractions of (a) crushed aggregates and (b) rounded aggregates.

Ultrasonic Measurement of Concrete Strength

The ultrasound technique is measuring amplitude of the reflected wave generated at the wave guide/sample, which is assumed to be primarily composed of cement paste. As a consequence, this technique does not account for the impact of the aggregates or air voids (or fibers when present) on the total strength. An estimation of the concrete elastic modulus, E_c, is required to compute the concrete strength. E_c is computed using the lower bounds of the Hashin-Shtrikman equation [27]. Calculations require measurements of the paste elastic modulus, which have be computed by ultrasonic measurements, and the elastic modulus of the aggregates. Aggregate elastic modulus is dependent upon the mineralogy and can have a wide range of reported values such as those reported in [25]. Siliceous aggregates used in this study are assumed to have an elastic modulus of 80 GPa. The strength of the bond between the aggregate and the cement paste is an important factor. The nature of the interfacial transition zone (ITZ) is dependent on time, type of aggregate, and its reactivity with the cement paste, and is not easy to quantify. In fact, both strength of the aggregates and their ITZ are difficult to access [14, 12, 20]. The Hashin-Shtrikman equation does not account for such effects and as such, the ultrasonic-based predictions of concrete strength are insensitive to the nature of the paste-aggregate bond.

The dependence of the concrete elastic modulus (and strength) on aggregate content is schematically represented in Figure 6a where the range is bounded by the strength of the cement paste (VF $=$ 0 %) and that of the aggregate (VF $=$ 100 %). As the aggregate strength remains constant as cement undergoes hydration reactions, and is higher than the strength of the cement paste at early ages, the concrete strength is only a function of the cement paste strength and time. Assuming the aggregates do not change the reactivity of the cement, one can use the strength evolution of the cement paste to compute the concrete strength using the Hashin-Shtrikman model. This method is demonstrated in Figure 6b where both the cement strength (black line) and the computed concrete strength (cyan line) are plotted. Penetration test results are displayed as cyan squares. The agreement between the results of the penetration test and ultrasonic measurements is interpreted to validate the use of the Hashin-Shtrikman model for indirect concrete compressive strength measurements.

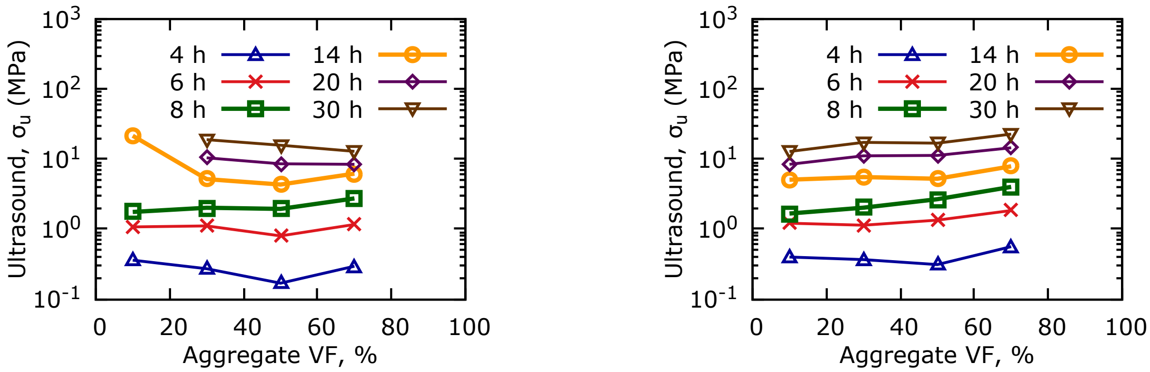


(a) Hashin-Shtrikman Lower Bound

(b) Development of compressive strength with time

Figure 6: (a) Elastic modulus of concrete computed by Hashin-Shtrikman lower bound equation. The elastic modulus of the cement paste phase changes with time. (b) Evolution of the strength as a function of the time for a cement and a concrete. The points are obtained with mechanical tests and the upper line calculated from the ultrasonic measurements made on the cement paste.

A direct measurement of concrete compressive strength may be obtained by exploring the relationship between σ_c and σ_u for samples containing aggregates. Compressive strengths from ultrasonic measurements are computed using Equation 1 and the Hashin-Shtrikman lower bound equation. The results are reported in Figure 7 and show that ultrasonic measurements of compressive strength appear to be independent of volume fraction and shape. This is expected as the amplitude of the 1$^{\text{st}}$ reflected wave is dependent upon the acoustic impedance of the sample, which changes as a result of the formation of hydration products and does not directly assess the interior. Moreover, the compressive strength measurements made with ultrasound are different from those obtained by quasi-static compression, reported in Figure 5, as the strength for the rounded aggregates increases with increasing aggregate content for all time points.



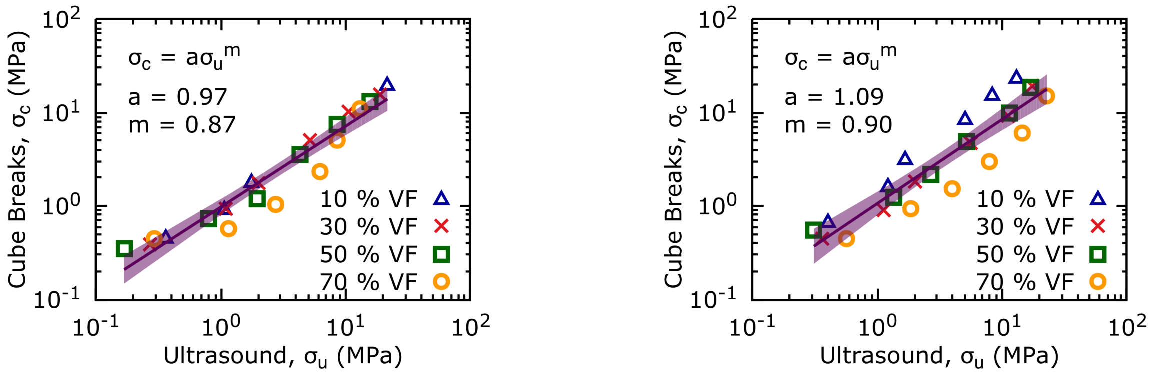
(a) Crushed Aggregate

(b) Rounded Aggregate

Figure 7: Compressive strength of mortar cubes, measured by ultrasonic methods, at various volume fractions of (a) crushed aggregates and (b) rounded aggregates.

The relationship between the strengths measured with ultrasound and quasi-static compression for all concentrations and type of aggregates are represented in Figure 8. The cube strength measured by quasi-static compression testing as a function of compressive strength measured by the ultrasonic method follows a power-law relationship for volume fraction of aggregates up to 50 %. At 70 % volume fraction of aggregates, excess entrained air during the spray process causes the quasi-static compressive strength to be lower than the strength estimated by the ultrasonic method.

For the crushed aggregates, the quasi static compressive strength fall within the 95 % confidence intervals demonstrating the possibility to use ultrasonic measurements to estimate the compressive strength of a concrete. In the case of the rounded aggregates, the quasi static compressive strengths predictions are also within the 95% except for the 10% volume fraction test. In both case, the power law exponent for the correction is about 0.9 which a value identical to the one obtained for the cement paste. Table 7 reports the parameters $\log(a)$ and m, in Equation 6, estimated by linear least squares regression for the cases of the crushed and rounded aggregates.



(a) Crushed Aggregates

(b) Rounded Aggregates

Figure 8: Relationship between compressive strengths of mortar cubes with (a) crushed aggregates and (b) rounded aggregates measured by the ultrasonic method and quasi-static loading. The solid line represents the results of a linear least squares regression of Equation 6b onto the data in (a) an (b). The shaded region is the estimated 95 % confidence interval of the regression.

Table 7: Parameters estimated by linear least squares regression of the data reported in Figure 8 using Equation 6

	Crushed Aggregates		Rounded Aggregates	
	Estimate	Std. Error	Estimate	Std. Error
$\log(a)$	-0.011	0.040	0.036	0.060
m	0.865	0.054	0.900	0.077

For the case of crushed and round aggregates, the relationship $\sigma_c = a\sigma_u^m$ may be used with a equal to 0.97 and 1.14, respectively, and m equal to 0.865 and 0.900, respectively. With these parameters, the difference is compressive strengths measured by quasi-static compression testing and the ultrasonic method is $\pm$ 20 % over the 3 decades of compressive strengths in this study. As σ_u is a a function of E_{agg}, this relationship is very likely to be dependent of the nature of the aggregates. Nevertheless, we demonstrate the possibility to predict indirectly the compressive strength of a mortar or a concrete over time. This method is useful during the development of a new mortar/concrete when a lot of screening experiments are required, because the ultrasonic device enables quick and precise comparison between samples. Obviously, this method does not aim to replace all the compressive strength measurements but could be used to reduce drastically the amount of samples to be crushed during a development campaign.

Conclusions

The compressive strength of concrete containing rounded and crushed aggregates at volume fractions from 10 % to 70 % was measured in quasi-static compression and estimated from the reflection of an ultrasonic wave. When the sample contains heterogeneity larger than the wavelengths of the ultrasonic waves, the strength of the sample is estimated by computing the composite shear modulus of the sample using the Hashin-Shtrikan lower bound model, which is used to compute the elastic modulus and, finally, the strength. Results from both methods were compared where it was found that the dependence of the compressive strength of the sample measured by quasi-static compression on the compressive strength estimated using the ultrasonic method can be described by a power-law function. The difference in compressive strengths measured by both methods is estimated to be ± 20 % over a range of compressive strength spanning 3 decades. As the volume fraction of aggregates increase to 70 %, the quasi-static compressive strengths deviates from the power-law depencence on the compressive strengths measured by the ultrasonic method. This is attributed to excess air which is entrained in the sample during mixing. The results presented in this study suggest that ultrasonic wave reflection is a suitable technique for compressive strength measurements; however, further tests are required to assess the validity of this method for other mixtures such as high strength, low permeability concretes with aggregates greater than 8 mm and mixtures with entrained air.

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