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Mechanical Properties of Concrete Produced with Coarse Aggregates from Different Mineralogical Origins Using Ultrasonic Tests

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Abstract

The use of nondestructive techniques in the technological control of concrete allows to evaluate and monitor the condition of the material without interfering with its properties; therefore, it is highly desirable in on-site inspections. Among these techniques, ultrasonic testing stands out as one of the most promising by its speed and simplicity to obtain results. However, inferences of strength and stiffness properties using ultrasound parameters should be made with caution, since many factors may interfere with wave propagation. This research aimed to evaluate the behavior of parameters obtained by ultrasonic testing (velocity of wave propagation [V] and stiffness coefficient [C = density × V^2]) as predictors of the strength (f_c) and stiffness (E_{ci}) of concrete produced with coarse aggregates from different mineralogical origins. To achieve the objective, 128 specimens were produced with four aggregate mineralogical origins and four water-cement ratios, with 8 replications each. The ultrasonic tests were performed with two-frequency transducers (45 and 80 kHz). Prediction models of f_c and E_{ci} were statistically significant (P-value < 0,05) for both frequencies. The model using [C] as independent variable present better correlation with E_{ci} ($R^2 > 91,2\%$) and with f_c ($R^2 > 82\%$) than the model using only [V]. General regression models (regardless of the gravel type) were also statistically significant (P-value < 0.05), with $R^2 > 79\%$ and prediction errors higher than those obtained for the specific models for different rock types.

Keywords Basalt, Limestone, Gneiss, Granite, Modulus of elasticity of concrete, Compressive strength of concrete, Quality control of concrete

1 Introduction and Background

The technological control of concrete is very important in several types of applications of this material. Studies carried out by Neto and Helene (2002), Fortes and Merigui (2004), Bezerra et al. (2009), and Metha and Monteiro (2014) have shown that the technological control of concrete allows to deepen the knowledge about its mechanical properties and about parameters related to its response leading to the limit state, allowing the structural design to be closer to the real behavior of the structure. However, technological control requires tools, methods, and models capable of inferring concrete properties with enough accuracy.

By allowing material evaluations without interfering with their properties and thus making it possible to perform on-site inspections and material tracking over time, nondestructive techniques are important tools used for technological control. Nevertheless, according to BS 1881:203 (1988), ACI 228 (2003), and EN 12504 (2004) standards, the increased accuracy of nondestructive testing on the inference of the mechanical properties of concrete is obtained using correlation models with

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destructive testing for the same type of concrete under analysis. Similar results have been reported by Popovics and Popovics (1997), Evangelista et al. (2003), Machado et al. (2009), and Mahure et al. (2011), who attribute the achievement of reliable results to nondestructive techniques when used along with correlation models developed for the same type of concrete under study.

For concrete, the challenge of obtaining generalist models of the correlation between field-applicable (nondestructive) testing and the mechanical properties is amplified because different compositions will affect the rheology (Berodier et al., 2018; Gjorv, 2016; Schmidt et al., 2018), making models that are adjusted for one composition not directly applicable to others. In particular, different rock types react differently with water absorption, thus altering the compactness of the concrete transition zone (Mohammed & Mahmood, 2016) and altering the strength and stiffness.

One of the nondestructive techniques that is considered feasible for the evaluation of the concrete quality is the ultrasound. For this type of testing, the literature proposes several models to examine the correlation between the wave propagation velocity and the compressive strength (f_c) of concrete (Abo-Qudais, 2005; Al-zharani et al., 2016; Câmara, 2006; Evangelista, 2002; Giacon, 2009; Giacon et al., 2010; Gonçalves et al., 2011; Lawson et al., 2011; Lin et al., 2007; Lorenzi et al., 2007; Machado et al., 2009; Mahure et al., 2011; Metha & Monteiro, 2014; Mohamad et al., 2015; Popovics, 2001; Prado, 2006; Rodrigues & Figueiredo, 2004; Silva et al., 2020; Torgal & Gomes, 2006; Trtnik et al., 2009; Yildirim & Sengul, 2011). Nevertheless a few studies have examined correlation models between the initial modulus of elasticity of concrete (E_{ci}) obtained in static testing and the stiffness coefficient obtained by ultrasonic testing (Giacon, 2009; Giacon et al., 2010; Mohamed et al., 2015; Silva et al., 2020); (Carbonari et al., 2010; Santos et al., 2013; Bogas & Gomes, 2014; Martinez et al., 2014). These correlation models involve concretes with variations of different parameters, such as the water-cement ratio, aggregate amount and type, curing time and conditions, porosity, cement type, and concrete age.

In Brazil, the types of rock used in the production of aggregates are granite and gneiss (85%), limestone (10%), and basalt (5%) (ANEPAC—www.anepac.org.br), which are distributed in different regions of the country. As a result, concrete produced with aggregates from these rocks can be found throughout the country, internally expanding the importance of studies aiming at technological control.

Considering the abovementioned factors, this research aims to evaluate the behavior of the parameters obtained by ultrasonic testing, with two different transducer frequencies, as predictors of the strength and stiffness of concrete produced with coarse aggregates from four different mineralogical origins (granite, gneiss, basalt, and limestone).

Although there are several studies that focus on evaluating the influence of different parameters (including aggregate properties) on the physical, mechanical, and acoustic properties of concrete, few studies present an approach involving the analysis where the aggregate type is the only factor of variation in the concrete. In addition, few studies have focused on prediction models of the strength (f_c) and stiffness (E_{ci}) properties from more than one ultrasonic testing parameter obtained with different transducer frequencies. Thus, these aims constitute the differential scientific contributions of this paper.

2 Experimental Procedures

2.1 Sampling

The samples consisted of 128 specimens with a diameter of 150 mm and a height of 300 mm (ABNT NBR5738, 2015), with 8 replications of each of the four aggregate mineralogical origins (granite, gneiss, basalt, and limestone) produced with four mix ratios, varying only the water-cement ratio (0.5; 0.7; 0.9, and 1.0). The water/cement ratio variation was used to obtain the range of the characteristic compressive strengths (f_{ck}), allowing fundamental variability for the regression model evaluation. The concrete specimens were cured in the open, weather-protected, and demolded after 24 h. The aggregate was obtained using locations defined by the Brazilian Geological Service (CPRM, 2020), that have a geological map of Brazil gathering the knowledge of a century of geological surveys and five decades of academic research.

2.2 Preparation and characteristics of the Specimen Concrete

The following constituents were used to prepare the mix ratio: drinking water, Portland cement type CP II-F-40 (CP = Portland cement, II = compound, F = filer, 40 = strength of 40 MPa), quartz natural fine aggregates (sand), polypropylene macrofiber, and crushed coarse aggregates (gravel) of different types of mineralogy, chosen from the most abundant of the five regions of Brazil (granite, gneiss, basalt, and limestone). No additives were used during the experimental design.

Aggregate characterization was performed according to the recommendations of the ABNT-NBR standards for fine aggregates (NM248, 2003; NM30, 2001; NM45, 2006; NM52, 2009) and coarse aggregates (NM248, 2003; NM45, 2006; NM53, 2009). The results of both (Table 1) were within the acceptable limits, according to (NBR7211, 2022).

Table 1 Results of the physical characterization of the fine and coarse aggregates

Aggregates	Specific mass (kg.m^{-3})	Unit mass (kg.m^{-3})	Maximum aggregate size (mm)	Absorption (%)	Fineness modulus
Granite	2520	1510	9.5	0.62	5.24
Gneiss	2550	1310	9.5	0.57	5.65
Basalt	2810	1680	10.0	1.12	5.58
Limestone	2710	1600	9.5	0.32	5.96
Sand	2590	1390	4.8	0.70	2.71

The defined basic mix had a 1:2:3 ratio between the materials (cement, sand, gravel), as used for the construction of retaining walls according to Silva et al. (2020). The sand moisture content was corrected to define the water-cement ratio. The cement and the aggregates were measured by mass, with the addition of 175 g of polypropylene macrofiber. The polypropylene macrofiber content used in the concrete mixes was considered low (less than 1% by 50 kg of cement). Kim et al. (2010), Hassanpour et al. (2012) and Bentur and Mindess (2014) evaluated the mechanical behavior of concrete produced with a low polypropylene macrofiber content; they found no significant effect on the compressive strength and modulus of elasticity. The addition of this fraction of fibers was solely for the purpose of reducing the cracking of the pieces.

2.3 Density

At 28 days, the mass of each specimen was determined by weighing them on a precision scale (0.1 g resolution), and their dimensions were measured with a digital caliper to calculate the volume; then, the density (ρ) of the specimens was calculated.

The average densities of the concrete produced with different aggregates decreased as the water-cement ratio increased, as expected (Table 2). Additionally, there was an increase in the slump (NM67, 1998) as the water-cement ratio increased, as expected (Table 2). Despite the variations in the densities, the values of all the densities were within the limits that are considered normal for concrete, from 2000 kg.m^{-3} to 2800 kg.m^{-3}, according to the Brazilian standard (ABNT NBR6118, 2014) and the literature (Gonçalves et al., 2011; Turgut, 2004).

2.4 Ultrasonic Testing

Prior to testing, the equipment was calibrated using an acrylic material in which the propagation time was constant and known (Fig. 1a). To minimize signal attenuation, a medical gel was used as a coupler on the transducer faces. The specimens were subjected to ultrasonic testing at 28 days using ultrasound equipment (USLAB, Agricef, Brazil) and 45 and 80 kHz frequency longitudinal transducers with plane faces. The direct test (volume or compression wave) was performed by placing the transducers on opposite sides of the specimen, as proposed by Brazilian (ABNT NBR8802, 2019), American (ACI 228.2R, 2013), English (BS 1881, 1988), and European (EN 12504, 2004) standards (Fig. 1b).

Table 2 Slump and average density values of concretes produced with aggregates from different mineralogical origins and water/cement (W/C) ratios

Aggregates used in concrete production	W/C ratio	Slump (mm)	Average density (kg. m^{-3})
Granite	0.5	20	2295
	0.7	220	2145
	0.9	250	2065
	1.0	280	2044
Gneiss	0.5	70	2264
	0.7	100	2231
	0.9	200	2155
	1.0	280	2150
Limestone	0.5	30	2330
	0.7	170	2291
	0.9	270	2127
	1.0	290	2123
Basalt	0.5	80	2134
	0.7	200	2240
	0.9	230	2164
	1.0	280	2135

To produce an overall evaluation of the specimen, propagation time measurements were performed by placing the transducers at three different points on the cross-sectional face of the specimen, one in the center and the other two near the ends, adopting the average as the final time value (t). From the specimen length (L) and the results of the wave propagation time (t), the propagation velocity of the ultrasound waves (V) was calculated. With the velocity and density of the specimen, the stiffness coefficient (C) was calculated—Eq. 1.

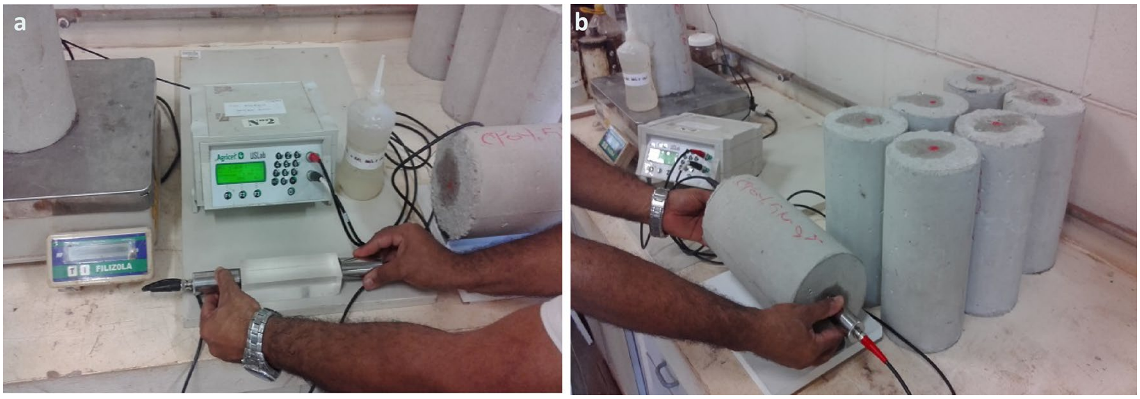

Fig.1 **a** equipment calibrated using an acrylic material; **b** specimens subjected to ultrasonic testing longitudinal

$$C = \rho.V^2 \tag{1}$$

where C = the stiffness coefficient (MPa), V = the wave propagation velocity ($m.s^{-1}$), and ρ = the concrete density ($kg.m^{-3}$).

2.5 Static Compression Tests

After ultrasonic testing, the specimens were capped with sulfur paste to ensure the parallelism of the faces during the compression tests, as specified in the Brazilian standard (ABNT NBR5739, 2018).

Compression tests were performed at 28 days on a 300-kN load capacity testing machine (EMIC, Brazil), following the specifications of the Brazilian standard (ABNT NBR5739, 2018). These tests allowed the calculation of the compression strength (f_c)—Eq. 2. The specimens were also instrumented with 0.01-mm-resolution strain gauges to determine the initial modulus of elasticity (E_{ci}), calculated according to the Brazilian standard (ABNT NBR8522, 2021)—Eq. 3.

$$f_c = \frac{4.F}{\pi.D^2} \tag{2}$$

$$E_{ci} = \frac{\sigma_b - 0.5}{\varepsilon_b - \varepsilon_a} \tag{3}$$

where f_c = the compression strength (MPa); F = the maximum force (N); D = the diameter (mm); σ_b = the stress (MPa) obtained at 30% of the maximum compression force; 0.5 = the initial reference stress (MPa); and ε_b and ε_a = the concrete-specific deformations under a stress corresponding to 30% of the maximum force and under the initial reference stress, respectively.

2.6 Characteristic Compressive Strength

The characteristic compressive strength was estimated using the Brazilian standard (ABNT NBR 12655, 2022)—Eq. 4.

$$f_{ck,est} = 2\frac{f_1 + f_2 + \cdots + f_{m-1}}{m-1} - f_m \tag{4}$$

where $f_{ck,est}$ = the estimated characteristic strength; m = the number of specimens/2, in the case of this research m = 8/2 = 4; f_1, f_2,..., f_m = the values of the individual strengths of the specimens, in ascending order. For $f_{ck,est}$, one does not assume a value lower than Ψ_6 x f_1, adopting Ψ_6 according to the table as a function of the variability (standard deviation) and the number of specimens in the sample, which in the case of this research was 0.95 (corresponding to 8 specimens and a standard deviation below 4.0 MPa—Table 3).

Since the objective of the research is to obtain regression models, the characteristic compressive strength

Table 3 Characteristic compressive strengths (first line, in MPa), average strengths and standard deviation (second line, in MPa) for concrete produced with aggregates from different mineralogical origins and water/cement (W/C) ratios

W/C ratio	Aggregate mineralogical origins			
	Basalt	Limestone	Gneiss	granite
0.5	18.3	21.7	22.0	27.1
	(21.3; 2.0)	(26.3; 2.4)	(24.8; 2.1)	(30.3; 1.7)
0.7	12.5	18.0	20.0	12.5
	(15.1; 1.3)	(21.0; 1.7)	(23.0; 1.9)	(16.4; 2.2)
0.9	8.0	9.3	12.2	6.3
	(11.6; 1.8)	(10.6; 0.7)	(14.0; 0.9)	(10.2; 1.8)
1.0	8.8	8.4	9.6	7.7
	(9.8; 0.6)	(9.8; 0.8)	(11.3; 0.8)	(9.2; 1.1)

(f_{ck}) was important for indicating the degree of variability of the sample. The results showed that it was possible to obtain the variability of f_{ck} (from 6,3 to 27.1 MPa, considering all types of gravel) by varying the W/C ratio (Table 3). Considering the sampling (8 specimens) within the same water-cement ratio, as expected the variability was low, with coefficients of variation (CV) generally ranging between 5 and 15% for the strength (f_c) and between 3 and 8% for the modulus of elasticity (E_{ci}), which could be considered as minimally dispersed (Crespo, 2002). In addition, the range of the coefficient of variation obtained in this study was of the same order of magnitude as that obtained by Martins (2008), Santiago and Beck (2011), Leal (2012), and Araújo et al., (2012, 2016), between 5 and 10% (f_c), and 3% and 12% (E_{ci}). Therefore, it was verified that the coefficient of variation of the modulus of elasticity of the concrete had the same order of magnitude as that of the strength, as indicated by the International Concrete Committee (CEB-FIP, 1993) and the literature.

For limestone and gneiss, f_{ck} decreased with increasing W/C (Table 3), as generally expected. However, for basalt and granite, this behavior was verified up to W/C = 0.9, increasing again for W/C = 1.0 (Table 3), indicating that the influence of this relationship depended on the aggregate characteristics and how these characteristics affected the concrete rheology (Olliver et al., 1995 and Schmidt et al., 2018). There are differential impact of the W/C ratio on the characteristic strength in each type of rock (Table 3) showing that not only the strength and density of the aggregates, but also the porosity, and consequent water absorption, will affect the rheological properties of the concrete.

2.7 Data Analysis

The first aspects that were analyzed were the frequency distribution of all the parameters obtained during ultrasonic testing and static compression test. This analysis aimed to verify whether normality could be accepted for these parameters, thus validating the use of parametric statistics. The normality was assessed by the asymmetry and kurtosis limits, between −2 and +2. After evaluating the normality of the data, regression models were determined between the parameters obtained in the ultrasonic and static compression tests. The regression models that best fit the data and that presented higher correlation coefficients and lower prediction errors were highlighted by statistical analysis program.

3 Results and Discussion

The parameters obtained during ultrasonic testing, i.e., the velocity (V) and stiffness coefficient (C) for both frequencies (45 and 80 kHz), and the parameters obtained during static compression testing, i.e., the strength (f_c) and modulus of elasticity (E_{ci}), for concrete produced with coarse aggregates from different mineralogical origins and with different water-cement ratios were normally distributed (Tables 4 and 5). The velocities presented values that were consistent with the results from the literature for concrete produced with the same rock types (Evangelista, 2002; Lorenzi et al., 2007; and Machado et al., 2009), indicating that the methodology was properly applied.

Since coarse aggregates occupied approximately 70% to 80% of the total volume of concrete, the aggregate quality and strength are expected to be determinants of the concrete strength and stiffness (Bayan et al., 2016; Hassanpour et al., 2012; Kim et al., 2010; Mohammed et al., 2015). Considering the average compressive strength ranges for the coarse aggregates (Table 4), the strength rating in descending order would be granite (22.5 MPa), basalt (22.0 MPa), gneiss (20.0 MPa), and limestone (15.0 MPa). However, different authors (Evangelista, 2002; Evangelista et al., 2003; Lorenzi et al., 2007; Metha & Monteiro, 2014; Rodrigues & Figueiredo, 2004; Torgal & Gomes, 2006) have already reported that aspects other than the rock strength affect the properties of concretes produced with aggregates originating from these rock types, such as the density (basalt ≅ 2710 $kg.m^{-3}$, granite and gneiss ≅ 2600. $kg.m^{-3}$, and limestone ≅ 2009 $kg.m^{-3}$) and porosity (gneiss, the porosity is usually very low; basalt and granite < 1.5%; and limestone ≅ 5%). These parameters are in turn, related to water absorption and therefore to the reactions that affect the concrete rheology. These findings may explain the results of this research, in which the concrete compression strengths (Fig. 2) did not follow the same expected strength order for the rocks from which the aggregates were obtained. Fig. 2 also shows that the behavior of the ultrasonic parameters, mainly the stiffness coefficient, is more consistent for the stiffness than for the strength obtained from the static compression test.

The acoustic parameters and the modulus of elasticity depend not only on the strength and density of the aggregates (Table 3) but also on the porosity and consequent water absorption, which in turn will affect the rheological properties. The propagation of the ultrasonic waves is much more closely related to the rigidity and the internal configuration of the elements that make up the internal structure of the material than to the density (Bucur, 2006); therefore, compatible with the behavior of the results. The production of concrete with different workability (W/C ratio) but with the same types of aggregates generates changes in the volumes of the mortar and coarse aggregates. These

Table 4 Velocity of ultrasonic wave propagation (V) and stiffness coefficient (C) obtained from ultrasound testing at frequencies of 45 kHz and 80 kHz for the mix ratios produced with different types of coarse aggregate

Gravel type	Parameter	45 kHz				80 kHz			
		Min	Max	Average	CV (%)	Min	Max	Average	CV (%)
Basalt	V ($m.s^{-1}$)	3287	3927	3547	6.9	3306	3944	3575	6.7
	A and K	1.5 and – 1.1				1.3 and – 1.0			
	C (GPa)	23.1	35.7	28.1	17.3	23.4	36.0	28.5	16.9
	A and K	1.5 and – 1.1				1.4 and – 1.1			
Limestone	V ($m.s^{-1}$)	3501	4497	3956	10.8	3563	4515	3996	10.5
	A and K	0.3 and – 2.0				0.2 and – 2.0			
	C (GPa)	26.0	47.1	35.4	25.7	27.0	47.5	36.1	25.1
	A and K	0.4 and – 2.0				0.3 and – 2.0			
Gneiss	V ($m.s^{-1}$)	3347	4106	3704	8.1	3361	4176	3736	8.5
	A and K	0.3 and – 1.6				0.5 and – 1.6			
	C (GPa)	24.1	38.2	30.5	18.5	24.3	39.5	31.0	19.3
	A and K	0.5 and – 1.7				0.7 and – 1.6			
Granite	V ($m.s^{-1}$)	3350	4283	3688	9.5	3358	4322	3721	10
	A and K	1.6 and – 0.9				1.5 and – 1.2			
	C (GPa)	23.0	42.1	29.4	24.4	23.0	42.9	30.0	25.6
	A and K	2.0 and – 0.7				1.9 and – 1.0			
General	V ($m.s^{-1}$)	3371	4203	3724	8.8	3397	4239	3757	8.9
	C (GPa)	24.1	40.8	30.9	21.5	24.4	41.5	31.4	21.7

Statistical parameters: Minimum (Min), maximum (Max), average values, coefficients of variation (CV), asymmetry (A), and kurtosis (K)

Table 5 Strength (f_c) and initial modulus of elasticity (E_{ci}) obtained from the concrete compression test for the mix ratios produced with different types of coarse aggregates

Gravel Type	Parameter	Min	Max	Average	CV (%)
Basalt	f_c (MPa)	15.1	21.3	14.5	32.5
	A and K	1.5 and – 0.8			
	E_{ci} (GPa)	13.6	22.0	16.7	20.5
	A and K	2.0 and – 0.6			
Limestone	f_c (MPa)	9.8	26.3	16.9	42.9
	A and K	0.7 and 1.9			
	E_{ci} (GPa)	17.5	28.7	21.4	33.1
	A and K	0.7 and – 1.8			
Gneiss	f_c (MPa)	11.4	24.8	18.3	32.9
	A and K	0.2 and – 1.9			
	E_{ci} (GPa)	13.4	22.6	17.2	22.0
	A and K	0.7 and – 1.5			
Granite	f_c (MPa)	9.2	30.3	16.5	52.7
	A and K	1.9 and – 1.0			
	E_{ci} (GPa)	17.0	30.2	19.7	31.2
	A and K	2.0 and – 0.5			
General	f_c (MPa)	11.4	25.7	16.6	40.3
	E_{ci} (GPa)	15.4	25.9	18.8	26.7

Statistical parameters: Minimum (Min), maximum (Max), average values, coefficients of variation (CV), asymmetry (A), and kurtosis (K)

volumetric changes affect the wave propagation velocity of the ultrasonic pulses but not necessarily the compressive strength.

All regression models associating compression and ultrasonic tests were statistically significant at a 95% significance level (P-value < 0.05) for both of the evaluated transducer frequencies (Tables 6 and 7). The types of regression models that best explained the variations in the properties obtained from static compression testing due to the properties obtained from ultrasound testing were the same for the different gravel types (Tables 6 and 7). The numerical variations of the model parameters were generally higher for granite (Tables 6 and 7). Given the magnitude of the differences in the coefficients of determination and error, we found that if the type of gravel is known, the use of the specific model is more appropriate; however, the general models are also statistically significant (P < 0.05), with the coefficients of determination showing that the parameters obtained by from ultrasound testing account for 78.5% to 93.6% of the variability in the parameters obtained from static compression testing for the 45 kHz transducer (Table 6) and 78.8% to 92.8% for the 80 kHz transducer (Table 7). The best correlations occur between the initial modulus of elasticity (E_{ci}) and the stiffness coefficient (C), and the worst correlations occur between the compressive strength (f_c) and the velocity (V)—Tables 6 and 7.

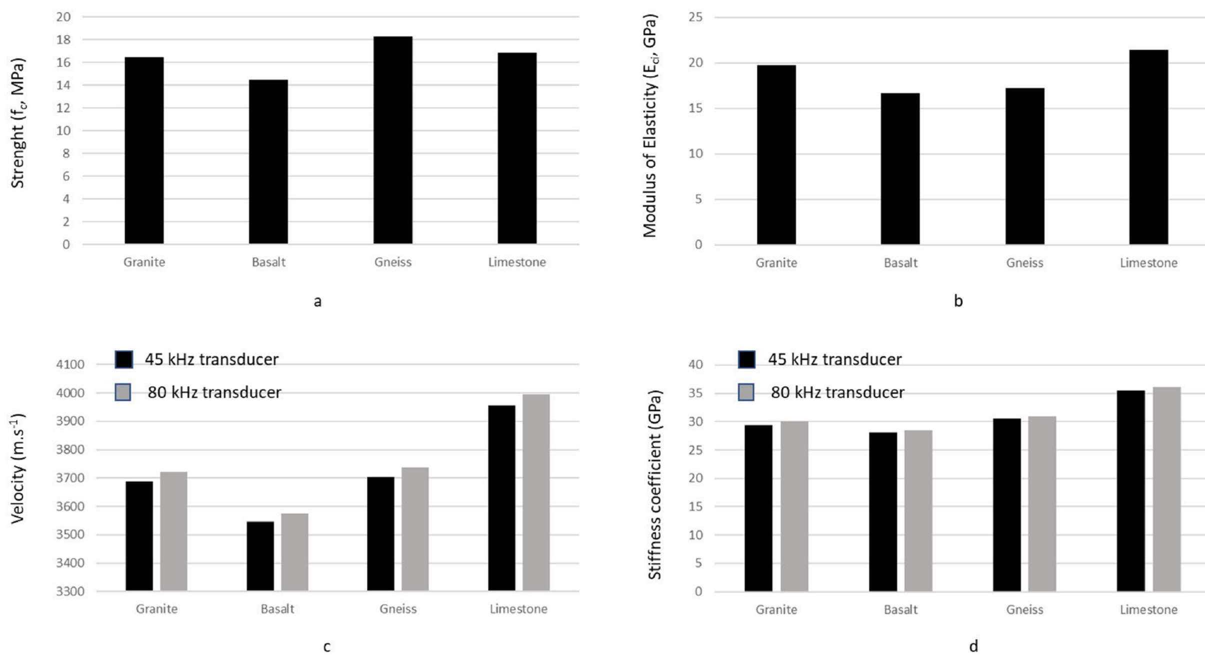

Fig. 2 Behavior of the concrete average parameters obtained in the static compression tests (**a**, **b**) and in the ultrasonic tests (**c**, **d**)

Table 6 Correlation models between the velocity (V) and stiffness coefficient (C), obtained by ultrasound testing, and the initial modulus of elasticity (E_{ci}) and strength (f_c), obtained by static compression testing for each type of rock from which the gravel was obtained—45 kHz frequency transducer

Parameters	Gravel type	Model	P-value	R^2 (%)	Estimate error	Relative error[a] (%)
E_{ci} x C	Basalt	$E_{ci}=7.5+0.011*C^2$	0.0000	91.5	1.02	6.1
	Limestone	$E_{ci}=7.2+0.011*C^2$	0.0000	97.6	1.11	5.2
	Gneiss	$Eci=7.1+0.011*C^2$	0.0000	94.1	0.94	5.5
	Granite	$Eci=8.9+0.011*C^2$	0.0000	97.0	0.93	4.7
E_{ci} x C	General	$Eci=8.1+0.010*C^2$	0.0000	93.6	1.37	7.2
E_{ci} x V	Basalt	$E_{ci}=(1.30+2.2*10^{-7}*V^2)^2$	0.0000	90.7	0.13	0.8
	Limestone	$E_{ci}=(1.05+2.2*10^{-7}*V^2)^2$	0.0000	97.6	0.12	0.6
	Gneiss	$E_{ci}=(1.43+1.9*10^{-7}*V^2)^2$	0.0000	92.5	0.13	0.8
	Granite	$E_{ci}=(1.51+2.1*10^{-7}*V^2)^2$	0.0000	94.5	0.13	0.7
E_{ci} x V	General	$E_{ci}=(1.44+2.0*10^{-7}*V^2)^2$	0.0000	92.5	0.16	0.9
f_c x C	Basalt	$f_c=(7.24-95.4/C)^2$	0.0000	86.0	0.23	1.6
	Limestone	$f_c=(7.47-114.5/C)^2$	0.0000	95.9	0.18	1.1
	Gneiss	$f_c=(7.92-109.3/C)^2$	0.0000	89.4	0.24	1.3
	Granite	$f_c=(8.21-122.9/C)^2$	0.0000	87.7	0.35	2.0
f_c x C	General	$f_c=(7.48-103.4/C)^2$	0.0000	82.7	0.34	2.0
f_c x V	Basalt	$f_c=-17.1+2.5*10^{-6}*V^2$	0.0000	88.1	1.65	11.4
	Limestone	$f_c=-16.1+2.1*10^{-6}*V^2$	0.0000	95.5	1.57	9.3
	Gneiss	$f_c=-16.1+2.5*10^{-6}*V^2$	0.0000	86.2	2.27	12.4
	Granite	$f_c=-25.7+3.0*10^{-6}*V^2$	0.0000	91.5	2.49	15.1
f_c x V	General	$f_c=-13.5+2.1*10^{-6}*V^2$	0.0000	78.5	3.15	19.0

[a] ratio between the estimated error and the average value

Table 7 Correlation models between the velocity (V) and stiffness coefficient (C), obtained by ultrasound testing, and the initial modulus of elasticity (E_{ci}) and strength (f_c), obtained by static compression testing for each type of rock from which the gravel was obtained – 80 kHz frequency

Parameters	Gravel type	Model	P-value	R^2 (%)	Estimate error	Relative error[a] (%)
E_{ci} x C	Basalt	$E_{ci} = 7.2 + 0.011*C^2$	0.0000	91.2	1.04	6.2
	Limestone	$E_{ci} = 6.9 + 0.011*C^2$	0.0000	97.4	1.16	5.4
	Gneiss	$E_{ci} = 7.6 + 0.010* C^2$	0.0000	95.5	0.82	4.7
	Granite	$E_{ci} = 9.1 + 0.011* C^2$	0.0000	97.1	0.99	5.0
E_{ci} x C	General	$E_{ci} = 8.1 + 0.010* C^2$	0.0000	92.8	1.47	8.9
E_{ci} x V	Basalt	$E_{ci} = (1.24 + 2.2*10^{-7}*V^2)^2$	0.0000	90.0	0.13	0.8
	Limestone	$E_{ci} = (0.96 + 2.2*10^{-7}*V^2)^2$	0.0000	97.4	0.13	0.6
	Gneiss	$E_{ci} = (1.55 + 1.9*10^{-7}*V^2)^2$	0.0000	94.3	0.11	0.6
	Granite	$E_{ci} = (1.45 + 2.0*10^{-7}*V^2)^2$	0.0000	95.0	0.14	0.7
E_{ci} x V	General	$E_{ci} = (1.45 + 2.0*10^{-7}*V^2)^2$	0.0000	91.6	0.17	1.0
f_c x C	Basalt	$f_c = (7.24–95.4/C)^2$	0.0000	86.0	0.23	1.6
	Limestone	$f_c = (7.51–118.4/C)^2$	0.0000	95.4	0.19	1.1
	Gneiss	$f_c = (7.77–106.5/C)^2$	0.0000	88.6	0.24	1.3
	Granite	$f_c = (8.18–122.5/C)^2$	0.0000	89.1	0.34	2.0
f_c x C	General	$f_c = (7.44–103.8/C)^2$	0.0000	82.0	0.35	2.1
fc x V	Basalt	$f_c = -17.8 + 2.5*10^{-6}*V^2$	0.0000	87.0	1.72	11.9
	Limestone	$f_c = -17.1 + 2.1*10^{-6}*V^2$	0.0000	95.6	1.54	9.1
	Gneiss	$f_c = -14.1 + 2.3*10^{-6}*V^2$	0.0000	84.7	2.39	13.1
	Granite	$f_c = -24.4 + 2.9*10^{-6}*V^2$	0.0000	92.8	2.36	14.3
f_cx V	General	$f_c = -13.5 + 2.1*10^{-6}*V^2$	0.0000	78.8	3.16	19.2

[a] ratio between the estimated error and the average value

The best correlations between the parameters obtained from ultrasound and compression testing were found in limestone (Tables 6 and 7). This result can be explained by the microstructure characteristics arising from the relationship of limestone with water absorption (W/C ratio). Torga & Gomes (2006) concluded, when comparing concrete produced with limestone and granite, that better correlations between the ultrasonic wave propagation velocity and water absorption were obtained for limestone. Additionally, the literature indicates that the propagation velocity in the limestone samples is higher than the velocities in other rocks because the compactness of the concrete transition zone is higher (Mohammed & Mahmood, 2016). However, the concrete porosity is related to the microstructural characteristics of the transition zone due to the chemical reactivity of the coarse aggregates. Limestone minerals have better reactivity with Portland cement by bonding with the cement paste, contributing to the transition zone properties around the limestone particles (Ollivier et al., 1995), which explains the more stable behavior of wave propagation in this type of rock, thus favoring good correlations with the mechanical properties.

Although the overall correlations were slightly higher and the errors were slightly lower for the 45 kHz transducer frequency than for the 80 kHz transducer frequency, both frequencies made it possible to obtain statistically significant models for the concrete strength and stiffness prediction for all gravel types (Tables 6 and 7). This result is expected since, considering the average velocity values, the wavelength (λ) is approximately 87 mm for the 45 kHz transducer and 49 mm for the 80 kHz transducer. These values indicate that the path length (specimen height) was between 3.5 and 6.0 times the wavelength. The relationship between the path length and wavelength is important for ensuring the theoretical free wave propagation condition, which minimizes the influence of the frequency on the propagation velocity. ASTM C597 (2016) recommends that the frequency range of the transducers used in concrete ultrasonic testing should be between 20 and 100 kHz and that the path length should be at least equal to the wavelength. EN 12505 (2004) suggests that frequencies from 20 to 150 kHz and path lengths at least equal to the wavelength should be used, so that the velocity is not affected. This same standard indicates that a frequency of 150 kHz should be adopted for small dimension parts (approximately 50 mm), resulting in a path length/wavelength ratio on the order of two, which was lower than the one obtained in this research. Although the correlation models between the initial modulus of elasticity (E_{ci}) and the stiffness coefficient (C) presented good correlation coefficients, the relationship between the estimated error and the average value (relative error) was low for the direct correlation models with the wave propagation velocity (Tables 6 and 7). The same was not true for the correlation models between the strength (f_c) and velocity, whose relative errors were the highest compared to that of other correlations (Tables 6 and 7).

The correlation models between the static compressive strength (f_c) and ultrasonic wave propagation velocity (V) were obtained by different authors for concrete produced with aggregates from different rocks (Evangelista, 2002 (gneiss, exponential model); Machado et al., 2009 (gneiss, power model); Trtnik et al., 2009 (limestone, exponential model); Giacon, 2009 (basalt, power model); Lawson et al., 2011 (limestone, exponential model); Mohamad et al., 2015 (basalt, power model)), with the coefficients of determination ranging from 60 to 98%. Similarly, models were obtained to correlate the modulus of elasticity (E_{ci}) obtained during static compression with the ultrasonic wave propagation velocity (V) (Rodrigues & Figueiredo, 2004 (granite and mica schist, exponential model); Prado, 2006 (mica schist, exponential model); Giacon, 2009 (basalt, linear model); Machado et al., 2009 (gneiss, polynomial model); Yildirim & Sengul, 2011 (limestone, exponential model), with the coefficients of determination ranging from 50 to 96%. The correlations between the stiffness and strength parameters obtained during the compression test and the stiffness coefficients obtained by ultrasound testing were only found in the studies of Giacon (2009) and Giacon et al. (2010), with linear correlation models for basalt aggregate concrete and coefficients of determination of 87% (stiffness) and 79% (strength). Thus, this research is different due to the fact that all the types of aggregates were evaluated in the concrete that is produced by fixing all other parameters, including the methodology and equipment, which allows the effective measurement of the influence of the type of aggregate.

The regression models (squared-X and double squared) obtained in this research (Tables 6 and 7) were validated in a studied by Silva et al. (2020). The authors (Silva et al., 2020) applied the models proposed here in precast parts for retaining walls, before (classification) the installation in loco to verified if they allowed to infer parameters representative of their quality (strength and stiffness). The results by Silva et al. (2020) showed that direct ultrasound measurement can be used to monitor and assess the integrity of precast systems during their manufacture.

4 Conclusions

- The regression models between the ultrasonic and compression tests (squared-X and double squared), obtained using transducers at two frequencies (45 kHz and 80 kHz), are statistically significant (P-value = 0.0000) for concrete produced with all the studied rocks, and the coefficients of determination are higher than around 85%, indicating that both frequencies can be used to infer the strength and stiffness of the concrete.
- As expected by the theoretical framework of the wave propagation test, the concrete stiffness (modulus of elasticity – E_{ci}) predicted models by ultrasonic testing has better correlations than the strength (f_c) prediction models. The stiffness coefficient obtained by ultrasound testing (C) present a better correlation with the stiffness ($R^2 > 92{,}8\%$) and strength ($R^2 > 82\%$) of the concrete than with the wave propagation velocity (V). This result is also expected since the stiffness coefficient includes a physical parameter of the concrete (density).
- By separating the regression models by aggregate type, the same prediction model type can be considered for all aggregates for the inference of E_{ci} and f_c by the velocity (V) or by the stiffness coefficient (C).
- General regression models, regardless of the gravel type, were also statistically significant (P-value < 0.05) at the 95% confidence level, with coefficients of determination higher than 79% and prediction errors higher than those obtained for the specific models for different rock types.

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RRCS contributed to the conception, the acquisition and analysis of data and in the construction of the manuscript. The author approved the submission version. RG contributed to the conception, the analysis and interpretation of data and in the correction of the manuscript and submission version. She is the corresponding author. CB contributed to the analysis of data and in the construction of the manuscript. The author approved the submission version.

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Availability of data and materials
The datasets generated and analysed during the current study will be available, after the paper has been accepted, in the University's Data Repository (REDU), which is Unicamp's official tool for depositing, preserving and sharing all research data produced at the University (https://redu.unicamp.br).

Declarations

Competing interests
The authors declare that they have no competing interests.

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