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Ultrasonic Evaluation of Dimensional and Technological Parameters of Cement Mortars

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ABSTRACT

In this work, we calculated the ultrasonic velocity of compression (v_L) and shear (v_T) waves, and the ultrasound elastic constants of mortars. The 14 specimens investigated were manufactured using different cement (22.5, 32.5 and 42.5 N/mm^2) and water / cement ratio varying from 0.4 to 0.6. Each specimen was made with 2 distinct geometries: prismatic (4x4x16 cm^3) and cylindrical (30 cm length and 15 cm diameter).

Firstly, we found that the prismatic samples, with dimensions exactly those set out in the Spanish regulatory norms for the evaluation of the mechanical resistance of cements, were too small for the ultrasound frequencies used (200 kHz). This implies that erroneous values will be obtained in determining the ultrasound parameters of mortars made with this geometry, and hence that there will be no possibility of establishing simple mathematical relationships between those parameters and the non-ultrasound variables. Nevertheless, the samples made with the two geometries presented similar mechanical properties.

At the same time, the knowledge of other parameters (flexion/compressive strengths) of these mortars allowed us to study different correlations between the ultrasound and the non-ultrasound parameters. Of special interest in these results were the following: (1) The prismatic samples are not valid for carrying out the ultrasound study due to their small size, while the cylindrical ones are (2) The strengths of the samples made with the same water/cement ratio can be quantified in situ from the ultrasound variables.

INTRODUCTION

Given that the characteristics of ultrasound propagation depend on the physical properties and the state of the medium, the analysis of the propagation of these waves in some material provides information on that material's properties. In particular, determining the propagation speeds of the longitudinal and shear ultrasound waves and the ultrasound elastic constants (Young's modulus of elasticity, modulus of rigidity or shear modulus, Poisson's ratio, bulk modulus and Lamé's constant) in different materials is a commonly used technique, since, in employing low energy ultrasound, the physical, chemical, geological, etc., properties of the material being inspected are left unaltered [1-6].

Ultrasonic methods have been used more than 60 years ago for concrete testing. The high degree of attenuation in the propagation of sound means that the ultrasound frequencies usually employed in their inspection do not surpass 1 MHz for transmission techniques and 500 kHz for pulse-echo techniques [7-10]. Nevertheless, as is indicated in some regulatory norms [11,12], the frequency is not the only variable to consider in correctly performing an ultrasound inspection: these norms set out mathematical relationships for the dominant wavelength of the pulse train λ, and the minimum lateral dimension D or the average grain size d of the test specimen (see Eq. [1] and [2]).

$$D \geq 5\lambda \quad [1]$$

$$\lambda \geq 3d \quad [2]$$

In this context, a study was made of the ultrasound and mechanical parameters of various cement mortars. A primary objective of the present study was to check the validity of the geometry established by Spanish regulations governing determinations of the mechanical resistance of cements [13] by measuring their corresponding speed of propagation of ultrasound pulses [14]. An additional goal was to lay the foundations for the establishment of correlations between the ultrasound parameters and structural and mechanical parameters of cement mortars, thus contributing further information to other similar relationships given in the literature [5,10,14].

MATERIALS, INSTRUMENTATION AND TECHNIQUES

Specimen description

Fourteen cement mortar specimens were fabricated, and two samples were fabricated from each: cylinder of diameter 15 and 30 cm height and prism of 4x4x16 cm^3. There were thus 28 samples prepared for ultrasound inspection, each corresponding to different requirements and hence having certain specific characteristics. The mortar used is of a fine grain type, made up of normalized sand and using cements of type CEM II 22.5, 32.5 and 42.5. Table 1 lists the cement type and the cement:sand:water proportion for each specimen.

Table 1. Cement type and proportion of the specimens

Specimen	Cement CEM II type (N/mm^2)	Cement:Sand:Water proportion
A	42.5	1:3:0,5
A’	42.5	1:3:0,5
B	32.5	1:3:0,5
B’	32.5	1:3:0,5
C	22.5	1:3:0,5
C’	22.5	1:3:0,5
D	42.5	1:3:0,4
D’	42.5	1:3:0,4
E	42.5	1:3:0,6
E’	42.5	1:3:0,6
F	22.5	1:3:0,4
F’	22.5	1:3:0,4
G	22.5	1:3:0,6
G’	22.5	1:3:0,6

The regulatory norms were followed at all times during the process of fabrication, curing, and conservation [13]. After preparation, the specimens were placed in a humidity chamber at (20±1)°C and 90% humidity.

The measurement protocol was as follows. At 28 days after fabrication [13,15], the specimens were removed from the humidity chamber, carefully weighed and analysed by ultrasound and strength tests.

Ultrasonic tests

The velocity of the propagation of longitudinal (v_L) and shear (v_T) ultrasonic waves was measured by direct transmission using a Krautkrämer USM23 LF ultrasound device (Germany) [16] (see Fig. 1).

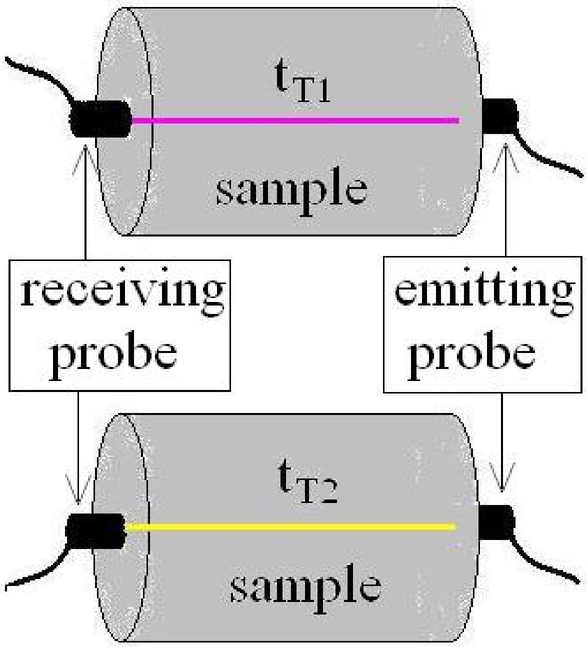
Figure 1. Ultrasonic device for velocity measurements

For v_L, the transducers (wave frequency 200 kHz) were placed at the centre of opposite faces, measuring the transit time t_L of the sound from emission until reception. Since the dimensions of the sample were known (l=14 cm for prism and l=30 cm for cylinder), the determination of v_L was immediate from Eq. [3].

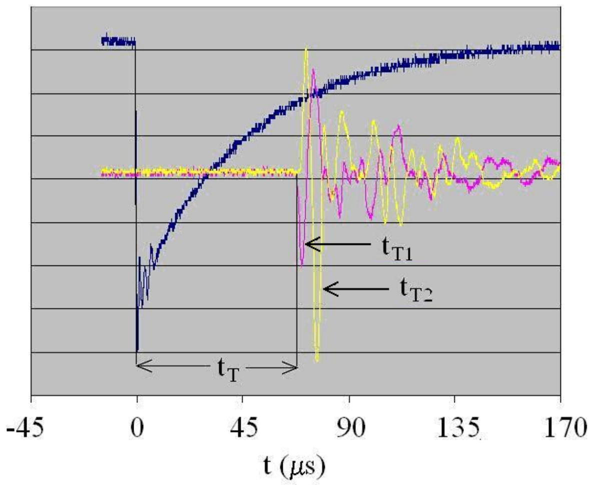
$$v_L = \frac{l}{t_L} \quad [3]$$

The normal incidence shear wave transducers (wave frequency 100 kHz) were located at the centre of opposite faces, introducing shear waves directly into the test piece without the use of refraction. The determination of the transit time of the first arriving shear oscillation is often difficult to recognise on the oscilloscope because when shear wave are excited longitudinal waves are also excited [8, 17-19]. With our method it is, however, easy to find the first shear wave flank by rotating the receiving probe 180º about its symmetrical axis. The longitudinal wave will not change, but the shear wave will change by generating a voltage of reversed sign (see Fig. 2). Hence, denoting by t_T the transit time of the first shear wave, equation [4] applies.

$$v_T = \frac{l}{t_T} \quad [4]$$



(a)



(b)

Figure 2. Measurement of shear pulse velocity by direct transmission: (a) Measurement setup by rotating the receiving probe 180º about its symmetrical axis. (b) Transmitted pulses (t_{T1} and t_{T2} lines) and estimation of transit time t_T

We can thus assign ultrasound elastic constants to each variety: shear modulus (rigidity) μ, bulk modulus (incompressibility) k, Lamé’s constant λ, Young’s modulus E and Poisson’s ratio ν. Sometimes the compressibility $1/k$ is used as an elastic constant rather than the bulk modulus. These constants are calculated from the values of v_L, v_T and density ρ, using Eqs. [5], [6], [7], [8] and [9]. The elastic constants are defined in such a way that they are positive numbers. As a consequence of this, ν must have values between 0 and 0.5. Values range from 0.05 for very hard rocks to about 0.45 for soft, poorly consolidated materials. Rigidity μ is a measure of the resistance to shearing strain. Liquids have no resistance to shear and hence for them μ=0 and ν=0.5. For most rocks, E, k and μ lie in the range from 20 to 120 GPa (2×10^{10} to 12×10^{10} N/m^2), E generally being the largest and μ the smallest of the three [20, 21].

$$\mu = \rho {v_T}^2 \quad [5]$$

$$k = \frac{\rho\left(3{v_L}^2 - 4{v_T}^2\right)}{3} \quad [6]$$

$$\lambda = \rho\left({v_L}^2 - 2{v_T}^2\right) \quad [7]$$

$$E = \frac{\rho {v_T}^2\left(3{v_L}^2 - 4{v_T}^2\right)}{{v_L}^2 - {v_T}^2} \quad [8]$$

$$\nu = \frac{\left({v_L}^2 - 2{v_T}^2\right)}{2\left({v_L}^2 - {v_T}^2\right)} \quad [9]$$

Strength tests

For prisms, the flexion strength S_F was determined using a testing device capable of applying loads of up to 10 kN with a precision of ±1%, and a load rate of (50±10) N/s (see Fig. 3). As a result of this trial, the sample was divided into two portions, which were later tested by means of compression. For prisms and cylinders, the compressive strength S_C was determined using a hydraulic press with a load rate of (2400±200) N/s, as specified by the regulatory norm [15] (see Fig 4).

Figure 3. Device for flexion strength S_F measurements

EFFECTS OF SAMPLE DIMENSION ON PULSE VELOCITY

Figure 5 shows the longitudinal velocities measured in each specimen for the two geometries. As one observes, there was no apparent relationship between the two sets of velocities, even though a positive linear correlation might have been expected. Indeed, the linear correlation coefficient calculated for these data was only 0.203, indicating a relatively weak relationship between the variables. In principle, we would attribute this result to the size of the prismatic samples (D_{prism} = 4 cm) which is too small compared to what is required by the frequency of the longitudinal ultrasound pulses used (f_L = 200 kHz) [22]. In particular, for the mean value of the velocity obtained in these specimens ($\langle v_{L\text{-}prism}\rangle$=3894 m/s), the wavelength is approximately $\lambda_L = v_{L\text{-}prism}/f_L$ = 1.9 cm, which does not satisfy Eq. [1]. The cylindrical specimens ($D_{cylinder}$=15 cm), however, comfortably satisfy Eq. [1]. The case is the same for the transversal ultrasound pulses used (ν_T = 100 kHz).

Figure 4. Hydraulic press for compressive strength S_C measurements

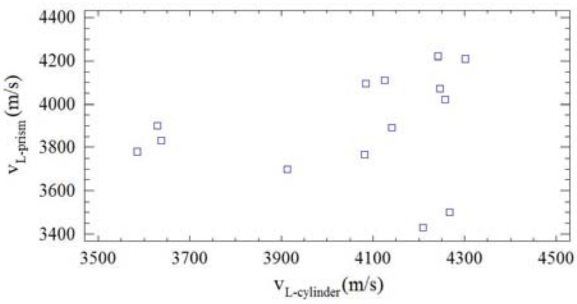


Figure 5. Plot of the ultrasound velocities of compression waves in the respective prismatic ($v_{L\text{-}prism}$) and cylindrical ($v_{L\text{-}cylinder}$) specimens of different samples

The same reasons would lie behind the almost total lack of simple mathematical relationships found between the non-ultrasound and ultrasound parameters of the prismatic specimens.

Nonetheless, since the two geometries of each sample were fabricated differently, could it be that they have different structural and mechanical properties? Visually at least, the answer is no. As verification of this immediate visual response, Fig. 6 shows the relationship between the compressive strengths measured in the prismatic ($S_{C\text{-}p}$) and cylindrical ($S_{C\text{-}c}$), samples of each specimen. As was to be expected, there was a significant increase of $S_{C\text{-}p}$ with increasing $S_{C\text{-}c}$. The high value of the linear correlation coefficient obtained removes any doubt about the good quality of the specimens made with both geometries. One notes even that, within the margins of error, the slope and the intersect of the straight line regression include the values 1 and 0, respectively. One concludes therefore that all the samples were correctly prepared since they show similar mechanical responses.

For the above reasons, we rejected from further consideration the values of the longitudinal and transversal ultrasound pulse velocities measured in the prismatic specimens, considering solely their values of flexional strength, and taking as their values of density, velocity, and compressive strength those corresponding to the respective cylindrical specimen.

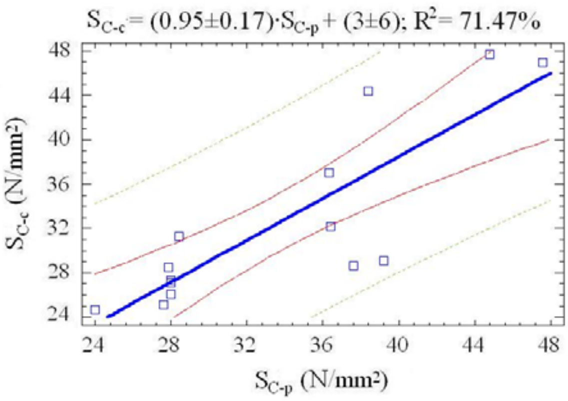


Figure 6. Variation of the compressive strength of the prismatic specimens ($S_{C\text{-}p}$) versus the compressive strength of the cylindrical specimens ($S_{C\text{-}c}$) of each sample, together with the linear fit and its equation

RESULTS

Table 2 lists a summary of the values of the ultrasound parameters measured in the 14 cement mortars. These results are coherent with the literature data [19,20,23]. Particularly, Lafhaj et al. report values of v_L and v_T for mortar with variable water / cement ratio and water content of [4000-5000] m/s and [2200-2800] m/s, respectively [10]. Popovics et al. report values of v_L for paste-mortar of [3600-4200] m/s [14].

Table 2. Statistical summary of the ultrasonic parameters for the 14 cement mortars studied (ρ: density; v_L: longitudinal velocity; v_T: shear velocity; E: Young's modulus; μ: Shear modulus; ν: Poisson's ratio; k: Bulk modulus; λ: Lamé's constant).

	Mean	SD	Range
ρ (kg/m^3)	2072	58	1955-2126
v_L (m/s)	4051	256	3586-4301
v_T (m/s)	2144	137	1840-2323
E (10^8 Pa)	250	36	179-293
μ (10^8 Pa)	96	14	67-114
ν	0.305	0.015	0.286-0.334
k (10^8 Pa)	215	34	154-256
λ (10^8 Pa)	151	26	105-193

Table 3 shows a summary concerning the influence that the structural and mechanical parameters (y-axis) exert over the ultrasonic parameters (x-axis) of the specimens. This influence was evaluated by establishing a fit to the straight line $y = A\cdot x + B$ as suggested by some studies in the literature [10,24-26]. If the value of the coefficient of linear correlation, R, is insignificant, its value is only indicated in the corresponding square. Some comments are in order about some of the results:

In general, there were no significant correlations between the measured ultrasound parameters and the strength. This does not mean that there is no relationship between pulse propagation parameters and mortar strength, but rather that such a relationship could be quite complex and the details of this have not yet been established [14]. Obviously, there is some correlation between flexion/compressive strength and ultrasound parameters, but ultrasound parameters are affected strongly by other factors such as the water / cement ratio or the cement type of the specimen. Indeed, as will be seen below, the strength estimates are less reliable because different cement mortars have different calibration curves. This is so because the composition of a cement mortar does not affect its strength in the same way as it does the pulse velocity.

Table 3. Coefficients obtained when fitting the equation of a straight line (y=Ax+B) of each one of the structural and mechanical parameters (y-axis) with the ultrasonic parameters (x-axis) tested in this work (R: Coefficient of linear correlation; *: Standard error)

	ρ (kg/m^3)	*Cement type* (N/mm^2)
v_L (m/s)	A=0.218±0.017* B=1190±70 R=0.966	R=0.057
v_T (m/s)	A=0.36±0.07 B=1310±140 R=0.844	R=0.127
E (10^8 Pa)	A=(1.47±0.19)10^{-8} B=1700±50 R=0.915	R=0.114
μ (10^8 Pa)	A=(3.7±0.6)10^{-8} B=1720±50 R=0.886	R=0.128
ν	R=0.257	R=-0.133
k (10^8 Pa)	A=(1.65±0.14)10^{-8} B=1720±30 R=0.959	R=0.007
λ (10^8 Pa)	A=(2.0±0.3)10^{-8} B=1780±40 R=0.905	R=-0.036

Table 3 (Cont.).

	S_F (kg/cm^2)	S_C (N/mm^2)
v_L (m/s)	A=0.018±0.009 B=-10±40 R=0.512	R=0.452
v_T (m/s)	A=0.039±0.015 B=-20±30 R=0.594	A=0.033±0.014 B=-40±30 R=0.558
E (10^8 Pa)	A=(1.5±0.6)10^{-9} B=24±15 R=0.582	A=(1.2±0.5)10^{-9} B=2±14 R=0.544
μ (10^8 Pa)	A=(3.9±1.5)10^{-9} B=24±15 R=0.593	A=(3.3±1.4)10^{-9} B=1±14 R=0.560
ν	R=-0.188	R=-0.225
k (10^8 Pa)	R=0.427	R=0.355
λ (10^8 Pa)	R=0.333	R=0.253

Note that only the density vs. practically all of the ultrasound parameters (except Poisson's ratio ν) have a much better single fit which seems applicable to all types of mixtures regardless of the composition of our specimens. These results are coherent with the literature data [14].

With respect to the effects of the water/cement ratio, Fig. 7 illustrates the variation of (a) velocities (v_L and v_T), (b) Young's modulus E and shear modulus (rigidity) μ, and (c) bulk modulus (incompressibility) k and Lamé's constant λ, with w / c ratio. The relationships are obviously not linear. The ultrasound parameters were observed to decrease with increasing values of the w / c ratio, as was expected given the findings of other workers of a nonlinear increase of porosity as this ratio is increased [10]. This trend was independent of the type of cement used – the nonlinear decrease of the ultrasound parameters with increasing dosages of water was observed both in the six specimens made with 42.5 N/mm^2 cement and in the six made with 22.5 N/mm^2 cement.

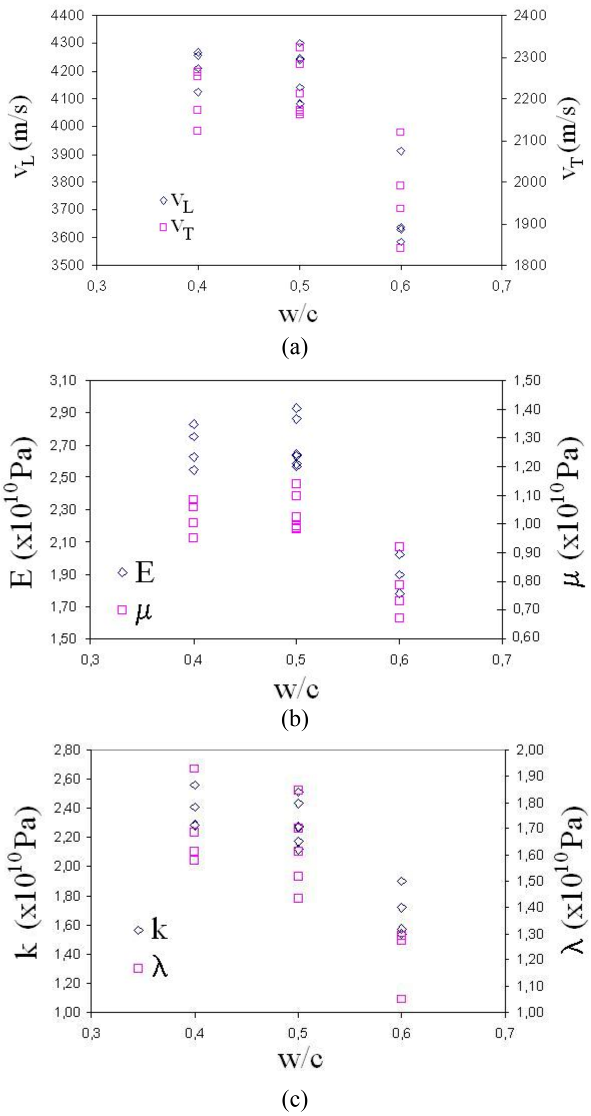


Figure 7. Variation of (a) velocities (v_L and v_T), (b) Young's modulus E and shear modulus (rigidity) μ, and (c) bulk modulus (incompressibility) k and Lamé's constant λ, with water / cement ratio

Effects of cement type

Having excluded the density, we next performed a study similar to that of the previous section, with now the specimens to test being only those that differed in the type of cement used for their manufacture. In particular, the specimens used were those whose mix was 1:3:0.5, i.e., cylinders A, A', B, B', C, and C' (see Table 1).

With these specimens, therefore, it was possible to study how the type of cement used influences the values of the ultrasound parameters. The results are presented in Table 4. An aspect that we would like to highlight is the general improvement in the linear correlation coefficients.

One observes that all the trends indicated when the 14 specimens were considered are still valid, and that the linear correlation coefficient is greater in practically all of the fits which involve the flexion/compressive strengths. Also, the positive slopes obtained for all the cases seem logical. By way of example, Fig. 8 shows the corresponding linear fits of the strengths to the longitudinal velocities. This means that the pulse velocity, the Young's modulus or rigidity, in the present form, can be used accurately enough for in-situ determination of mortar strength. In this way, we have established the bases on which to elaborate in similar future work the corresponding calibration curves to complete and improve the linear correlation coefficients obtained in this type of study by fabricating samples of different mixture ratios.

Table 4. The same as Table 3, but for the 6 varieties in which the Cement:Sand:Water proportion is 1:3:0.5 (*: Standard error)

	Cement type (N/mm^2)
v_L (m/s)	A=0.07±0.03* B=280±130 R=0.768
v_T (m/s)	A=0.10±0.05 B=180±100 R=0.727
E (10^8 Pa)	A=(4.8±1.7)10^{-9} B=-100±50 R=0.819
μ (10^8 Pa)	A=(1.1±0.5)10^{-8} B=-80±50 R=0.772
ν	R=-0.195
k (10^8 Pa)	R=-0.262
λ (10^8 Pa)	R=0.486

Table 4 (Cont.).

	S_F (kg/cm^2)	S_C (N/mm^2)
v_L (m/s)	A=0.09±0.03 B=-310±140 R=0.803	A=0.08±0.03 B=-320±150 R=0.770
v_T (m/s)	A=0.10±0.06 B=-150±130 R=0.645	A=0.14±0.03 B=-270±70 R=0.918
E (10^8 Pa)	A=(5.1±2.2)10^{-9} B=-70±60 R=0.760	A=(6.3±0.9)10^{-9} B=-138±24 R=0.962
μ (10^8 Pa)	A=(1.1±0.6)10^{-8} B=-50±60 R=0.697	A=(1.5±0.3)10^{-8} B=-120±30 R=0.938
ν	R=-0.068	R=-0.413
k (10^8 Pa)	R=0.376	R=0.089
λ (10^8 Pa)	A=(4±3)10^{-9} B=-30±60 R=0.578	R=0.361

There also appear new significant correlations. Thus, the effects of the cement type used in the manufacture of the mortars are patent in the study with samples of identical mixture ratios. The positive slopes obtained in all these fits indicate a great nominal resistance of the cement type in those varieties with high ultrasound propagation speeds or greater strength to deformation.

CONCLUSIONS

In the present study, we determined the propagation velocities of longitudinal and shear ultrasound waves, and the ultrasound elastic constants of 14 specimens of cement mortars made with two distinct geometries: prismatic (4x4x16 cm^3) and cylindrical (30 cm length and 15 cm diameter). All the results were consistent with the literature values. At the same time, the knowledge of other parameters (density, water / cement ratio, cement type, flexion/compressive strengths) of these mortars allowed us to study different correlations between the ultrasound and the non-ultrasound parameters.

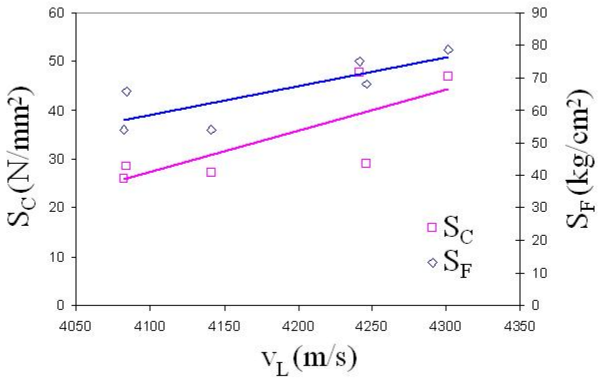


Figure 8. Plot of the compressive (S_C) and flexion (S_F) strengths versus the longitudinal velocity (v_L) for the mortars studied, together with the linear fit from Table 4

Firstly, we found that the prismatic samples, with dimensions exactly those set out in the Spanish regulatory norms for the evaluation of the mechanical resistance of cements, were too small for the ultrasound frequencies used (200 kHz). This implies that erroneous values will be obtained in determining the ultrasound parameters of mortars made with this geometry, and hence that there will be no possibility of establishing simple mathematical relationships between those parameters and the non-ultrasound variables. Nevertheless, the samples made with the two geometries presented similar mechanical properties.

In general, there is some correlation between flexion/compressive strength and ultrasound parameters, but ultrasound parameters are affected strongly by other factors such as the water / cement ratio or the cement type of the specimen. In particular, ultrasound parameters are observed to decrease with *w / c* ratio. Only the density vs. practically all of the ultrasound parameters (except shear modulus μ) have a much better single fit which seems applicable to all types of mixtures regardless of the composition of our specimens.

In the study conducted only on the specimens of identical mixture ratio, one observes that the linear correlation coefficient was greater in practically all of the fits which involved the flexional and compressive strengths. This means that the pulse velocity, the Young's modulus or rigidity, in the present form, can be used accurately enough for in-situ determination of mortar strength. It was also clear in these samples of identical mixture ratio that the highest ultrasound velocities corresponded to mortars made with cements of the greatest nominal resistance.

ACKNOWLEDGEMENTS

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