Mechanical characterization of limestone from sound velocity measurement

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Abstract

The aim of this research was to establish correlations between different physical properties (Sound velocity, V_p, bulk density, ρ, and open porosity, P_0) and mechanical properties (compressive strength, R_c, tensile strength, R_t, static elasticity modulus, E_0, and Poisson's ratio, ν) of limestones. The first step of the work consisted in an experimental campaign on limestone cores drilled from a gothic building in Paris. Eight cores were extracted from the monument and tested in the laboratory. Secondly, the experimental results were added to those proposed by 14 authors in the international scientific literature and all of these data were analyzed using the generalized least-squares method so that correlation curves could be suggested. Seven correlations are proposed: R_c - V_P, R_c - ρ, ρ - V_p, P_0- ρ, E_0 - R_C, ν - V_p, R_t - R_c. Finally, the dispersion of the results led to an estimated confidence level of 90% according to statistical considerations.

Highlights

- We carried out an experimental physical and mechanical campaign on limestones cores
- Correlations between different physical and mechanical properties are established.
- Dispersion of results led to an estimated confidence level according to statistical considerations

Keyword

Sound velocity, Limestones, Physical properties, Mechanical properties, Correlations

1. Introduction

The present research studies the mechanical properties of rocks from a civil engineering point of view, taking particular interest in the preservation of architectural heritage. It deals with old monuments built with limestone masonry. The work was carried out in order to make a structural assessment of a gothic construction built in the center of Paris in the 13th century (Old Refectory of the Saint-Martin des Champs priory – 1230) (**Fig. 1**). The structural analysis of this monument required the mechanical properties of the limestone masonry to be known.

Fig. 1. Gothic construction: « Refectory of priory Saint Martin des Champs »

Masonry is a complex heterogeneous geomaterial composed of blocs bound together by mortar joints. Therefore, its mechanical characteristics depend both on the geometry and arrangement of the blocks and on the characteristics of each of the constituents. The present work focuses only on the main mechanical and physical characteristics of limestone blocks.

At construction time, the limestone was chosen carefully according to its structural role [1,2]. Therefore, in the monument, there are various distinct zones, where the materials have different mechanical qualities. Ultrasound velocity measurements carried out on the construction walls highlighted these different zones. However, the use of natural limestone implies that the characteristics of the blocks in a given zone may vary quite strongly because of the heterogeneity and diversity of the original quarries. Thus, for each area of the building, high variability of the mechanical properties was observed. The ideal would be to measure the mechanical characteristics and their variability using laboratory tests on samples drilled from the building. However, limits imposed on coring by the heritage character of the building and limits imposed on laboratory tests because of their cost led non-destructive measurement to be preferred whenever possible.

The mechanical properties of stones required to find the masonry constitutive law are numerous. The principal ones are: bulk density, ρ, compressive strength, R_c (also noted UCS), tensile strength, R_t, static elasticity modulus, E_0, and Poisson's ratio, ν. However, the velocity of the longitudinal sound wave, V_p, is easily obtained on site using ultrasonic test equipment such as a Pundit lab. This simple measurement becomes even more obviously indicated when we consider that many mechanical characteristics of limestone can be correlated with sound velocity [3-5] (in particular, bulk density and compressive strength). Thus, it seems interesting to propose improved correlation laws taking a large panel of limestones into account.

In this article, first, an experimental campaign carried out on specimens drilled out of the monument is presented. Eight cores were analyzed. P wave sound velocity measurements were made on the building and on the samples. Then physical and mechanical tests were conducted on the cores, in the laboratory, in order to determine the following physical and mechanical characteristics: bulk density, ρ, open porosity, P_0, compressive strength, $R_{c,}$ tensile strength, R_t, static elasticity modulus, $E_{0,}$ and Poisson's ratio, ν. Lastly, correlation laws were proposed on the basis of data obtained from 14 authors in the existing literature and from the results of the experimental campaign. The aim is to cover a wide and varied range of limestone types. Limestones identified in the literature review had densities ranging from 1250 kg/m3 (soft limestone) to 2770 kg/m3 (hard limestone). Seven correlations were found: R_c - V_P, R_c - ρ, ρ - V_p, P_0- ρ, E_0 - R_C, ν - V_p, R_T - R_c. Moreover, the proposed correlations are given with confidence level of 90. Finally the results of these correlations are discussed.

2. Literature review

Data were collected from the work of 14 authors [3 - 18]. All data collected in the literature are shown in **Fig. 5** to **Fig. 11**. On these figures, each point represents one rock type. It is the average of a minimum of 3 tests carried out on samples taken from the same stone layer, in the same quarry.

2.1. Sound velocity tests

In the field of civil engineering, the measurement of the velocity of a longitudinal sonic wave in a material is a widely used non-destructive test. It can be an indicator of the depth of a crack observed on the surface [19][20]. When this technique is coupled with sonic tomography, it can probe the interior of an element (wall or column) in order to study its composition or the presence of a possible defect [21][22]. Here, the aim of the study was to correlate the sound velocity with different mechanical properties.

Laboratory measurement of the velocity of an elastic longitudinal sound wave can be carried out using high and low frequency techniques or a resonance method [23, 24]. However, no standard provides a test method for on-site measurement and it is generally assumed that correlations exist between sound velocity and compressive strength [3, 4, 6, 7, 8, 25].

2.2. Bulk density

The bulk density is relatively easy to measure. This data is essential for weight calculations. Moreover, it allows the compressive strength to be estimated via experimentally established correlations [3, 4].

2.3. Compressive strength

Knowledge of the compressive strength of limestones is essential if the structural behavior of masonry buildings, and particularly the structure failure mode, is to be assessed. This strength is measured by a uniaxial compressive test on a sample. Different standards are proposed internationally [26-28] and all recommend surfacing of the specimens and slow application of the loading force. However, the size of test specimens often differs and the compressive strength of a limestone specimen depends on (i) its size (scale effect) and (ii) its shape (slenderness ratio, cube or cylinder) [29, 30]. This is why the shape and size of the specimens tested must be considered when the results are compared. The table of corrective factors applicable to compressive strength proposed in European standard EN 772-1 [26] was used in order to convert all the strength measurements to hypothetical values that would be obtained on 50-mm-wide cylindrical or rectangular specimens with two slenderness ratios. This choice seems relevant because most tests were performed on samples of that size. Moreover the two slenderness ratios provide a quasi-uniaxial compression state in the middle of the specimen and thus a measure of the intrinsic strength of the stone. This avoids having to consider the confinement induced by the friction between the cylinder and the plate of the press, which can lead to increased compressive strength values in specimens with lower slenderness.

2.4. Tensile strength

The compressive strength of the masonry depends partly on the tensile strength of the blocks that compose it [31], which can be obtained by direct tensile tests. This type of test is complex to achieve because it requires attaching the two opposite faces of the sample to the press in order to subject it to a displacement in the direction of pull. For this reason, numerous authors prefer indirect methods such as the split test or the three point bending test [7,9]. It should be noted that the tensile strengths obtained with these last tests are different from the direct uniaxial tensile strength values.

2.5. Elastic characteristics E_0 and ν

The static elasticity modulus and Poisson's ratio of limestones have not been subjected to as many tests as the compressive strength. This is explained by the fact that the mechanical tests for these characteristics are more difficult to perform (especially with the introduction of strain gauges on the sample). However, some authors propose measurement results for the elastic characteristics of limestone [10,11,18]. It is interesting to note that these tests were carried out on samples having 2 slenderness ratios.

3. Experimental investigation carried out on the refectory and on laboratory

3.1. In situ sampling

Eight cores were drilled from the monument. The cores were about 100 mm in diameter and 300 mm in length. Two distinct zones of the building were studied: Upper level walls (cores C11, C21, C23 and C31) and Base level walls (cores C41, C43, C51 and C53) (**Fig 2.**).

Fig 2. Cores drilled out on the monument

3.2. Sound velocity measurement

Sound velocity measurements were carried out firstly on the 8 blocks of the monument chosen for the coring operation. Secondly, laboratory measurements were made on the cores drilled from the blocks. The laboratory tests were carried out according to standard NF EN 14579 [24]. This standard requires a minimum of 6 measurements per sample. The laboratory measurements on cores were direct while measurements *in situ* were indirect. The results are presented in **Table 1.** The coefficient µ corresponds to the mean values of sound velocity and coefficient of variation of each group of four tests.

Table 1
Sound velocity measurement.

Sound Velocity measurements		Upper level					Base level				
		C11	**C21**	**C23**	**C31**	**µ**	**C41**	**C43**	**C51**	**C53**	**µ**
In situ	Sound velocity (m/s)	2509	3139	3257	2984	**2972**	3762	3937	3345	4415	**3865**
	Coefficient of variation (%)	5%	8%	3%	4%	**5%**	6%	9%	4%	7%	**6%**
In laboratory (on cores)	Sound velocity (m/s)	2799	3064	3153	2895	**2977**	3951	4072	3982	4855	**4215**
	Coefficient of variation (%)	1%	3%	1%	3%	**2%**	1%	2%	6%	4%	**3%**

The cores drilled from the upper level showed negligible deviation between sound velocities measured *in situ* (2972 m/s) and those measured in the laboratory (2977 m/s). However, this difference reached 7% for stones of the base level. This can be explained by the dispersion of results foreseeable when measurements are made on natural stone and also by differences in measurement procedures: firstly, measurements carried out on site are indirect whereas those conducted in the laboratory are direct and, secondly, the humidity and temperature conditions are not controlled on site.

Finally, a difference was observed in the sound velocity measured in the laboratory between base level stones (average: 3895 m/s, coefficient of variation: 5%) and upper level stones (average: 2977 m/s, coefficient of variation: 10%).

3.3. Bulk density and open porosity measurements

Bulk density and open porosity of the samples were measured according to standard NF EN 1936 [32]. The results are shown in the **Table 2** with mean values, µ, and coefficient of variation, CV. Limestones sampled at the base level had a higher bulk density and a lower density than those of the upper level. This observation is consistent with the sound velocity measurements.

Table 2
Bulk density and porosity measurement.

		Bulk density (kg/m^3)	Porosity (%)
Upper Level	**C11**	1711	36.2
	C21	1790	32.9
	C23	1830	32.7
	C31	1830	33.7
	µ	**1790**	**33.9**
	CV	**3.1%**	**4.7%**
Base Level	**C41**	2190	17.1
	C43	2230	16.7
	C51	2160	20.1
	C53	2460	4.6
	µ	**2260**	**14.6**
	CV	**6.0%**	**46%**

3.4. Measurements of elastic characteristics

Six measurements of static elasticity modulus were carried out according to standard NF EN 14580 [33]. Three cores drilled at the base level (C43, C51 and C41) and three cores from the upper level (C11, C21 and C31) were characterized. The testing machine applied 3 cycles between the pre-load of 1.0 Mpa and 33% of the estimated failure load. Core samples C11, C31, C43 and C53 were equipped with 2 vertical gauges and 2 longitudinal gauges. The measurements of radial strains gave an estimate of the Poisson's ratio of the 4 specimens. The stress-strain curves are shown in **Fig. 3**. Note that these specimens were not stressed to rupture during these tests.

The shape of the stress-strain curves shows quasi linear behavior of limestone between the pre-load and 33% of the failure load at the first loading cycle. Thus, no pre-damage, characterized by a loss of stiffness of the material, was observed in this strain interval. **Table 3** indicates the values of elasticity modulus and Poisson's ratio of the tested samples. The average modulus was about 34.2 GPa for the base level stones (CV=40%) and 10.8 GPa for the upper level stones (CV=20%). This observation is in line with sound velocity and compressive strength measurements: the base level stones were stiffer than the upper level stones.

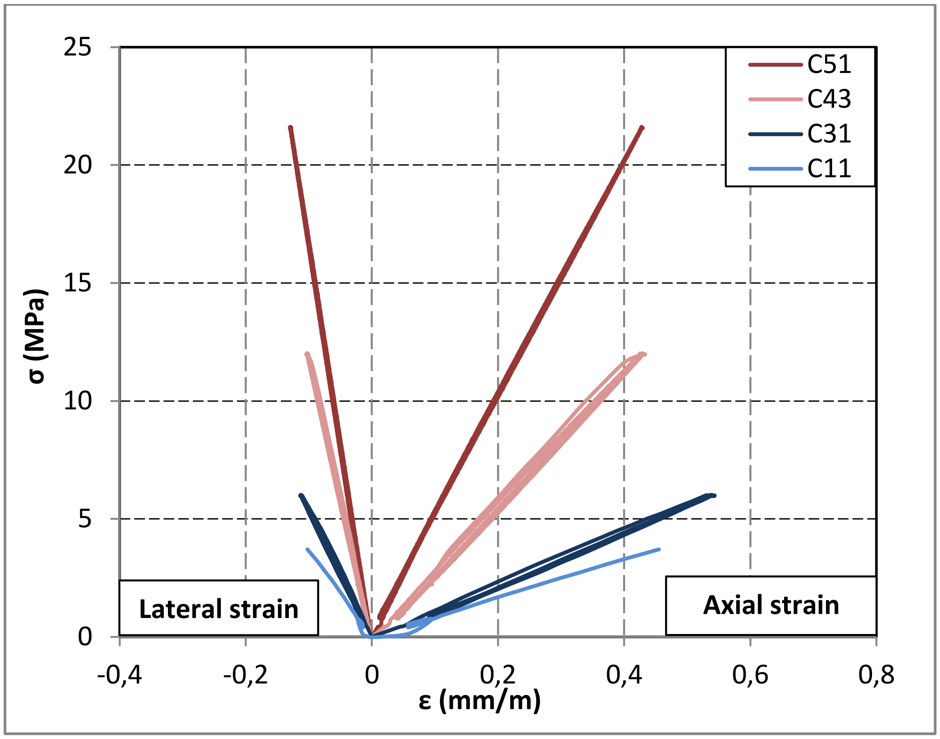

Fig. 3. Experimental elastic behaviour in compression

Table 3
Elastic properties of limestone.

Elastic properties	Upper Level					Base Level				
	C11	C21	C31	μ	CV (%)	C41	C43	C53	μ	CV (%)
Poisson Ratio ν	0.22	-	0.21	**0.215**	**3**	-	0.24	0.29	**0.265**	**13**
Elasticity Modulus (GPa)	8.3	12.6	11.5	**10.8**	**20**	24.1	28.5	49.9	**34.2**	**40**

3.5. Mechanical behavior up to failure

After the elasticity modulus tests, the four cores equipped with gauges (C11, C31, C43 and C53) were subjected to compression tests up to failure. The load was increased at a rate of 1 MPa/s. The stress-strain curves are shown in **Fig. 4**. The compressive strength observed for the upper level cores (about 10 Mpa) was lower than that found for those of the base level (between 24 and 50 MPa). Moreover, it is interesting to note that the peak compressive strains for all specimens were relatively similar (0.5 mm/m for transversal strain and 1.6 mm/m for longitudinal strains). In parallel, the other four cores were subjected to direct compressive tests to obtain their compressive strength.

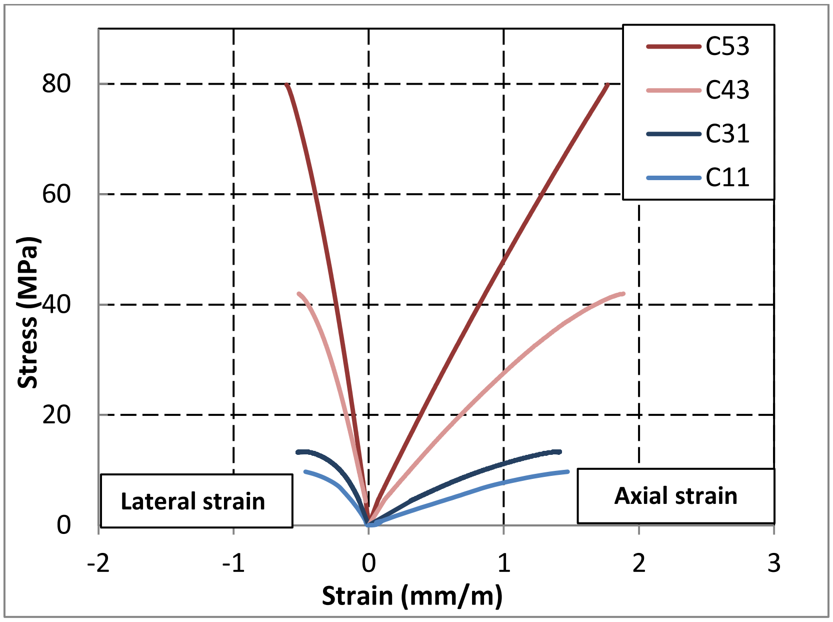

Fig. 4. Experimental compression behavior law

3.6. Tensile strength tests

Cores C23 and C51 were subjected to uniaxial tensile tests. The tensile strength was about 2.0 MPa for core C23 and 4.5 MPa for core C51.

3.7. Summary of experimental results

Table 4 summarizes the data obtained during the experimental campaign. Note that the missing values are due to limitations of the tests on each core. The standard requires a minimum slenderness ratio of about 2 for elasticity modulus measurements. The average length of cores was about 300 mm and their diameter was about 100 mm. Thus, it was not possible to perform all the required mechanical tests.

Table 4
Summary of experimental results.

		V_p (m/s)	ρ (kg/m^3)	P_0 (%)	R_c (MPa)	R_T (MPa)	E_0 (GPa)	ν	ε_{pc} (mm/m)
Upper Level	**C11**	2799	1711	36.2	9.7	-	8.3	0.22	1.5
	C21	3064	1790	32.9	10.0	-	12.6	-	-
	C23	3153	1830	32.7	13.0	2.0	-	-	-
	C31	2895	1830	33.7	13.3	-	11.5	0.21	1.4
	μ	**2978**	**1790**	**33.9**	**11.5**	**2**	**10.8**	**0.215**	**1.45**
	CV (%)	**5.4 %**	**3.1%**	**4.8%**	**16.6%**	**-**	**20.7%**	**3.3%**	**4.9%**
Base Level	**C41**	3951	2190	17.1	46.5	-	24.1	-	-
	C43	4072	2230	16.7	41.9	-	28.5	0.24	1.8
	C51	3982	2160	20.1	45.5	4.5	-	-	-
	C53	4855	2460	4.6	79.9	-	49.9	0.29	1.75
	μ	**4215**	**2260**	**14.6**	**53.3**	**4.5**	**34.2**	**0.265**	**1.775**
	CV (%)	**10.2%**	**6.0%**	**46.9%**	**33.2%**	**-**	**40.4%**	**13.3%**	**2.0%**

4. Correlation laws

A series of 7 correlation curves is proposed here. The relations are summarized in **Table 5** and plotted on **Fig. 5** to **Fig. 11**. The laws were obtained by minimizing the error between the experimental and theoretical values (generalized least-squares method). Each point corresponds to a group of specimens taken from the same quarry layer. For each point, the error minimization is weighted by the number of specimens. The main criterion for the choice of type of mathematical function is the minimization of the weighted error between the theoretical value and the experimental value. For each correlation, 2 dotted curves delimit the interval of variation around the theoretical value with a confidence level of 90%. This interval is based on the calculation of the coefficient of variation, CV, of experimental values normalized by the theoretical value. A normal distribution of the population is assumed here. Moreover, CV is an interesting indicator of the dispersion of experimental values with respect to the theoretical value defined by the correlation function.

Table 5
Summary of correlation laws.

Parameters	Correlation curves	Number of different stones	Total number of specimens	CV	R^2	Figure
$\boldsymbol{R_c}$ *(MPa)* - $\boldsymbol{V_P}$ *(m/s)*	$R_C = 5.61 * 10^{-9}\, V_p^{\,2.75}$	215	1150	34%	0.86	5
$\boldsymbol{R_c}$ *(MPa)*- $\boldsymbol{\rho}$ *(kg/m³)*	$R_C = 0.144 * \mathrm{e}^{\,(2{,}50.10^{-3} * \rho)}$	220	1150	36%	0.80	6
$\boldsymbol{\rho}$ *(kg/m³)* - $\boldsymbol{V_p}$ *(m/s)*	$\rho = 946 \ln(V_P) - 5561$	220	1150	6%	0.84	7
$\boldsymbol{P_0}$ *(%)* - $\boldsymbol{\rho}$ *(kg/m³)*	$P_0 = -3.68 * 10^{-2}\rho + 99.5$	119	650	2%	0.99	8
$\boldsymbol{E_0}$ *(GPa)* - $\boldsymbol{R_C}$ *(MPa)*	$E_0 = 0.965\, V_p^{\,0.810}$	30	98	37%	0.77	9
$\boldsymbol{\nu}$ - $\boldsymbol{V_p}$ *(m/s)*	$\nu = 0.152\, V_p^{\,0.126}$	15	43	10%	0.67	10
$\boldsymbol{R_T}$ *(MPa)* - $\boldsymbol{R_c}$ *(MPa)*	$R_T = 3.84 \ln(R_C) - 6.49$	35	90	34%	0.73	11

The first three correlations between uniaxial compressive strength, bulk density and ultrasonic velocity are each based on more than 200 different stones, and about 1150 samples. They present correlation coefficients R^2 of 0.86, 0.80 and 0.84 respectively for the correlations R_c - V_P, $R_c - \rho$, *et* ρ – Vp.

The relation between bulk density ρ and porosity P_0 is linear and its correlation coefficient is about 0.99. In fact, porosity P_0, bulk density ρ and particle density $\rho_{particle}$ are linked by **Eq. 1**. It is verified that, for a porosity of 100%, the bulk density is nearly zero and for a porosity equal to 0%, the bulk density reaches the density of pure calcite ($\rho_{calcite} = 2780\, kg/m^3$). The correlation coefficient near to 1 (R^2=0.99) supports the conclusion that knowing the bulk density of a limestone enable the open porosity to be estimated with a relative error of 2%. Finally, the coefficients of the linear equation of 100% and the value of $\rho_{calcite}$ confirm that all the stones studied consisted predominantly of calcite.

$$P_0 = 1 - \frac{\rho}{\rho_{particle}} \qquad \textbf{Eq. 1}$$

The last three correlations E_0 - V_p, ν - V_p and R_t - R_c present correlation coefficients R^2 of 0.77, 0.67 and 0.73. However, data for establishing these equations were more limited (between 15 and 35 types of rock).

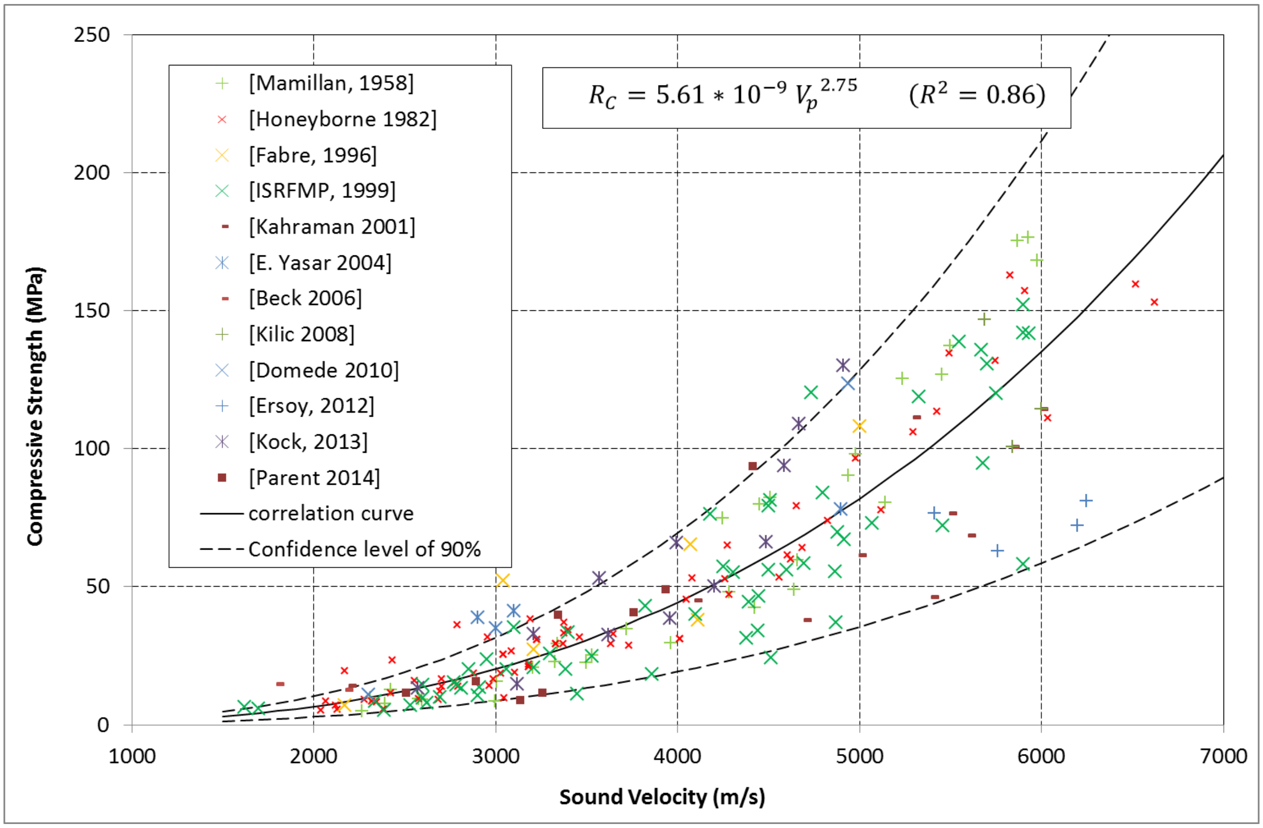

Fig. 5. Correlation between Compressive strength and Sound velocity.

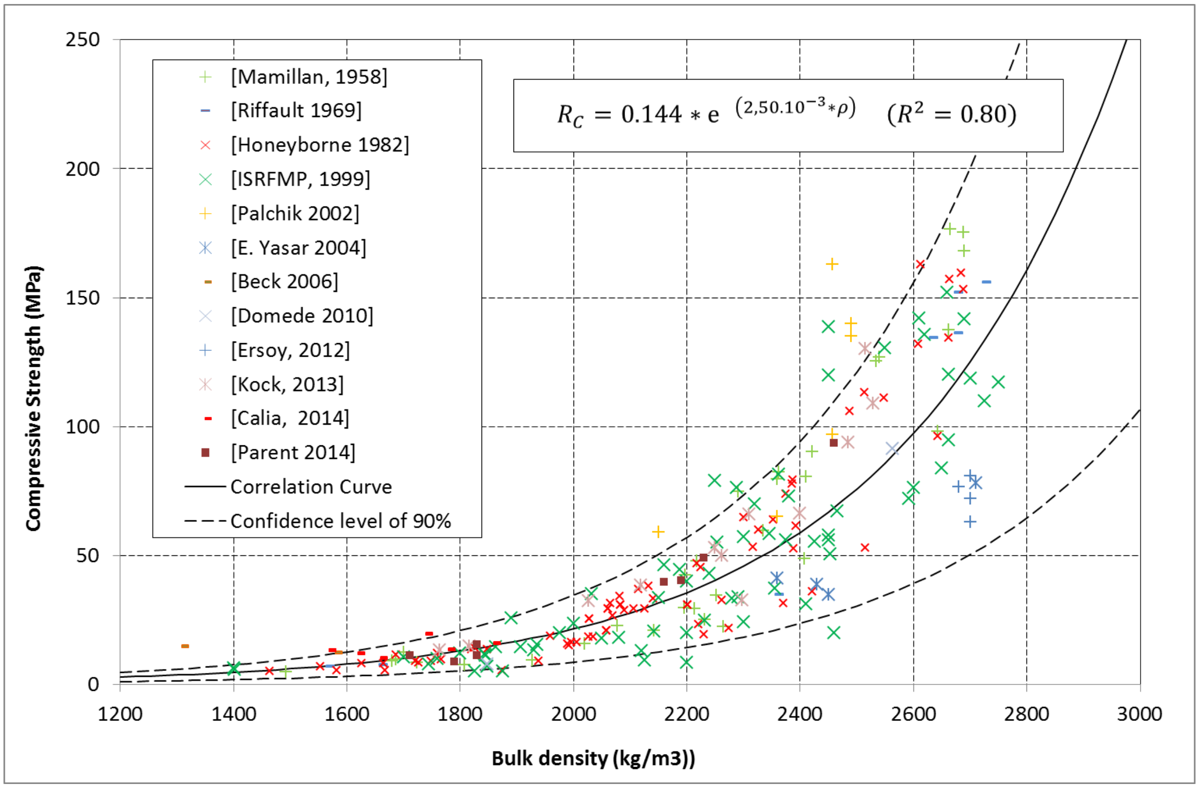

Fig. 6. Correlation between Compressive strength and Bulk density.

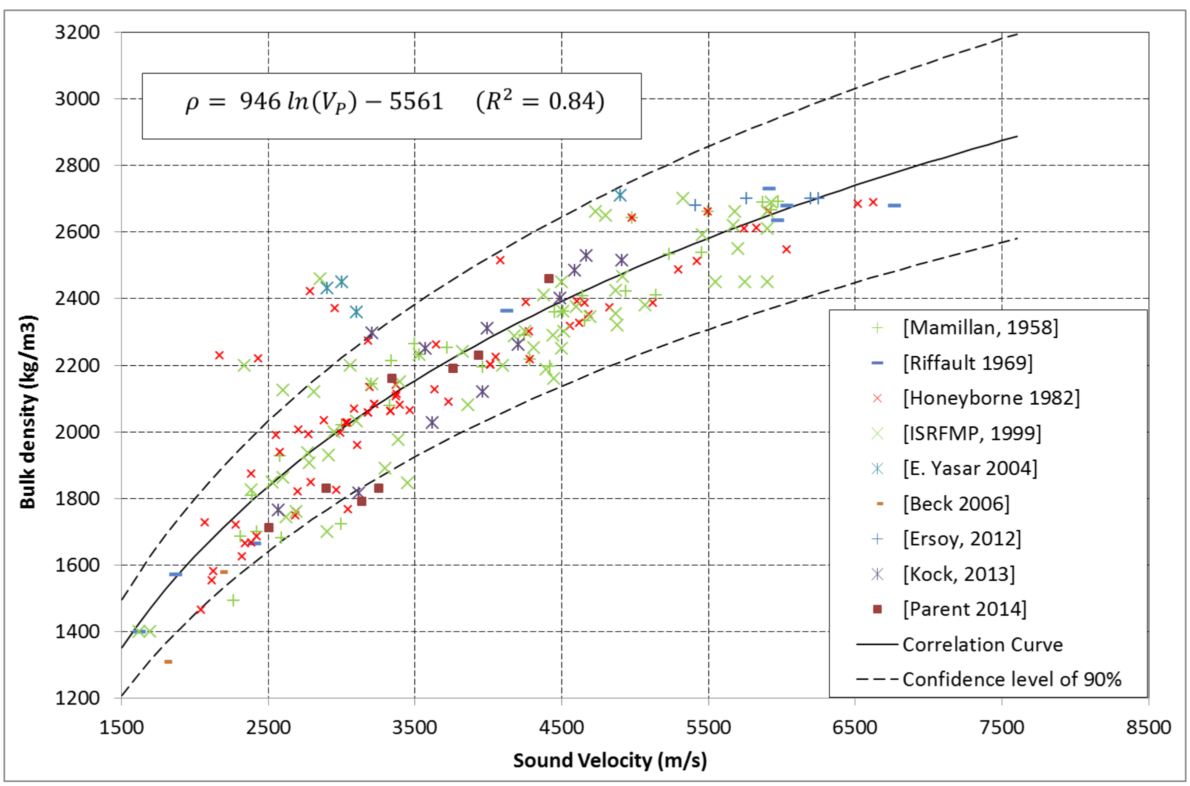

Fig. 7. Correlation between bulk density and Sound velocity.

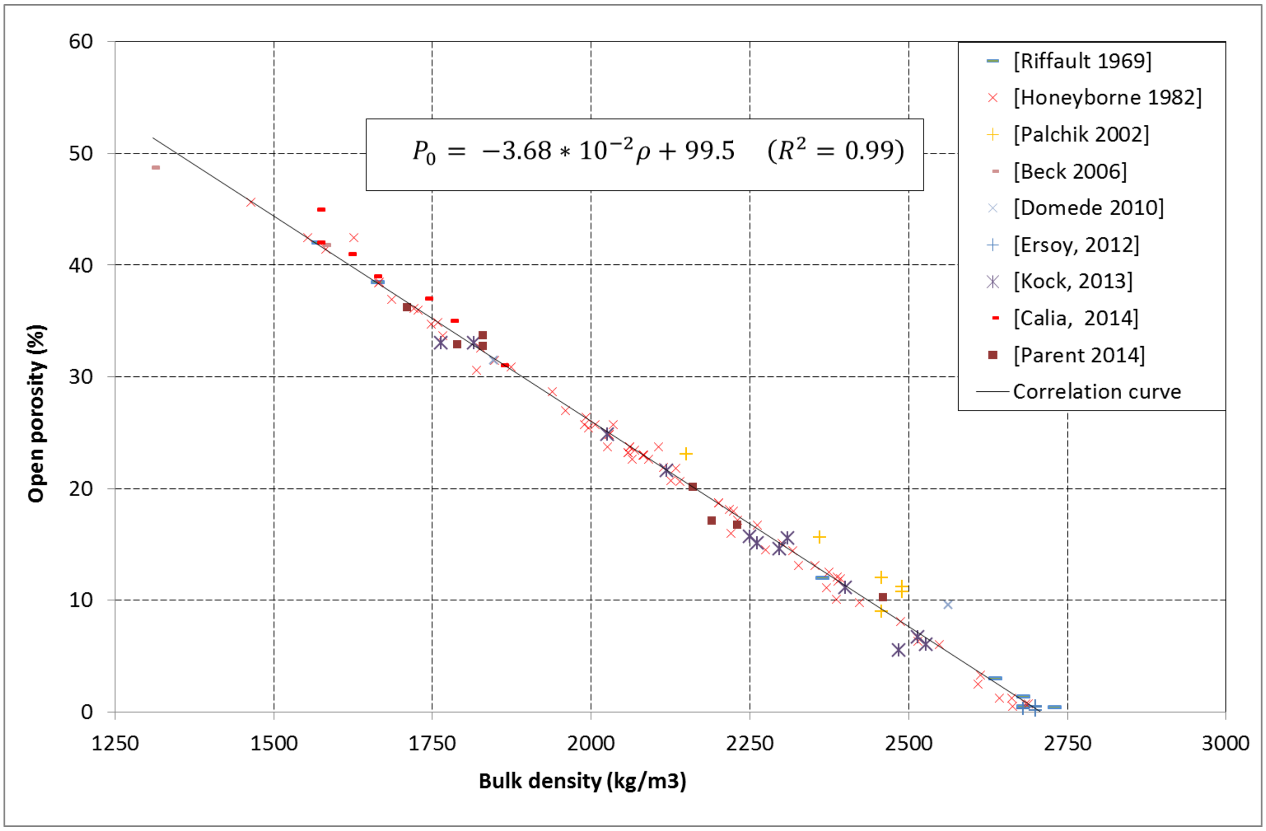

Fig. 8. Correlation between Porosity and Bulk density.

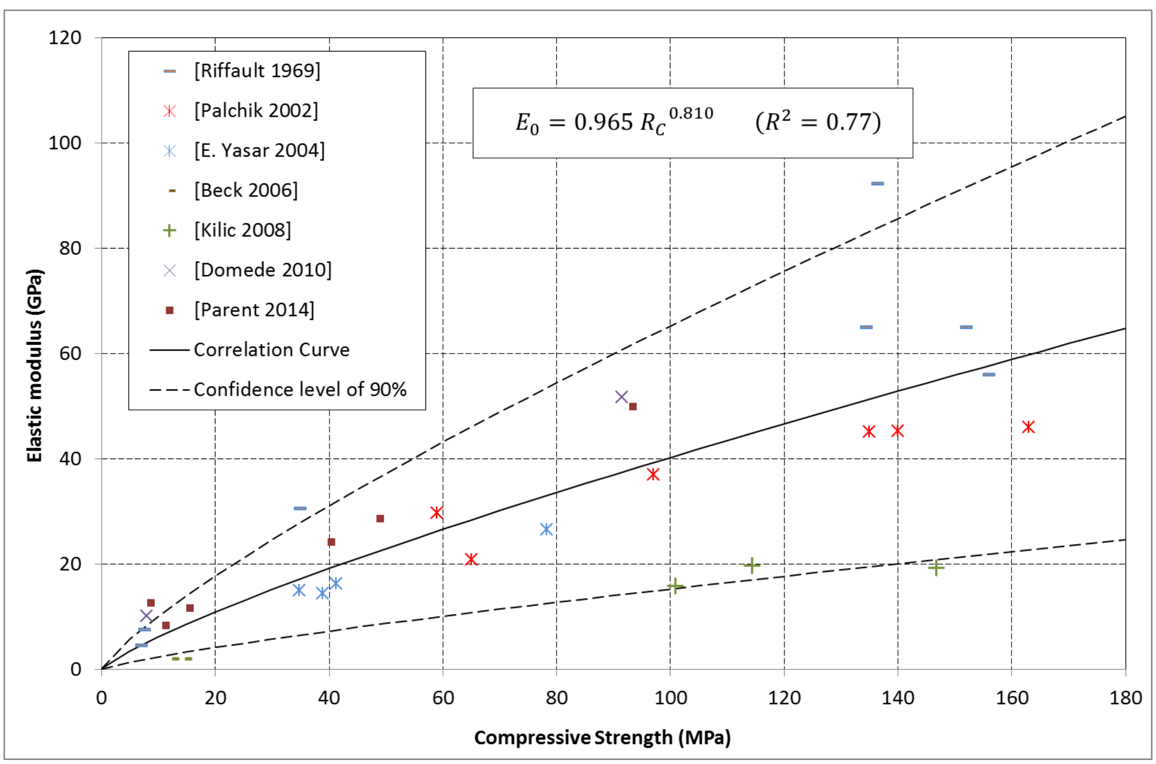

Fig. 9. Correlation between Elastic modulus and Compressive strength.

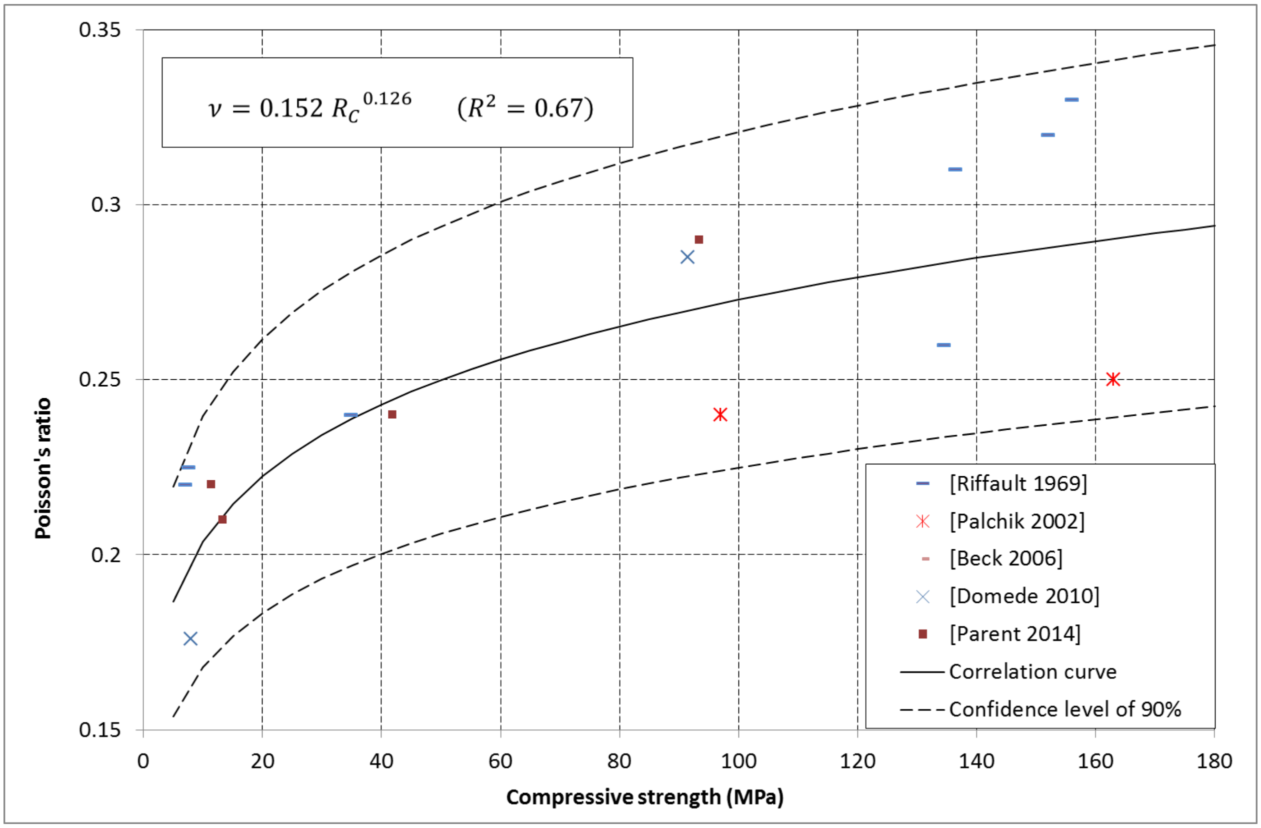

Fig. 10. Correlation between Poisson's ratio and Compressive strength.

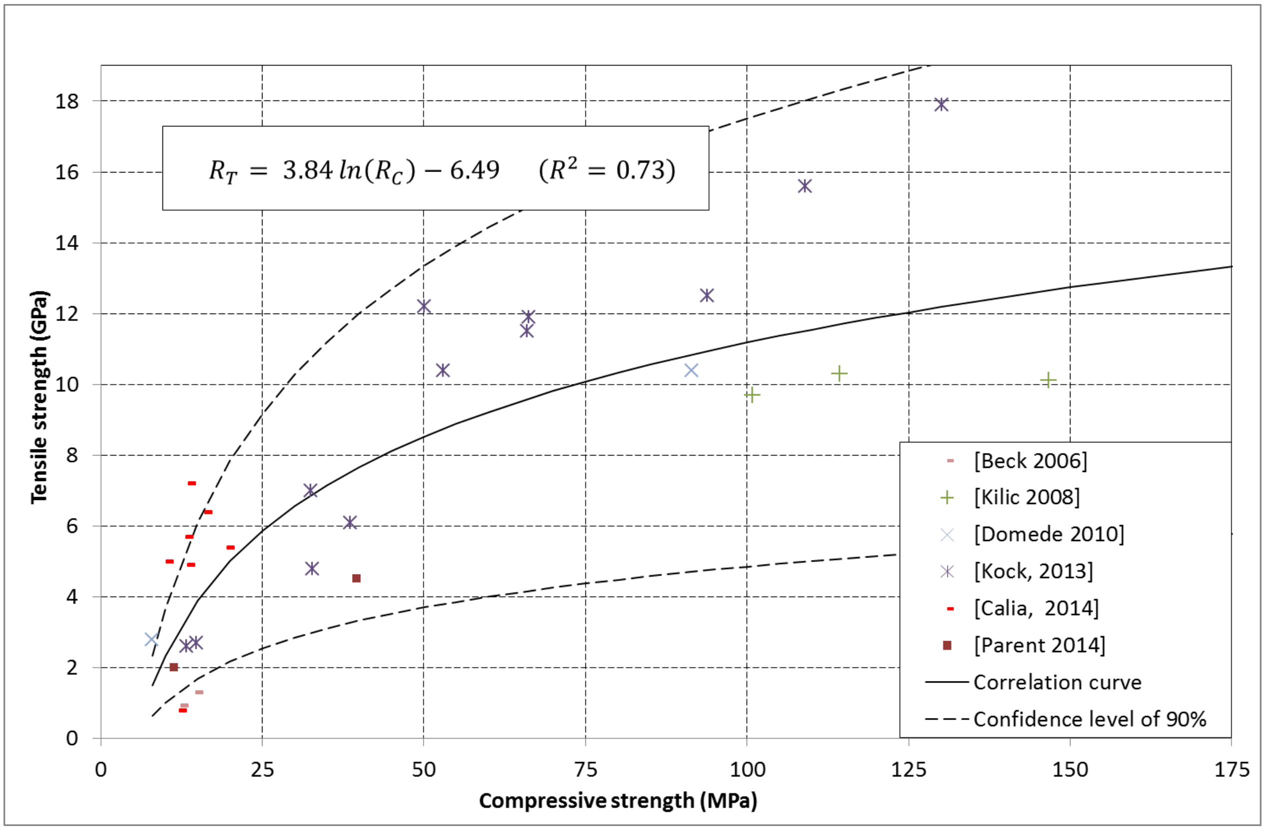

Fig. 11. Correlation between Tensile strength and Compressive strength.

5. Conclusion

Experimental tests were carried out to determine the mechanical characteristics (R_t, R_c, E_0 and ν) and physical properties (P_0 and V_P) of limestone cores drilled from a Parisian gothic building. The results of the experimental campaign were combined with mechanical and physical data for limestones proposed by 14 authors published in the international scientific literature. The large number of samples coming from different quarries in the world led us to consider a wide range of calcareous stone (bulk density from 1300 kg/m3 to 2770 kg/m3). Correlation laws are proposed from those data.

The relations have various forms:

- Power function of the form $y = ax^b$ for the R_C - V_p, E_0 - R_C *and* ν - R_C relations.
- Exponential function of the form $y = ae^{bx}$ for the R_C - ρ relation.
- Logarithmic function of the form $y = a\ln(x) + b$ for the ρ -V_p and R_t - R_c. relations
- Linear function of the form $y = a\mathrm{x} + b$ pour for the P_0-ρ relation.

In terms of dispersion, the correlations R_C - V_P, $R_C - \rho$, E_0 - R_C and R_T - R_C present coefficients of variation CV of 34%, 36%, 37% and 34% respectively. These significant dispersions resulted in a large confidence level being obtained. Inversely, correlations ρ -V_p, P_0-ρ and ν - R_C present coefficients of variation lower than 10%, leading to a lower confidence level of 90%.

Finally, the proposed correlations allow many mechanical characteristics useful for the scientific assessment of historical monuments to be obtained from simple *in situ* non-destructive tests based on measurements of the velocity of sound. Thanks to these data, non-linear mechanical analyses can be carried out in order to assess the strength capacity of a damaged structure and objectively analyze the efficiency of a repair solution.

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