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THE USE OF THE ULTRASONIC METHOD FOR THE CONTROL OF THE COMPRESSIVE STRENGTH ON DIFFERENT TYPES OF STANDARDIZED CEMENT MORTARS

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Abstract

The present work proposes to use ultrasounds as a non-destructive method of control applied to cement mortars whose composition is quantified and defined by weight, as a preliminary tool of investigation used to minimize the manifold factors (curing conditions, composition, age, [etc].) affecting the search for the strength/velocity relationship in the definition of possible curves of reference for the characterization of mortars in types and classes of the main products of the cement industry.

The formulation of the above mentioned criterion, used to seek a relationship between the two magnitudes of velocity and strength, extended to the non-destructive control on a meaningful number of samples consisting of prismatic samples of cement mortar manufactured with different types of binder, becomes functional if curves of correlation of type $R = KV^a$ are assumed and made explicit on every representative specimen of each of the different examined cement mortar types.

According to this assumption, the interpolation of the laboratory data, ordered with the same cumulative frequency, on each specimen representing the individual type of cement mortar has allowed to establish the appropriate "K" and "α" parameters of the investigated curves of correlation, expressing the relationship between the velocity of propagation and the compressive strength of the most meaningful compositions of cement mortars.

1. Introduction

This work fits into a larger field of research addressed to the characterization of repair mortars for concrete structures subjected to sever loading and/ or environmental conditions; structures that require mortars whose performances aim at the specification of strength ,durability and of the compatibility with the support.

As a first phase of the research, the values of compressive strength and of ultrasonic velocity having been assumed as indexes of quality of the cement mortars , the purposes of the work will be pursued, if it is possible to define the elastic behaviour and the strength capacity of the material with a small

number of statistically variable mechanical quantities. This quantities, once established and acquired in laboratory, will be used and statistically processed to foresee the global behaviour of cement mortars for a great number of types and classes of different hydraulic binders.
In the case of one-dimensional bodies, where a dimension is much greater than the others, (cylindrical or parallelepiped-shaped specimens with H>> D, where D represents the diameter or the greatest dimension of the cross section of the specimen) the integration of the equation of motion governing the phenomenon leads to express the velocity of propagation of the longitudinal waves, otherwise known as principal velocity, in the simplified form:

$$V_p = \sqrt{E/\rho} \qquad (Km/s) \qquad (1.1)$$

where:

E = Modulus of normal elasticity (N/mm^2)
ρ = density of the mean ($[kg]/m^3$)

The above relation generally applies to one-dimensional bodies with linear elasticity; previous considerations, derived from the connections existing between the principal velocity of propagation and the elastic characteristics for homogeneous one-dimension means, have induced some authors to formulate the following relation for concrete or cement mortar elements irrespective of their shape:

$$V^2 = K\ E/\rho \qquad (1.2)$$

where K is a constant taking into account both the Poisson coefficient (of mortar or concrete and the specimen's shape; this type of relation has been accepted also in the normative framework by ASTM with the standard C 597 (1).
The introduced simplification, together with the test method normally used in the attribution of classes of strength to the hydraulic binders, currently conducted applying the reference procedures defined in the European standard UNI EN 196- 197, suggests to directly correlate the velocity value, acquired through the ultrasonic method, with the standardized compressive strength R_c of cement mortar. At the same time it should be known that there is no univocal functional relation between the two variables, but the connection between the velocity of propagation of the longitudinal waves and the normalized compressive strength, measured on specimens of cement mortar, depends on several factors, namely: curing conditions, humidity conditions, type of normalized sand, type and class of cement used and water/cement ratio employed.
In order to obtain an estimate of standardized strength R_c (28-day compressive strength determined according to standard EN 196-1) it is necessary to establish meaningful curves of correlation between the standardized compressive strengths and the longitudinal velocity of propagation, on some statistically representative specimens of the most meaningful types of cement mortars defined with reference to their volumetric composition according to the recommendations given at paragraph 6 of standard UNI EN 196-1.
The purpose of the present work is to present the interpretative results of a procedure for the estimate of standardized compressive strength R_c, by using the principal velocity independent variable of the

ultrasonic waves obtained on a meaningful number of representative specimens of four statistical samples of cement mortars typologically defined as to their weight volumetric composition and to their strength class.

2. The Experimental program

In investigating the strength capacity of cement mortars, the first parameters to consider are the type and class of cement used in the preparation of the mix.
At present there are 25 different types of "normal cement" on the market, therefore the choice of the cement type needed for the preparation of the specimens being experimentally investigated is limited mainly to the two types that are mostly used in the building industry, which are:

- the composite Portland cement (ENV 197-1 CEM II, hereafter denominated PTL),
- the blast furnace cement (ENV 197-1 CEM III, hereafter denominated AF).

From a product analysis point of view, the classes of strength in association with the cement types previously selected for the preparation of the reference mortars studied and analyzed in the experimental programme, have been identified in classes, 32.5 42,5, 52,5 for composite Portland cement, while for blast furnace cement, only class 32,5 has been used.
The sand used for all the mixes manufactured for the preparation of reference mortars was the normalized sand deriving from the quarry of Torre del Lago (Pisa) mixed according to an aggregate/cement ratio of 3/1 in compliance with the recommendations of point 6 of standard UNI EN 196- 1, which has been adopted also for the composition, (water/cement ratio 0,5), the dosage, the mixing of the mortars, and then applied for the preparation, the shakeout and the seasoning in water of the specimens which were manufactured by using the mixes obtained from the above mentioned formulations.
As it could be deduced from the above statements, for what concerns the preparation of subsequent tests for the determination of the principal velocity of the ultrasonic waves and for the specification of the standardized compressive strength, the experimental programme has considered and referred to four different cement mortars, characterized by weight from the same aggregates, from the same values of water/cement ratio (W/ C= 0,5) and individually diversified as to the type and class of cement used in the mixture.
From these mortars, hereafter referred to as M1 (A), M1 (B), M1 (C), M1 (D) respectively, 365 prismatic samples with dimensions 40 x [mm] 40 x [mm] 160 [mm] have been globally manufactured. After having been cured in water for 28 days, these specimens have been used for the execution of the standardized compressive strength tests, after determination of the velocity of propagation of the ultrasonic impulses, by using the ultrasounds in compliance with standard. UNI 9524.
The test programme for the characterisation of strength capacity and the determination of the principal velocity of the elastic waves transmitted in the samples, has been divided in the following four series:

M1(A), CEM 325 AF o ENV 197-1 CEM III 32,5, 30 samples,
· M1(B), CEM 325 PTL o ENV 197-1 CEM II 32,5, 94 samples,
· M1(C), CEM 425 PTL o ENV 197-1 CEM II 42,5, 159 samples,
· M1(D), CEM 525 PTL o ENV 197-1 CEM II 52,5, 82 samples,

For the determination of the standardized compressive strength the procedure was that specified in standard UNI EN 196- 1.
The technique used to measure the velocity of propagation of ultrasounds on the samples manufactured for the experimentation is the one known as direct transmission technique, otherwise known as transparency method; with this technique, the receiving and transmitting probes are placed on the opposite faces of the two smaller bases of the samples, in such a position as to reduce the distance between them to the minimum.

3. Interpretation of the results of the tests

The numerical results (V_i, R_{ci}), obtained in the single tests of the experimental programme have been considered and treated as representative statistical specimens of the four respective typologies of cement mortars, M1 (A), M1 (B), M1 (C), M1 (D) selected to obtain an analytical description of the most probable connections between the two physical quantities, that is to say standardized compressive strength R_c and principal velocity of the longitudinal waves V_p.
Tables 1 and 2 respectively report, for the two random variables of principal velocity V_p and standardized compressive strength R_c, the main statistic parameters estimated on the samples obtained from the four respective populations that are assumed to be normally distributed.
For the individual random variables of principal velocity of propagation V_p and standardized compressive strength R_c, the tables report the estimated values of the mean, of the deviation standard, of the coefficient of variance intended as percent ratio between the standard deviation and the mean of the characteristic values or fractiles of rank 0.05 of V_p and R_c, and finally of maximum and minimum values whose difference shows the amplitude of the respective samples extracted from the populations to which they belong.
For what concerns the modalities for the determination of the characteristic values of rank 0.05 concerning the principal velocity of the ultrasonic impulses V_p (0,05) and the standardized compressive strength R_c (0,05) of the four statistical specimens, extracted from the respective populations that have been assumed to be normally distributed and describing the individual statistical properties under investigation of mortar types M1 (A), M1 (B), M1 (C), M1 (D), it is advisable to briefly remind the properties of the standardized normal distribution (2).

Table 1. Statistic parameters concerning the tests for the determination of the principal velocity V_p (m/s) on the tested mortar samples.

Mortars typology	M1(A)	M1(B)	M1(C)	M1(D)
Number of specimens	30	94	159	82
Mean value of velocities (m/s)	4311	4305	4405	4408
standard deviation.	69,84	88,56	62,17	71,50
coefficient of variance %	1,620	2,057	1,411	1,622
characteristic value rank 0.05	4196	4159	4303	4290
Max. Velocity value	4430	4480	4550	4550
Min. Velocity value	4180	4050	4190	4240

Table 2. Statistic Parameters concerning the tests of standardized compressive strength R_c (daN/ cm^2) on the tested mortar samples.

Mortars typology	M1(A)	M1(B)	M1(C)	M1(D)
Number of specimens	30	94	159	82
mean value of standard. compressive strength	418	445	549	647
standard deviation	49,49	35,02	44,12	54,81
coefficient of variance %	11,83	7,872	8,031	8,469
characteristic value rank 0.05	337	387	476	557
Max. compressive strength value	520	520	670	780
Min. compressive strength value	330	400	480	535

It is known that the substitution with the dimensionless variable

$$u = (x - \mu(x)) / \rho(x) \quad (3.1)$$

which takes the name of reduced variable u and whose property is to be an increasing function of the primary variable x, (for the purposes of the present work x could take the meaning of independent random variable R_c or V_p of the respective specimen being analyzed, while μ (x) and ρ (x) respectively represent the mean and the mean square deviation of the primary normal distribution considered) turns a generic normal distribution, represented by the probability function P(x) and probability density function p(x) in the standardized normal distribution, represented by the probability function Q(u) which is characterized by its mean value μ (u)= 0 and its standard deviation ρ (u)= 1. Having therefore Q (u) and q (u) respectively been called the probability function and the probability density function of the normal standardized distribution it could be demonstrated that the following properties are satisfied

$$Q(u) = P(x) \quad (3.2)$$

$$q(u) = p(x)\, \rho(x) \quad (3.3)$$

and moreover from the (3.1) it is derived:

$x = u\,\rho(x) + \mu(x)$ (3.4)

When it comes to determine a certain value of the random variable x (in the present work x is replaced from time to time by the random variables R_c or by V_p that entirely describe the investigated quantities of the respective populations M1 (A), M1 (B), M1 (C), M1 (D)) concerning an assigned probability P (x), (characteristic value of rank 0.05 where in the following analysis P (x)= 0,05) the variable being assumed to be normally distributed with mean $\mu(x) = \mu$ and mean square deviation ρ (x)=ρ, these parameters having been estimated with the statistical criterion of the moments, due to the known property of the probability function Q (u) of the standardized normal distribution (P (x)= Q (u)), it will be enough to read, on the specific tabulation tables of the probability function Q (u) of the standardized normal distribution, the corresponding value of u that satisfies the relation 3.2 (for Q (u)= 0.05 it results that u=- 1,64521) and then calculate the fractiles of the respective probability functions Pi (x) replacing, from time to time on the statistic specimen, the corresponding values of the mean and of mean square deviation in the reference relation 3.4. For the four specimens consisting of the respective series of values of principal velocity of propagation summed up in table 1, we have:

· M1(A) $Vp_{(0,05)}$ = -1,64521x69,84+4311 = 4196 m/s
· M1(B) $Vp_{(0,05)}$ = -1,64521x88,56+4305 = 4159 m/s
· M1(C) $Vp_{(0,05)}$ = -1,64521x62,17+4405 = 4303 m/s
· M1(D) $Vp_{(0,05)}$ = -1,64521x71,50+4408 = 4290 m/s

characteristics values reported in the above mentioned table; acting in a similar way on the reference parameters of table 2, for the characteristic values of rank 0.05 of the standardized compressive strength, the following is obtained:

· M1(A) $Rc_{(0,05)}$ = -1,64521x49,49+418 = 337 daN/cm2
· M1(B) $Rc_{(0,05)}$ = -1,64521x35,02+445 = 387 daN/cm2
· M1(C) $Rc_{(0,05)}$ = -1,64521x44,12+549 = 476 daN/cm2
· M1(D) $Rc_{(0,05)}$ = -1,64521x54,81+647 = 557 daN/cm2

For each single statistic sample, characterized either by the random variable velocity of ultrasonic propagation V_p or by the standardized compressive strength R_c, the sample being individually extracted from its own population of reference through the acquisition of the V_p or R_c values assumed from the respective random variable during the tests executed on the four series of specimens manufactured with mortar types M1 (A), M1 (B), M1 (C), M1 (D), the corresponding diagram of distribution of the cumulative relative frequency has been constructed.

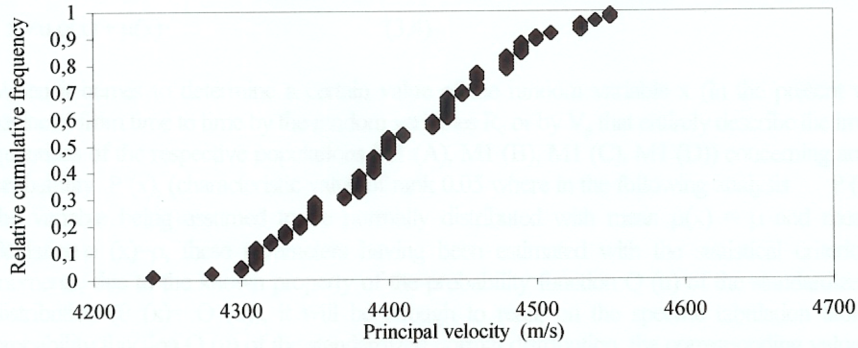

Figure 1. Mortar type M1 (D) with PTL cement 52.5 cured 28 days. Diagram of cumulative distribution of the principal velocity of the ultrasonic impulses.

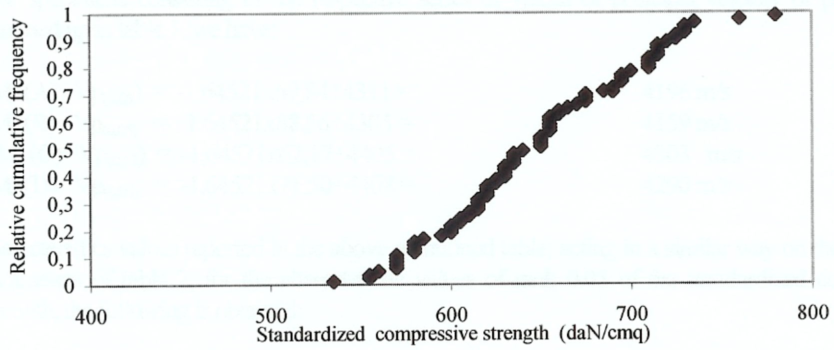

Figure 2. Mortar type M1 (D) with cement PTL 52,5 cured 28 days. Diagram of cumulative distribution of the standardized compressive strength.

To graphically underline what has been indicated, figures 1 and 2 represent, for data V_p and R_c measured on samples made of cement mortar M1(D), taken as explicative reference, the respective diagrams of distribution of the relative cumulative frequency corresponding to the values assumed from the principal velocity of the ultrasonic impulses V_p and from the standardized compressive strength R_c; in each diagram, referred to the random variable V_p or R_c, the relative cumulative frequency of the individual datum of the sample stands for the ratio between the order number of the datum itself, following the classification of the data according to an increasing order, and the corresponding dimension of the sample increased by one unit.

The obtainable cumulative frequency curves, represent an approximate estimate of the probability functions Pi (V_p) and Pi (R_c) of the random variables of principal velocity and standardized compressive strength R_c of the four respective reference cement mortars.
If we abandon the idea of constructing the statistics of the two random variables of standardized compressive strength R and principal velocity V_p and just calculate and interpret the correlation coefficient of Pearson:

$$r = \frac{\sum_{i=1}^{n} (Ri - R)(Vi - V)}{\sqrt{\sum_{i=1}^{n} (Ri - R)^2 \sum_{i=1}^{n} (Vi - V)^2}} \qquad (3.5)$$

dimensionlessly defined as the ratio between the covariance and the outcome of the mean square deviations of the two random variables of principal velocity and standardized compressive strength; ratio, varying in the interval $-1 \leq r \leq 1$, calculated on the four specimens of original mortar M1 (A), M1 (B), M1 (C), M1 (D) and for the corresponding fictitious samples obtained ordering the couples of data (V_i, R_i) having the same value of relative cumulative frequency or in other terms of probability; for the samples of the four mortars we have:

Mortars typology	M1 (A)	M1 (B)	M1 (C)	M1 (D)
r original	0,0509	0,5109	0,1820	0,5343
r fictitious	0,9817	0,9261	0,9704	0,9907

it is now possible to make the following considerations on the reached results; given the meaning of the linear correlation coefficient of Pearson which could be considered as a measure of the linearity of the connection between the variables of principal velocity and standardized compressive strength (strictly linear for $r = \pm 1$, no correlation for $r = 0$) and of the meaning of positive direct correlation for $r > 0$, it is possible to draw the first qualitative results:
(a) for all the examined samples, the existing correlation between the principal velocity V_p and the standardized compressive strength is of positive or direct type ($r > 0$); this observation implies that statistically, as the principal velocity increases the standardized compressive strength increases too,
(b) the connection of the couples (Vi, Ri) of the values of random variables of velocity and standardized compressive strength tends to linearity ($r = 1$) if, acting on fictitious samples, the data of velocity and standardized compressive strength are ranked according to an increasing order with the same value as the respective probability function ($P(V_p i) = P(R_c i)$).
The qualitative results to which the preceding considerations make reference, induces us to complete a further statistical analysis for the research of the functional relations between the two variables velocity and strength, analysis that is deduced from the study of the regression operating on the collected data examined from the four specimens of cement mortar.

Once established which of the two variables will take on the role of independent variable in the functional empirical connection and which that of dependent variable or, in equivalent terms, the type of regression to adopt (R on V), the method implies an a priori choice of the type of curves of regression to adopt; the chosen ones are of the following type:

linear $R = C_0 + C_1 V$ (3.6)
power $R = C_2 V^{C3}$ (3.7)

where R and V are the standardized compressive strength and the principal velocity respectively, while the individual coefficients C_0, C_1, C_2, C3 of the respective representative curves of the mechanical characteristics of the considered mortars are to be individually determined for each curve of regression, by reducing the sum to the minimum:

$S = \Sigma (Ri - Ris)^2$ (3.8)

of the squares of the deviations between the observed values of the variable of standardized compressive strength Ri and the corresponding Ris values that, with an equal value of principal velocity V, are read on the regression curve.
The results of this analysis are synthetically reported in table 3, where, for each statistical sample of the investigated mortars, ordered with N couples of values (Ri, Vi), values that take the same relative cumulative frequency, we have reported the analytical expressions of the curves of regression R = f (V) selected to describe the functional dependence of the standardized compressive strength from the ultrasonic velocity in the different mortars taken into consideration.

Table 3. Recapitulation of the analytical expressions R= f (V) obtained from the analysis of regression conducted on the four specimens of mortar.

Mortar type	Regession line type (linear/power)	r^2
M1(A)	$R = -2580{,}8 + 0{,}69562V$	0,964
	$R = 3{,}144\ e\text{-}24\ V^{7{,}1868}$	0,961
M1(B)	$R = -1132{,}3 + 0{,}36632V$	0,858
	$R = 9{,}0978\ e\text{-}11\ V^{3{,}4915}$	0,862
M1(C)	$R = -2484{,}4 + 0{,}68870V$	0,942
	$R = 8{,}4993\ e\text{-}18\ V^{5{,}4362}$	0,948
M1(D)	R = - 2700,0 + 0?75937V	0,981
	$R = 8{,}9712\ e\text{-}12\ V^{5{,}1745}$	0,983

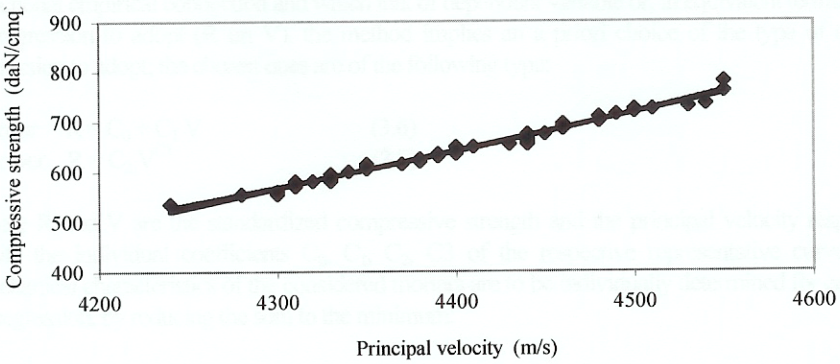

Figure 3. Mortar type M1 (D) with PTL cement 52.5 cured 28 days. Values of the data ordered with the same value of cumulative relative frequency and corresponding line of trend.

Figure 3 shows the trend of the line of linear regression for the reference values of mortar M1(D), taken as an explicative example; it is important to notice the excellent adaptation of the lines to the data; this result is also confirmed, for all the investigated mortar typologies, by the individual values assumed from the coefficient of determination r^2_i very close to the unit, as shown in table 3.

4. Conclusions

On the basis of the above statements it is underlined that the ultrasonic investigation joined to the statistical analysis is intended as a method of non-destructive control to be applied to cement mortars for the measure of the strength capacity of mortars themselves.

The method is not only interesting due to the possibility it offers to forecast the compressive strength, when the specific calibration curve of the analyzed mortar has been traced, but also and chiefly because of the possibility offered by this method to appraise the curing degree of mortars over the time; this value is measurable with the increase of the velocity of propagation that can be measured on the mortar specimens

5. References

1. ASTM C 597-83 'Standard Test Method for Pulse Velocity Through Concrete', Reapproved 1999

2. Brownlee K., 'Statistical Theory and Methodology in Science and Engineering', J. Wiley P.,1965, 63 - 67