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Ultrasonics 42 (2004) 527–530
Ultrasonics
www.elsevier.com/locate/ultras

Characterization and hardening of concrete with ultrasonic testing

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Abstract

In this study, we describe a technique which can be used to characterize some relevant properties of 26 cylindrical samples (15×30 cm^2) of concrete. The characterization has been performed, according to Spanish regulations in force, by some destructive and ultrasound-based techniques using frequencies of 40 kHz. Samples were manufactured using different water/cement ratios (w/c), ranging from 0.48 to 0.80, in order to simulate different values of compressive strength at each sample.

We have correlated the propagation velocity v of ultrasonic waves through the samples to compressive strength R values. As some other authors remark, there exists an exponential relationship between the two above parameters. We have found that a highly linear relationship is present between R and w/c concentration at the samples. Nevertheless, when the same linear model is adopted to describe the relationship between v and w/c, the value of r decreases significantly. Thus, we have performed a multiple regression analysis which takes into account the impact of different concrete constituents (water, cement, sand, etc.) on ultrasound propagation speed.

One of the most relevant practical issues addressed in our study is the estimation of the hardening curve of concrete, which can be used to quantify the viability of applying the proposed method in a real scenario. Subsequently, we also show a detailed analysis of the temporal evolution of v and R through 61 days, beginning at the date where the samples were manufactured. After analyzing both parameters separately, a double reciprocal relationship is deduced. Using the above parameters, we develop an NDE-based model which can be used to estimate hardening time of concrete samples.

Keywords: Compressive strength; Concrete; Hardening; NDT; Ultrasonic velocity

1. Introduction

In this paper, we analyse the speeds of propagation of ultrasound in various samples of concrete, comparing the results with the samples' compressive strength characteristics as evaluated during destructive testing. Two types of study were performed. The first attempted to relate different physical variables of the concrete (density, compressive strength, water/cement proportion, etc.) with the speed of propagation of ultrasound waves. The second analysed the relationship between the ultrasound speed and the hardening of the concrete, i.e., the variation of those same physical variables as a function of the time lapsed after fabrication of the concrete. In all cases, we followed Spanish regulations concerning the inspection of concrete with ultrasound [1].

We prepared 26 specimens for inspection by ultrasound, each corresponding to different requirements and hence having certain specific characteristics. Two methods were used to obtain the proportions of the constituents—that of Carlos de la Peña and that of Bolomey [2]. Table 1 lists the resulting proportions for each specimen. The regulatory norms were followed at all times during the process of fabrication, curing, and conservation. The specimens were manufactured as cylinders of 15 cm diameter and 30 cm length, using cement of type CEM II 32.5 and crushed aggregates—specifically, 6/12 (minimum size/maximum size) pea gravel, 12/25 gravel, and washed river sand. After preparation, the specimens were placed in a humidity chamber at 20 °C and 90% humidity. Their compressive strength R was determined using a hydraulic press with a load rate of (2400 ± 200) N/s, as specified by the

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doi:10.1016/j.ultras.2004.01.053

Table 1
Constituent parts (the samples manufactured by the Bolomey method are in italics; the rest were manufactured by the Carlos de la Peña method), density (ρ), speed of ultrasound longitudinally, i.e., parallel to the axis of the cylinder (v), and radially (v'), and compressive strength (R) of the specimens

Specimen	Water (kg)	Cement (kg)	Ratio w/c	Sand (kg)	Pea gravel (kg)	Gravel (kg)	ρ (kg/m^3)	v (m/s)	v' (m/s)	R (N/mm^2)
1	*1.9*	*3.45*	*0.55*	*7.15*	*5.20*	*10.30*	*2554.80*	*4880 ± 50*	*5150 ± 130*	*23.760*
2	*1.9*	*3.45*	*0.55*	*7.15*	*5.20*	*10.30*	*2433.50*	*4310 ± 50*	*4490 ± 230*	*19.173*
3	2.0	4.20	0.48	9.00	5.33	10.56	2542.73	4710 ± 60	4820 ± 80	34.231
4	2.3	4.08	0.56	8.70	5.17	10.25	2490.10	4710 ± 50	4670 ± 160	29.123
5	2.3	4.08	0.56	8.70	5.17	10.25	2503.11	4700 ± 70	4860 ± 80	29.772
6	2.3	4.59	0.50	8.27	5.15	10.25	2457.27	4560 ± 30	4550 ± 210	28.263
7	2.0	4.20	0.48	9.00	5.33	10.56	2499.15	4461 ± 12	4400 ± 30	28.080
8	2.3	4.59	0.50	8.27	5.15	10.25	2448.41	4650 ± 40	4430 ± 100	31.724
9	2.3	4.59	0.50	8.27	5.15	10.25	2507.64	4600 ± 50	4590 ± 30	31.291
1a	2.2	3.63	0.61	8.60	4.28	8.52	2455.39	3920 ± 30	3870 ± 130	5.175
1b	2.2	3.63	0.61	8.60	4.28	8.52	2400.87	3890 ± 30	4710 ± 30	5.768
2a	2.2	3.63	0.61	8.60	4.28	8.52	2463.31	4280 ± 30	4220 ± 30	13.71
2b	2.2	3.63	0.61	8.60	4.28	8.52	2454.82	4235 ± 3	4260 ± 90	12.113
3a	2.2	3.63	0.61	8.60	4.28	8.52	2424.64	4504 ± 5	4370 ± 30	15.357
3b	2.2	3.63	0.61	8.60	4.28	8.52	2385.02	4433 ± 3	4400 ± 50	15.945
4a	2.2	3.63	0.61	8.60	4.28	8.52	2445.39	4553 ± 15	4580 ± 30	17.504
4b	2.2	3.63	0.61	8.60	4.28	8.52	2485.76	4507 ± 3	4573 ± 4	18.635
5a	2.2	3.63	0.61	8.60	4.28	8.52	2385.21	4700 ± 30	4620 ± 40	23.543
5b	2.2	3.63	0.61	8.60	4.28	8.52	2443.31	4400 ± 30	4630 ± 80	19.395
5c	2.2	3.63	0.61	8.60	4.28	8.52	2455.39	4480 ± 90	4600 ± 100	18.857
H1	*1.9*	*3.45*	*0.55*	*7.15*	*5.20*	*10.30*	*2449.54*	*4621 ± 24*	*4730 ± 80*	*23.554*
H2	*1.9*	*3.45*	*0.55*	*7.15*	*5.20*	*10.30*	*2455.57*	*4710 ± 100*	*4810 ± 180*	*20.055*
B1	*2.4*	*3.00*	*0.80*	*8.22*	*5.65*	*11.19*	*2435.20*	*4480 ± 60*	*4730 ± 90*	*11.114*
B2	*2.3*	*3.00*	*0.77*	*8.22*	*5.65*	*11.19*	*2490.10*	*4380 ± 100*	*4450 ± 90*	*12.839*
B3	*2.2*	*3.02*	*0.73*	*8.22*	*5.65*	*11.19*	*2481.04*	*4210 ± 70*	*4410 ± 60*	*11.220*
B4	*2.1*	*3.03*	*0.69*	*7.96*	*5.47*	*10.84*	*2452.37*	*4230 ± 50*	*4480 ± 50*	*13.860*

regulatory norm [3]. The velocity of the propagation of ultrasound pulses was measured by direct transmission using a Steinkamp BP-V ultrasound device (Germany). This measures the time of propagation of ultrasound pulses in a sample in the range (0.1–9999.9) μs with a precision of 0.1 μs. The transducers used were 28 mm in diameter, and had maximum resonant frequencies, as measured in our laboratory, of 42.5 kHz.

The samples used to study the relationship between the speed of ultrasound and the physical properties of the concrete were those labeled 1, 2, 3, 4, 5, 6, 7, 8, 9, B1, B2, B3, B4, H1, and H2 in Table 1. The measurement protocol was as follows. At 28 days after fabrication [3], the specimens were removed from the humidity chamber, carefully weighed, analysed by ultrasound, and sulfur capped for their subsequent rupture. For each specimen, 11 speed measurements were made, five longitudinally in the direction of the axis of the cylinder (v), and six radially (v').

The samples used to study the hardening of the concrete were those labeled 1a, 1b, 2a, 2b, 3a, 3b, 4a, 4b, 5a, 5b, and 5c in Table 1, all with identical proportions of the constituents. The specimens were removed from the humidity chamber to be weighed and analysed by ultrasound, and then returned to the chamber, except for those that were to be capped for their subsequent rupture. Rupture by hydraulic press was carried out mostly two at a time on days 2, 7, 14, 21, 28, and 61 after fabrication. The unbroken specimens were also weighed and analysed on intermediate days (5, 9, 12, 16, 19, 22, 26, 34, 41, 48, 55, and 61 days after fabrication) in order to observe their evolution.

2. Characterization

Fig. 1 shows the relationship between the compressive strength R and the speed of propagation of ultrasound v in different specimens. As has been observed by other workers [4,5], there exists an exponential relationship between the two variables. For the range of compressive strength of this present work, this relationship is represented by the expression of Eq. (1):

$$R = \exp[(-3.3 \pm 1.8) + (0.0014 \pm 0.0004) \cdot v] \quad (R^2 = 48.25\%) \tag{1}$$

where R^2 is the coefficient of determination.

A similar study of the relation between R and v' led to a very low value of R^2 ($R^2 = 6.35\%$), indicating a relatively weak relationship between the two variables. There are in principle two factors that could explain this fact. Firstly, the direction of the force R exerted by the press was longitudinal, so that it seems logical that there

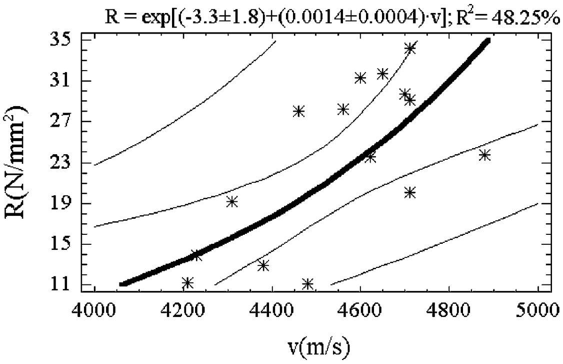

Fig. 1. Plot of the compressive strength, R, versus the longitudinal speed of ultrasound v for different specimens, together with the fit from Eq. (1).

should be a greater correlation with v. Secondly, the measurements of v' were performed on the curved surface of the specimens, so that the transducer-specimen coupling might have been poorer than in the case of the measurement of v, with a consequently greater dispersion of the data.

As indicated in the literature [6,7], the compressive strength of the concrete at 28 days increases with increasing cement content, c, and decreases with increasing water content, w. In the present case, this dependence is represented by the expression of Eq. (2):

$$R = (-67 \pm 9)\left(\frac{w}{c}\right) + (62 \pm 5) \quad (r = -0.898) \tag{2}$$

where r is the regression coefficient.

When a similar linear model is adopted to describe the relationship between v and w/c, however, the value of r decreases significantly. The corresponding functional form is given by Eq. (3):

$$v = (-1000 \pm 400)\left(\frac{w}{c}\right) + (5160 \pm 250) \quad (r = -0.571) \tag{3}$$

This would seem to suggest the existence of variables other than the ratio w/c that significantly influence the speed of propagation of ultrasound in these specimens of concrete. The use of ANOVA techniques [8,9] in this context can provide valuable information on the behaviour of compressive strength and ultrasound propagation speed. We therefore performed a multiple regression analysis which attempted to establish the relationships between the different components of the concrete (water, cement, sand, pea gravel, gravel, etc.) and the variables R and v. We carried out an exhaustive study which initially considered all the possible explanatory variables that could affect R. The best fit was obtained for the multiple linear regression model of Eq. (4):

$$R = (111 \pm 24) - (29 \pm 12)\frac{w}{c} - (180 \pm 50) \times \frac{\text{gravel} + \text{pea gravel}}{\text{mass}} + (129 \pm 24)\frac{\text{sand}}{\text{mass}} \tag{4}$$

The P-value in the ANOVA test was zero to four decimal places. With this model, we obtained on R^2 value of 95.18%, which when adjusted for the degrees of freedom reduced to 93.87%. These values indicate that the model explains almost all of the variability in the response variable R.

A similar study for v as the response variable resulted in the Eq. (5):

$$v = (10000 \pm 1500) + (1000 \pm 700)\frac{w}{c} - (10000 \pm 3000)\frac{\text{gravel} + \text{pea gravel}}{\text{mass}} \tag{5}$$

The P-value for the ANOVA test was found to be 0.0023. For this model, the R^2 value was 63.65%, which reduced to 57.60% when adjusted for the degrees of freedom. These values indicate that the model explains around 60% of the variability of v. We note that, in this case, we did not find the sand/mass ratio to have a significant influence on v. The importance of the proportion of gravel and pea gravel in the model, however, is explained by phenomena of dispersion of the ultrasound waves that these materials produce, thereby decreasing the measured speed.

3. Hardening

The specimens prepared for the study of the concrete's hardening curve all had identical proportions of the constituents. They will hence be considered as a single specimen in representing the evolution of the speed of propagation of ultrasound versus aging time, although those that were ruptured (in order to calculate the value of R) obviously no longer existed physically. Fig. 2 shows the cited evolution together with the least squares fit to the double reciprocal equation characterized by the function of Eq. (6):

$$v = \frac{1}{(2171 \pm 7) \times 10^{-7} + \frac{(107 \pm 3) \times 10^{-6}}{t}} \quad (R^2 = 92.92\%) \tag{6}$$

where v is expressed in m/s and t in days. Eq. (6) suggests that, many days after fabrication, v tends asymptotically to the value $1/A$ (m/s). Thus, from the fit for $n = 61$ days, Eq. (6) gives a value of $1/A = (4606 \pm 15)$ m/s corresponding to $t \to \infty$. Doing the same for $n = 28$ days (as is established in the Spanish legislation [1]) and $n = 5$ days, the estimates for $1/A$ are (4593 ± 15) and (4650 ± 90) m/s, with relative errors of 0.3% and 2%, respectively. In other words, according to the fitted

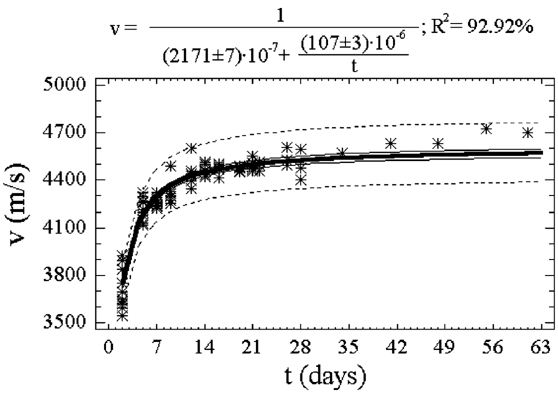

Fig. 2. Plot of the temporal evolution of the speed of ultrasound, v, with the time of aging, t, in different specimens, together with the fit from Eq. (6).

model given by Eq. (6), it would not be necessary to wait for 28 days or more in order to determine with high precision and accuracy the speed of propagation of ultrasound in manufactured specimens.

Finally, the exponential relationship between R and v for the specimens on which the hardening study was carried out takes the form of Eq. (7):

$$R = \exp[(-5.4 \pm 0.8) + (0.00185 \pm 0.00018) \cdot v] \quad (R^2 = 92.31\%) \tag{7}$$

As one can observe, on this occasion the quality of the fit is notably better than that corresponding to Eq. (1), since the hardening study specimens were all of a single type of concrete.

4. Conclusions

In this study, we firstly confirmed that there exists an exponential relationship between the compressive strength R of the cylindrical specimens of concrete and the longitudinal speed of propagation of ultrasound in them, v. Both variables depend significantly on the water-cement ratio and on the proportion of gravel and pea gravel present in the samples. Secondly, from the data on the hardening of the concrete, we developed a time-dependent model with which it was found to be straightforward to predict the value of R at 28 days after fabrication of a specimen on the basis of the measurement of v at only 2 and 5 days after fabrication.

Acknowledgements

The support of Isabel Peco and Juan Carlos Cadenas is gratefully acknowledged. Dr. Arthur Pewsey, Department of Mathematics, is also thanked for his assistance with the statistical questions.

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