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Analytical and genetic programming model of compressive strength of eco concretes by NDT according to curing temperature

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HIGHLIGHTS

- Estimation of compressive strength with non-destructive testing on concretes and eco-concretes.
- New analytical estimation models considering the curing temperature and other factors.
- Comparison of previous models with proposed models.
- Improved models using oriented genetic programming.
- A proposed model with a safety improvement.

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ABSTRACT

The use of non-destructive testing for estimating the compressive strength of concrete has great advantages both short term and long term. In the case of eco-concrete with recycled materials, it is of particular interest, since its use in many regulations is conditional on further studies. In this research we analyze the applicability of the most common models for estimating compressive strength by combining nondestructive testing. Specifically it was applied to 11 concrete with cement CEM-I, 3 self-compacting concrete and 8 vibrated concrete. There are two reference concretes (one of each) and the rest of concretes either have changed water/cement ratio or they contain different percentages of recycled materials (recycled aggregate fine and coarse together, or biomass ashes). Destructive tests have been made (compressive strength) and non-destructive (ultrasonic pulse velocity and compressive strength) in all concretes, at different ages and different curing temperatures, obtaining a total of 181 data sets. New estimation models were proposed for compressive strength with factors such as the curing temperature, the temperature history, the density of the concrete and the quantity of additive. These models substantially improve the results obtained with the usual methods. Finally, using genetic programming, it has managed to obtain an equation that allows, safely, estimating compressive strength with the information of non-destructive testing. The equation obtained improves current predictions with the peculiarity that minimizes uncertain results.

1. Introduction

Obtaining a good estimation of the compressive strength using non-destructive testing, has both long-term and short-term benefits. In the short term (during construction), it can allow an adjustment of the work deadlines, and at the same time, improve structural safety. In the long term (service, upgrading, modification and/or extension) it is of great importance, since it can predict the strength of concrete without having to take cores and consequently deteriorate concrete structures.

In the case of eco-concrete with recycled fine aggregate, recycled coarse aggregate (for percentages higher than 20%) or biomass ashes, getting greater insight and control over the compressive strength is of particular interest, since its use for the manufacture of structural concrete is either prohibited or conditioned to the development of complementary studies in multiple regulations [1–4].

The influence of curing temperature on the correlations between ultrasonic pulse velocity and compressive strength was

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observed in a previous study [5], concluding that the curing temperature is a critical factor when estimating the compressive strength through its correlation with ultrasonic pulse velocity (UPV), noting that for a same velocity, the lower the curing temperature is, the lower the corresponding strength. There are some previous studies [6–8] in which some influence of temperature on this correlation was observed. As can be seen in Table 1, in the usual estimation models combining non-destructive testing, curing temperature or historic internal temperatures are not usually considered as possible factors influencing the correlation between non-destructive tests and compressive strength.

Models which are more frequently used in this correlation are linear and exponential [9–11], although some authors consider other possibilities such as the potential or parabolic [9,12,13].

Huang et al. [14] develop a study comparing the results of 11 models, some of them collected in Table 1. They get the best fit with the most complex model they used, in which the input data are ultrasonic pulse velocity (UPV), age (t), the correlation water/cement (WC) and the rebound number (R). With this model a fit is obtained with an R^2 of 0.89.

Martínez-Molina [15] performed a comparative study of 10 models. Eight of these models use UPV, R, WC and t. Other models proposed also use the resonant frequency and the electrical resistivity, but the results do not improve significantly with respect to the formulation of Huang (who does not use resonant frequency or electrical resistivity).

Some investigations study the possibility of finding a better prediction of the compressive strength by using ultrasonic pulse velocity or by combining several non-destructive tests, using artificial neural networks [16,17], and they suggest that promising results and improving the accuracy of estimations can be obtained, however, an estimation equation including some important factors that can be applied easily in practice is not proposed. In a recent study, Ayaz et al. [18] using the M5 rule and M5P Tree proposes an equation for estimating the compressive strength using the ultrasonic pulse velocity modified, depending on the amount of cement, the amount of fly ash, amount of slag and the curing period. 10 different mixes are studied in which the amount of cement, fly ashes and slag are different. Data for each mix at 4 ages (3, 7, 28 and 120 days) is obtained. Therefore, the results of a total of 40 tests are used. Good estimation results are obtained, although it is necessary to note that in this investigation decisive factors on correlations such as the curing temperature [5,8] or the density of the resulting concrete among others are not considered. Other techniques used for estimating the mechanical properties of concrete and eco-concrete are, for example, the genetic programming, model tree and artificial neural network. As a result of using these techniques, significant improvements in the performance of predictive models can be obtained [19–26]. Therefore, one of the goals of this research is the analytical development and proposal of new models to estimate compressive strength, by combining non-destructive testing, considering the curing temperature, the history of internal temperatures and maturity of concrete. Other factors that can influence the correlations between non-destructive testing will be considered, especially in the case of eco-concrete, such as the density of the concrete (very important in the case of concrete with recycled aggregate) or the percentage of cement replacing biomass ashes. In addition, it aims to develop an equation for estimating the compressive strength on the safe side for conventional concrete and eco-concrete, for this purpose, analytical results are considered and the oriented genetic programming technique is used in which overestimation will be very sharply penalized.

Table 1
Common models for estimating compressive strength.

Reference	Model	Estimation model with END
–	M_{R0}	$\hat{s} = a_0 + a_1 \cdot UPV$
[9]	M_{R1}	$\hat{s} = a_1 \cdot UPV^{a_2}$
[9–11]	M_{R2}	$\hat{s} = a_1 \cdot e^{a_2 \cdot UPV}$
[9]	M_{R3}	$\hat{s} = a_0 + a_1 \cdot UPV^2 + a_2 \cdot UPV$
[14,15]	M_{R4}	$\hat{s} = a_0 + a_1 \cdot UPV + a_2 \cdot R$
[12,13,15]	M_{R5}	$\hat{s} = a_0 + a_1 \cdot UPV^2 + a_2 \cdot UPV + a_3 \cdot R$
[14,15]	M_{R6}	$\hat{s} = a_0 + a_1 \cdot UPV^3 + a_2 \cdot R^2$
	M_{R7}	$\hat{s} = a_0 + a_1 \cdot UPV + a_2 \ln(t) + a_3 \cdot WC^{-0.5} + a_4 \cdot R^2$

UPV: ultrasonic pulse velocity, (m/s), *R:* rebound number, *WC:* water/cement ratio, *t:* age (days) and $\hat{s}$: estimated strength (MPa).

2. Materials and methods

2.1. Materials

A total of 11 concretes are studied: 3 self-compacting concrete (SCC) and 8 vibrated concrete (VC). For each group, one reference concrete was set without recycled materials. The main intention was that these concretes were as different as possible in order to have diverse concretes. So, the following parameters were varied: type of concrete, quantity of cement, correlation water/cement, aggregate, maximum aggregate size, percentage of substitution of recycled aggregate and quantity of ashes.

For self-compacting concrete, one reference concrete was made without recycled aggregate (SCC0) and the other two with 20% and 50% substitutions of fine and coarse recycled aggregate used jointly, relative to the total aggregate (SCCR20 and SCCR50, respectively).

For manufacturing self-compacting concretes, the materials used in the mix were: a cement CEM I 52.5N/SR, a limestone filler, two fractions of quartzite fine natural aggregate 0/2.5 and 0/5, granitic gravel 6/12 and fine and coarse recycled aggregate from precast rejects with compressive strength between 35 and 45 MPa. After suitable treatment (crushing, magnetic separation and screening of 12 mm), the fraction 0/12 was obtained. In order to obtain a more sustainable resulting concrete, it was decided not to separate recycled sand and recycled gravel by sieving; thus, a saving is achieved in the energy consumed for obtaining recycled aggregates.

The total recycled aggregate has 40% of fine particles, which will be the partial replacement of fine aggregate 0/5, and 60% of coarse particles, which will partially replace the natural aggregate 6/12, due to the similarity of their particle size distribution.

For vibrated concrete, in addition to the reference concrete (VC0), three mixes are designed with different percentages (8%, 20% and 31%) of recycled aggregate, coarse and fine together (VCR8, VCR20 and VCR31 respectively), two with 15% and 30% cement replacement by biomass ashes (VCA15 and VCA30 respectively) and finally, two concretes with the same mix as the reference concrete but modifying the water/cement ratio (VC0-1 and VC0-2).

As for the materials used to manufacture the vibrated concrete, CEM I 52.5 S/SR-3 cement was used, two fine quartzite aggregate fractions 0/2 and 0/5, two coarse quartzite aggregate fractions 4/12 and 10/20 and a recycled aggregate, in this case the source was prefabricated concrete sleepers with concrete strengths of over 30 MPa, suitably treated.

Biomass ash used in concrete VCA15 and VCA30 are wastes generated in the process of obtaining energy through biomass combustion. Such biomass comes, in turn, from waste of the paper industry, which takes as raw material eucalyptus wood. A large characterization of this material is collected in another study [27].