Relevance of the Ultrasonic Pulse Velocity Test for Strength Assessment of High Strength Concretes

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Abstract. The present paper addresses the ultrasonic pulse velocity (UPV) as a non-destructive testing device for assessing the compressive strength of high strength concrete using a UPV-strength correlation model. UPV-strength correlation models are developed and used for normal strength concrete assessment; however, questions are raised as to the sensitivity of the ultrasonic pulse velocity test when applied for the strength assessment of denser, higher strength concretes. This study is an appraisal of the relevance of this non-destructive testing device for the high performances concrete strength assessment, aiming for a better knowledge of the applicability of this method as a way to improve the on-site non-destructive strength assessment of the high strength concrete. In the study, a high strength concrete within a specified strength range was targeted. Cylindrical concrete specimens were fabricated, left to harden then subjected to UPV and compressive tests so that a correlation model could be built. The developed model was then used to estimate the strength of a second high strength concrete made with the same type of aggregates. The estimated strength was compared to the real strength of this second HPC in order to assess the reliability of the developed model and hence of the ultrasonic pulse velocity testing. At a second stage, the proposed model was compared to the existing models for high strength concrete assessment, as a procedure to consolidate or negate the observations made in the first part. The results highlight the lack of sensitivity of the UPV method used for the assessment of high strength concrete. Indeed, each high strength concrete considered in this study, including those taken from the literature, varies within a particular strength range while the UPV measurements for all the high strength concretes considered vary narrowly within approximately the same range. This reveals that the UPV non-destructive testing method may not be fully reliable in estimating correctly the strength of a high strength concrete within a range different from that on which the model was built.

1. Introduction

The use of high strength concrete in structures has grown in popularity in the last decades. With its growth, the diagnosis and the assessment of the loading state and the service conditions of an existing reinforced concrete structure for the prediction of its remaining resisting capacity are becoming a major concern of the construction industry, especially since in addition to the fact that the use of such material is part of the policy of a sustainable development due to its improved performances durability wise as compared to normal strength concrete, its structural health monitoring, maintenance and rehabilitation using non-destructive techniques is also a step toward the preservation of the
environment. Thereby, such a structural assessment of a building should be carried out before any rehabilitation and maintenance work.

Estimating the compressive strength by non-destructive methods involves building regression models. This consists in constructing mathematical, empirical, linear or non-linear relationships, between two parameters, one destructive, the other non-destructive, which are supposed to be theoretically linked and having certain compatibility [1-4]. Indeed, such correlation is possible, because some properties of concrete such as its hardness, its rebound capacity and its ability to transmit ultrasonic waves are linked to its resistance, and can also be estimated by means of non-destructive tests. There are many non-destructive techniques allowing the construction of these correlations [5-7].

The ultrasonic pulse velocity technique (UPV) is one of the most popular and frequently used non-destructive techniques for the assessment of concrete properties. This method is an adequate means for examining the distribution of the concrete strength in a structural element. However, it has certain imperfections since it is influenced by a number of factors in addition to the fact that in a construction site, it is often difficult to ensure strict control of the proportions of the mixture [8]. According to Soutsos et al. [9], the non-homogeneity and the variation of the material at the heart of the same element can be at the origin of a reduction in the precision of the compressive strength estimation in the order of ± 10 MPa for a concrete of 30 MPa. Furthermore, the precision decreases even more when the strength increases. Therefore, for concrete strength exceeding 40 MPa, the estimation must be considered with caution.

Regarding the applicability of the UPV method to high performance concrete, studies have shown that it is perfectly suited for assessing the compressive strength of HPC [8]. However, the sensitivity which is defined as the ability of this technique to estimate the variation of the compressive strength, this sensitivity decreases with the increase of the compressive strength; this decrease is reflected in the value of the coefficient of correlation of the regression [8].

The present research is a contribution to the evaluation of the suitability of the UPV method for high performances concrete strength assessment, the aim being a better discernment of this method and its applicability and limits as a way to improve the non-destructive assessment of on-site high strength concrete. In the study, a high strength concrete within a specified strength range is targeted and a correlation model for this concrete strength assessment is built. To appreciate the relevance of the UPV method as a mean to estimate HPC strength, the developed model is first used to estimate the strength of a second high strength concrete made with the same type of aggregates. The comparison between the estimated and the actual strength, in this case, is an indicator of the reliability of the developed model and hence of the ultrasonic pulse velocity testing method. At the second part, the proposed model is compared to some existing models destined for high and ultrahigh strength concrete assessment in order to support the findings from the first part.

2. Experimental program and research methodology

2.1. Concrete mixing ingredients and mix proportions

High strength concretes in two different strength ranges were designed. The aggregate content, being one of the most influencing factors on UPV, was kept constant for those two concrete types to minimize the effects of influencing factors and hence to reduce the sources of variability and uncertainty in UPV measurements. The strength variation was obtained by varying the cement past contents of those concretes.

The concrete mixes were designed using a Portland cement with additives (CPJ-CEM II/A – 52.5 N) alongside with silica fume for the first high performance concrete; the cement used had a specific gravity of 2.24 and a specific surface area of 23 m²/g. Local limestone coarse aggregates (crushed
limestone rock) were used with a maximum size of 15 mm and a specific gravity of 2.69. Two types of local sands were used as fine aggregates: coarser river sand with a fineness modulus of 3.68 and a specific gravity of 2.65, and dune sand with a fineness modulus of 0.32 and a specific gravity of 2.63. The two types of sand were mixed at proportions of 75% of the coarse sand and 25% of the dune sand to give fine aggregates having a fineness modulus of 2.8. The superplasticizer used to improve the workability is based on Polycarboxylate polymers, with a specific gravity of 1.06 ± 0.01 and 30.2 ± 1.3 % solid content. The mixes had water/cement ratios (W/C) of 0.315 and 0.35 for HPC1 and HPC2 respectively. More details on the concrete mix proportions are given in Table 1.

| Constituent          | Content  | Unit    |
|----------------------|----------|---------|
|                      | HPC1     | HPC2    |
| Aggregates           | 177      | 177     |
|                      | kg/m³    | kg/m³   |
| Fine sand            | 177      | 177     |
| Coarse sand          | 536      | 536     |
|                      | kg/m³    | kg/m³   |
| Gravel 3/8           | 119      | 119     |
|                      | kg/m³    | kg/m³   |
| Gravel 8/15          | 1168     | 1168    |
|                      | kg/m³    | kg/m³   |
| Cement CPJ 52.5      | 450      | 400     |
|                      | kg/m³    | kg/m³   |
| Silica fume          | 36 (8%)  | /       |
|                      | kg/m³    | kg/m³   |
| Superplasticizer     | 9 (2%)   | 8 (2%)  |
|                      | kg/m³    | kg/m³   |
| Water                | 142      | 140     |
|                      | kg/m³    | kg/m³   |
| W/C                  | 0.315    | 0.35    |
|                      | /        | /       |
| Slump                | 16       | 16      |
|                      | cm       | cm      |
| Density of fresh concrete | 2.516 | 2.515 |
|                      | (g/cm³)  | (g/cm³) |
| Density of hardened concrete | 2.496 | 2.485 |
|                      | (g/cm³)  | (g/cm³) |

2.2 Casting of the concrete specimens and curing

Concrete specimens in the form of cylinders of dimensions 160mm x 320mm were cast from both concretes considered in this study. The cylindrical moulds were cast in two parts. After greasing the mould, the first layer, filling half the mould was placed and compacted; the second concrete layer was then placed and compacted. All the concrete specimens were kept covered with a damp hessian and plastic sheeting covering, in the laboratory of the room temperature for 24 hours until demoulding. The specimens were then weighed, placed outdoors and covered with plastic sheeting until the age of testing to reproduce in-situ curing conditions.

A total number of 99 cylindrical concrete specimens were made, 63 HPC1, and 36 in HPC2. The specimens were tested at the ages of 3, 7, 14, 28, 56, 91, and 182 days for HPC1, and 7, 28, 91, and 182 days for HPC2.

2.3 UPV testing and crushing

The longitudinal ultrasonic pulse velocity (UPV) was measured accordingly to the standard NF EN 12504-4 [10], using a 58-E0048 ultrasonic portable tester “Controls”. The cylindrical receiver and transmitter have 50 mm in diameter and a maximum resonance frequency of 54 kHz. UPV measurements were performed in the longitudinal direction, transit time was measured in three spots, and the mean value of the transit time was used to determine the UPV value for the specimen. All tested specimens were then crushed to determine the concrete strength.

3. Results and discussions

UPV measurements and crushing test results for HPC1 were used to describe UPV and strength evolution with the age of concrete (Figure 1 and 2). The gain in the concrete strength as a function of age is shown in figure (2). At three days, the compressive strength reached 59 MPa on average, which corresponds to 79% of the resistance at 28 days. Between 3 and 28 days, the strength increase is of 21%. After 28 days, the strength continues to increase but at a slower pace; thus from 28 to 91 days (3
months), the rate of increase is of 7.5% and from 28 days and 182 days (six months) it is of 16.2% (Table 2). We can conclude that the HPC gains most of its resistant capacities at a young age.

The evolution of the ultrasonic pulse velocity follows the same trend as the compressive strength. Indeed, a large part of the gain of this pulsation occurs at 3 days of age. Between 3 and 28 days, the increase in the ultrasonic pulse velocity is of 3.9% and therefore a slowdown in its evolution is initiated. The evolution curve of the ultrasonic pulse velocity begins to flatten from 28 days, in the same way as that of the strength evolution curve. In fact, the two curves in figure (1) and figure (2) are perfectly similar in their appearance, both at a young age where a significant evolution takes place for the two parameters; and at advanced ages where the evolution is in a great slowdown. However, in this phase of slowing down, the material gains comparatively more resistance than compactness and therefore of ultrasonic pulse velocity. In fact, while the strength increases by 12% from 28 to 182 days, UPV only increases by 3.45%. This confirms that the two parameters do not evolve in the same way, and that the ultrasonic pulse velocity becomes less and less sensitive to high resistances.

| Age              | UPV (m/s) | UPV (%) | Strength (MPa) | Strength (%) |
|------------------|-----------|---------|----------------|--------------|
| From 03 to 28 days | 187       | 3.9     | 15.77          | 20.98        |
| From 28 to 91 days | 17.5      | 0.35    | 5.64           | 7.5          |
| From 91 to 182 days | 154.8     | 3.09    | 6.54           | 8.09         |
| From 28 to 182 days | 172.2     | 3.45    | 12.18          | 16.20        |
| From 03 to 182 days | 359.4     | 7.49    | 27.95          | 47.04        |
The UPV measurements and the compressive strength results obtained from the crushing of the HPC1 specimens (strength varying from 55 MPa to 94 MPa) are plotted to give the curve as shown in figure 3 (compressive strength as a function of UPV). The Microsoft Excel regression data analysis tool was used to correlate the UPV measurements and the compressive strength results of this HPC1 with a confidence level of 95%. An exponential model was selected for the UPV-strength relationship, although no significant difference in accuracy as expressed by the coefficient of correlation $R^2$ was noticed between linear, polynomial, power and exponential law. The proposed correlation model is as in equation (1) with a coefficient of correlation of 0.789. Where the compressive strength $f_c$ is expressed in MPa and the pulse velocity $V$ is expressed in km/s.

$$f_c = 0.4704 \exp (1.0175 \ V)$$  \hspace{1cm} (1)

The proposed model as expressed by Equation (1) shows a good descriptive ability given its coefficient of correlation. A perfect correlation coefficient could not be obtained since in addition to the material variability at small scale and the lack of repeatability of measurements, variabilities may have occurred due to the fact that the tested specimens were cast from several batches. Another source of error would be the testing age. Indeed, this parameter, which is an important influencing factor as reported previously, was not constant varying from 3 to 182 days. Moreover, at higher ages, the UPV-strength sensitivity seems to decrease. Varying the testing age from 3 to 182 days led to a gap between the maximum and minimum value of about 350 m/s for UPV and 30 MPa for the actual compressive strength. Other sources of measurement errors such as local pathologies within the material were limited in this HPC1 (laboratory specimens); temperature and humidity fluctuations as possible sources of error were not accounted for since they were constant during the testing (laboratory environment), limiting thus the variability and uncertainty in the data.

![Figure 3. Correlation between the compressive strength ($f_c$) and the ultrasonic pulse velocity (UPV)](image)

The model proposed in Equation (1) was used to estimate the compressive strength of HPC1 based on the UPV measurements in order to assess the reliability of this developed model. In table 3 are presented the comparison of the estimated strength using the proposed model, and the actual strength of this HPC1 obtained by the crushing of the cylindrical specimens, as well as the statistical parameters for this ratio which will give an indication as to the accuracy of the correlation models. Results for the ratio $(f_c\text{ estimated} / f_c\text{ actual})$ translate a satisfactory estimation of the HPC1 strength at different ages, with a mean value $(f_c\text{ estimated/} f_c\text{ actual})$ of 1.002 and a variance coefficient of 6.06% (Table 3).

| Age (Days) | Specimen number | $f_c$ actual (MPa) | $f_c$ estimated (MPa) | $f_c$ estimated/ $f_c$ actual |
|------------|-----------------|--------------------|-----------------------|-----------------------------|
| 3          | Batch 1 01      | 63,1               | 62,29                 | 0,987                       |
| Batch | 02  | 03  | 04  | 05  | 06  | 07  | 08  | 09  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| 2     | 57,3| 60,79| 1,061|
| 3     | 59   | 61,41| 1,041|
| 4     | 59,7 | 61,91| 1,037|
| 5     | 55   | 61,54| 1,119|
| 6     | 58,1 | 62,29| 1,072|
| 7     | 59,2 | 63,38| 1,071|
| 8     | 60,9 | 63,51| 1,043|
| 9     | 62,4 | 62,29| 1,072|
| 10    | 66   | 66,49| 1,007|
| 11    | 68,5 | 66,62| 0,973|
| 12    | 62,5 | 65,61| 1,050|
| 13    | 67,9 | 66,82| 0,984|
| 14    | 63,6 | 65,95| 1,037|
| 15    | 67,3 | 66,62| 0,990|
| 16    | 68,4 | 66,82| 0,977|
| 17    | 65,5 | 66,49| 1,015|
| 18    | 64,8 | 65,61| 1,013|

| Batch | 20    | 21    | 22    | 23    | 24    | 25    | 26    | 27 |
|-------|-------|-------|-------|-------|-------|-------|-------|----|
| 4     | 66    | 66,49| 1,007|
| 5     | 68,5  | 66,62| 0,973|
| 6     | 62,5  | 65,61| 1,050|
| 7     | 67,9  | 66,82| 0,984|
| 8     | 63,6  | 65,95| 1,037|
| 9     | 67,3  | 66,62| 0,990|
| 10    | 68,4  | 66,82| 0,977|
| 11    | 65,5  | 66,49| 1,015|
| 12    | 64,8  | 65,61| 1,013|
| 13    | 63,6  | 65,95| 1,037|
| 14    | 67,3  | 66,62| 0,990|
| 15    | 68,4  | 66,82| 0,977|
| 16    | 65,5  | 66,49| 1,015|
| 17    | 64,8  | 65,61| 1,013|

| Batch | 28    | 29    | 30    | 31    | 32    | 33    | 34    | 35    | 36    |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 10    | 75    | 73,61| 0,981|
| 11    | 73,5  | 75,58| 1,028|
| 12    | 76,7  | 76,43| 0,996|
| 13    | 75,6  | 76,18| 1,008|
| 14    | 73,9  | 76,82| 1,040|
| 15    | 79,9  | 77,61| 0,971|
| 16    | 69,2  | 73,23| 1,058|
| 17    | 77,8  | 73,83| 0,949|
| 18    | 75    | 73,83| 0,984|

| Batch | 56    | 57    | 58    | 59    | 60    | 61    | 62    | 63    | 64    |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 13    | 79,3  | 74,43| 0,939|
| 14    | 76,9  | 79,28| 1,031|
| 15    | 76    | 75,20| 0,989|
| 16    | 83,9  | 76,82| 0,916|
| 17    | 81,1  | 71,18| 0,878|
| 18    | 79,7  | 74,59| 0,936|
| 19    | 78,6  | 76,04| 0,967|
| 20    | 79,1  | 80,83| 1,022|
| 21    | 83    | 80,42| 0,969|

| Batch | 91    | 92    | 93    | 94    | 95    | 96    | 97    | 98    | 99    |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 16    | 83    | 77,61| 0,935|
| 17    | 84,5  | 76,82| 0,909|
| 18    | 80,5  | 79,28| 0,985|
| 19    | 77,5  | 73,61| 0,950|
| 20    | 78,3  | 77,84| 0,994|
| 21    | 78    | 75,58| 0,969|
| 22    | 81,8  | 75,97| 0,929|
| 23    | 79,4  | 77,61| 0,977|
| 24    | 84,4  | 74,97| 0,888|

| Batch | 182   | 183   | 184   | 185   | 186   | 187   | 188   | 189   | 190   |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 19    | 86,1  | 96,58| 1,122|
The relationship between the actual compressive strength and the estimated one is illustrated in figure 4, where a relatively close fit between the actual strength and the estimated one is shown. This indicates that the proposed model is satisfactorily predictive for the range of the HPC1 targeted in this study. In effect, predicting the strength of concrete in real structures with a coefficient of variation (cv) around 5% could be considered as fairly accurate considering the complex and heterogeneous nature of concrete in general, which could also be greatly affected by its interaction with the environment.

Indeed, the coefficient of variation obtained for the present strength estimations (cv = 11.94 %) as in table 3 is closely comparable to that obtained for the crushing test of the same concrete (cv = 12.89 %) as given for fc actual in the same table. It is to be remembered that higher coefficients of variation for both actual and estimated strength could not be obtained because of the variation of one of the most influencing factors on UPV and fc; that is the testing age which varies in this study from 3 to 182 days.

In order to test and validate the applicability of the proposed correlation model furthermore, a second type of high strength concrete (HPC2) was designed, and the casted specimens subjected to UPV and crushing tests. The analysis of the results allowed us, first, to describe the evolution of the gain in the compressive strength of the concrete from its young age up to 182 days. The evolution of the ultrasonic pulse velocity and the compressive strength for HPC2 are plotted in figures (5) and (6) respectively.

This HPC2 reaches an average ultrasonic pulse velocity of 4,939 km /s for an average strength of 56 MPa at 7 days of age. From 7 to 182 days, UPV increase reaches barely 5% (Table 4) translating the stabilization often reported by the literature [11,12]. The UPV values for this HPC2 (figure 5) are comparable to those obtained for HPC1 (Figure 1) at the same ages, which further confirms the fact that this parameter remains practically invariable for high strengths as mentioned above. This
constancy of the ultrasonic pulse velocity is also due to the fact that in addition to the high strength for these two concretes (> 60 MPa), their granular skeleton is the same, a factor that strongly influences the UPV according to the literature [13, 14]. On the other hand, the compressive strength is comparatively higher for HPC1. The decrease in the compressive strength of HPC2 is due to the reduction in the dosage of cement since the granular skeleton is identical to that of HPC1.

![Figure 5. UPV evolution with the age of concrete](image1)

![Figure 6. Strength evolution with the age of concrete](image2)

| Table 4. Evolution the UPV and the compressive strength of HPC2 with the age of concrete |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Age                             | UPV (m/s) | (%) UPV | Strength (MPa) | Strength (%) |
| From 07 to 28 days              | 134,9     | 2,73    | 8,39            | 14,98         |
| From 07 to 182 days             | 222,7     | 4,51    | 11,67           | 20,85         |

The UPV results of HPC2 were used to test the applicability of the model developed for HPC1 to another high strength concrete whose strength range is different from the range based on which the model was built; this will allow us to validate this model. We will, therefore, estimate the strength of HPC2 using its UPV measurements along with the model proposed for HPC1 as expressed by equation (1). The estimated compressive strength is compared to the actual strength of HPC2 obtained by the crushing tests (Table 5 and Figure7).

| Table 5. Estimated strength and actual strength for HPC2 at different ages - statistical analysis of the data |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Age (Days)                     | Specimen number | fc actual (MPa) | fc estimated (MPa) | fc estimated/ fc actual |
| 7                              | Batch 1         | 50,26           | 75,43            | 1,501           |
|                                | 2               | 56,55           | 74,81            | 1,323           |
## Table

| Batch | 3   | 4   | 5   | 6   |
|-------|-----|-----|-----|-----|
|       | 50.31 | 70.67 | 1,405 |
| 2     | 57.01 | 67.65 | 1,187 |
| 4     | 53.45 | 66.89 | 1,251 |
| 5     | 59.86 | 70.81 | 1,183 |

| Batch | 7   | 8   | 9   |
|-------|-----|-----|-----|
|       | 57.32 | 73.23 | 1,278 |
| 3     | 59.18 | 72.12 | 1,219 |
| 5     | 59.89 | 73.46 | 1,227 |

| Batch | 10  | 11  | 12  |
|-------|-----|-----|-----|
|       | 64.69 | 86.53 | 1,338 |
| 4     | 68.39 | 84.02 | 1,228 |
| 6     | 64.97 | 83.50 | 1,285 |

| Batch | 13  | 14  | 15  |
|-------|-----|-----|-----|
|       | 66.92 | 81.24 | 1,214 |
| 5     | 69.74 | 84.44 | 1,211 |
| 7     | 65.95 | 79.77 | 1,210 |

| Batch | 16  | 17  | 18  |
|-------|-----|-----|-----|
|       | 59.75 | 79.77 | 1,335 |
| 6     | 61.05 | 84.02 | 1,376 |
| 8     | 57.84 | 76.59 | 1,324 |

| Batch | 19  | 20  | 21  |
|-------|-----|-----|-----|
|       | 59.17 | 89.76 | 1,517 |
| 7     | 66.66 | 86.44 | 1,297 |
| 9     | 66.48 | 97.47 | 1,466 |

| Batch | 22  | 23  | 24  |
|-------|-----|-----|-----|
|       | 69.16 | 78.64 | 1,137 |
| 8     | 64.17 | 77.45 | 1,207 |
| 10    | 69.01 | 75.20 | 1,090 |

| Batch | 25  | 26  | 27  |
|-------|-----|-----|-----|
|       | 62.38 | 83.76 | 1,343 |
| 9     | 66.66 | 87.77 | 1,317 |
| 11    | 63.67 | 82.41 | 1,294 |

| Batch | 28  | 29  | 30  |
|-------|-----|-----|-----|
|       | 66.87 | 83.76 | 1,253 |
| 10    | 66.55 | 94.25 | 1,416 |
| 12    | 61.11 | 90.77 | 1,485 |

| Batch | 31  | 32  | 33  |
|-------|-----|-----|-----|
|       | 70.34 | 92.64 | 1,317 |
| 11    | 69.49 | 95.31 | 1,372 |
| 13    | 71.5  | 89.76 | 1,255 |

| Batch | 34  | 35  | 36  |
|-------|-----|-----|-----|
|       | 68.36 | 92.07 | 1,347 |
| 12    | 65.93 | 86.53 | 1,312 |
| 14    | 68.73 | 84.19 | 1,225 |

| Mean (MPa) | 63.32 | 82.03 | 1,298 |
| Standard deviation (MPa) | 5.53 | 7.90 | 0.999 |
| cv (%)     | 8.73  | 9.63  | 7.62  |

### Figure 7

Comparison between the actual and the estimated compressive strength of HPC2 using the model developed for HPC1.
UPV measurements for HPC1 and HPC2 are quite similar; both concretes exhibit a high density. However, the mean value of the compressive strength of HPC1 from 7 to 182 days is of 77 MPa while for this same age range, the mean strength for HPC2 is 63 MPa. This gap of 14 MPa in the actual compressive strength between those two concretes is reproduced when estimating the compressive strength using UPV measurements for HPC2 along with the correlation model developed for HPC1 as can be seen from table 5. Indeed, as plotted in figure 7 where all the data are located above the line of equality (x = y), the estimated strength is overrated. The overestimation was calculated in this case at 19 MPa as a mean value which is close to the 14 MPa mentioned above as the mean value gap in the actual compressive strength between HPC1 and HPC2. In other words, for UPV measurements similar to those used in building the correlation model, and despite two different high strength ranges, the predicted strength falls within the strength range of the concrete used to develop the model; which in a way demonstrate the stability of the model, but also raises questions as to the sensitivity of the UPV method for HPC strength estimation.

The sensitivity of the UPV method for the strength estimation of high strength concretes has been addressed in the literature [7]; the results obtained seem to go in this direction. Indeed, these two concretes of high strength, but of different strength ranges, have a high density which leads to a similarity in the UPV measurements and this despite the differences in the formulation.

On the other hand, the similarity in the UPV values for these two high strength concretes, but of different composition, raises the question of the importance and the influence of the variation of the mix parameters on the UPV measurements when the concrete strength is high. The results obtained suggest that these parameters would become secondary to the primacy of the density of concrete. Indeed whatever these parameters, for high strengths, it would be the density of the concrete which would govern the non-destructive values. This would introduce us to the idea of a generalized correlation model for the strength estimation of concretes of the same strength range but of different mix parameters.

The proposed model (Equation 1) was fitted for a strength range varying from 55 to 94 MPa. As a procedure to assess the relevance of the UPV method when used for high strengths estimation, the developed model is compared to some of the models available in the literature destined for high and ultra-high strength assessment (Table 6). The results are plotted in figure 8.

The closest models to the proposed one are those developed by Khan et al. (2007) [15]. The first model (Mix1) fitted for an inferior strength range of (38-73) MPa slightly underestimates the compressive strength. The second model which varies within a similar strength range as compared to our model (61 to 91 MPa) is also the closest of the three models as plotted in figure 8. The third model intended for a higher strength range (68 to 104 MPa) slightly overestimates the compressive strength, indeed the regression line for this third model locates above the regression line of the proposed model. Thereby, the overestimate is noticed when the model destined for a higher strength range, as compared to the proposed model, is considered.

The models from Pascale et al. [16], [7] and Tsioulou et al. [17] developed for higher-strength concrete (up to 150 MPa) overestimate the compressive strength compared to the proposed model, especially the exponential model of Tsioulou et al. [17] built for UHPC strength prediction. These observations support and confirm our findings from part one since they highlight the lack of sensitivity of the ultrasonic testing method when it comes to high and ultra-higher strengths assessment.
Table 6. Some existing correlation models using the UPV

| Authors                  | Models                                      | R^2 | Strength range (MPa) |
|--------------------------|---------------------------------------------|-----|----------------------|
| Pascale et al. (2000)    | $f_c = 10^{-28} V^{0.1272}$                 | 0.84| 30.0 - 150           |
| Pascale et al. (2003)    | $f_c = 1.942x10^{-27} V^{7.76}$             | -   | 30 - 150             |
| Khatib (2008)           | $f_c = 0.003exp (0.0017V)$                  | 0.97| 5 - 85               |
| Khan et al. (2007)      | $f_c = 68.19 V - 263.21$ [Mix1]             | 0.92| 38 - 73              |
|                         | $f_c = 94.31 V - 379.75$ [Mix2]             | 0.63| 61 - 91              |
|                         | $f_c = 78.86 V - 300.42$ [Mix3]             | 0.76| 68 - 104             |
| Khan (2012)             | $V = 1.92 f_c^{0.20}$                       | 0.82| 45 - 115             |
| Tsioulou et al. (2017)  | $f_c = 0.06007 exp (0.00162 V)$             | 1   | 25 - 110             |
|                         | $f_c = 0.0852 V - 294.24$                   | 0.97|                     |

Figure 8. Comparison of the developed model to models available in the literature

4. Conclusions

Experimental data for HPC1 allowed us, using the Excel tool, to develop an ultrasonic correlation model. This model is reliable and leads to an estimation of the compressive strength with good precision as expressed by its correlation coefficient. A comparison of the resistance estimated by this model with the real resistance of HPC1 obtained by crushing test allowed us to appreciate the satisfactory accuracy. Indeed, the calculation of the statistical parameters for the actual strength / estimated strength ratio gives very acceptable values which are within the tolerated range for the estimation of the concrete strength by non-destructive methods.

HPC2 with a strength range close to that of HPC1 was used to test the reliability of the proposed model. UPV measurements collected on HPC2 were used to estimate the compressive strength of this concrete from the correlation model developed for HPC1. A comparison, statistical parameters at support, between the estimated strength and the actual strength of HPC 2 led to a strength gap very close or similar to the difference noted between the actual strength of HPC1 and that of HPC2, rated at 14 MPa. In other words, HPC2 strength estimation using the model developed for HPC1 reproduced a gap in the line of those that exist between the respective actual strength of these two concretes. This shows the stability of the proposed model when estimating the strength based on UPV values other than those for which it was built. In this part of the study, we noted a similarity in the ultrasonic results despite a difference in the composition of the two concretes mainly in the cement paste content. The question of the sensitivity of non-destructive measurements for high resistances has been asked repeatedly in the literature; the results obtained seem to go in this direction. Indeed, these two concretes of high strength but of different ranges have a high density which leads to a similarity in the non-destructive measurements and this despite the differences in the formulation.
Despite different classes, both concretes can be considered as belonging to the same high strengths range. This similarity raises the question of the importance and the influence of the mixture parameters variation on the non-destructive measurements when the compressive strength is important. The results obtained suggest that these parameters would become secondary when opposed to the primacy of the density of the concrete. Indeed whatever these parameters, for high strengths, it would be the density of the concrete which would govern the non-destructive values. This would allow us to propose the idea of a generalized correlation model for the estimation of the compressive strength of concretes of the same high strength range.

A comparison of the model proposed in this work with those drawn from the literature allowed us to consolidate our opinion as to the relevance of the UPV method in assessing the compressive strength of high strength concretes. Indeed, the fact that the regression lines of the literature models intended for high and ultrahigh strength locate above the regression line of the proposed model translates an overestimation of the concrete strength. Each model considered in the comparison varies within a particular strength range while the UPV measurements for all the high strength concretes considered vary narrowly within approximately the same range. This reveals that the UPV method may not be fully reliable in estimating correctly the strength of high strength concretes within a range different from that on which the model was built.

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