

A new approach to estimate compressive strength of concrete by the UPV method

Um novo procedimento para estimar a resistência à compressão do concreto pelo método VPU

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Abstract

Although the ultrasonic pulse velocity (UPV) method has been extensively used to estimate concrete compressive strength, the relationship between UPV and concrete strength is mixture dependent. As a result, the applicability of this method to estimate strength is well known to be limited. Aggregate type, cement type, mixture proportions, and water-cement ratio influence such a relationship. Nevertheless, UPV and strength are both governed by cement hydration, and thus, a relationship between UPV in the cement paste phase and concrete compressive strength would be expected to exist. By not taking into account the type and volume content of aggregates, this relationship could be the same for concrete mixtures with same type of cement and water-cement ratio, regardless the aggregate type used. This study investigates the existence of such a relationship. Concrete mixtures with water-cement ratios of 0.48, 0.55 and 0.64, with different paste volumes were prepared in the laboratory. For each mixture, compressive strength and ultrasonic pulse velocity were evaluated at various ages. The UPV of each concrete phase: paste, fine aggregate, and coarse aggregate, was obtained through paste and mortar specimens. This study indicated that it is possible to establish a unique relationship between the UPV in cement paste phase and the concrete compressive strength. This unique relationship could be applied to several concrete mixtures, greatly expanding the use of the UPV method to estimate compressive strength.

Keywords: compressive strength, mechanical properties, ultrasonic pulse velocity, non destructive methods.

Resumo

O método da velocidade do pulso ultrassônico (VPU) tem sido bastante utilizado para estimar a resistência à compressão do concreto, porém sabe-se que a relação entre a VPU e a resistência do concreto depende do traço da mistura. Como consequência, a aplicabilidade do referido método para estimativa da resistência torna-se limitada. Tipos de agregados, tipos de cimento, dosagem e relação água/cimento influenciam diretamente na relação entre VPU e resistência do concreto. No entanto, tanto a VPU quanto a resistência do material dependem da hidratação do cimento e assim é de se esperar que exista uma correlação entre a VPU na pasta de cimento e a resistência do concreto. Por não levar em consideração o tipo e volume dos agregados, esta correlação poderia ser a mesma para concretos com o mesmo tipo de cimento e relação água/cimento, independente dos tipos de agregados utilizados nas misturas. O presente estudo investiga a existência da referida correlação. Foram preparadas em laboratório misturas de concreto com relação água/cimento 0,48, 0,55 e 0,64, com diferentes volumes de pasta. Para cada mistura e em diferentes idades, foram obtidos valores da resistência à compressão e da velocidade do pulso ultrassônico. A VPU para cada constituinte do concreto (pasta, agregado fino e agregado graúdo), foi obtida por meio de corpos de prova de pasta e de argamassa. O estudo mostrou que é possível estabelecer uma correlação única entre a VPU na pasta de cimento e a resistência à compressão do concreto. Esta correlação única poderia ser aplicada para diversas misturas, ampliando sobremaneira a aplicação da VPU para estimar a resistência à compressão do concreto.

Palavras-chave: resistência à compressão; propriedades mecânicas; velocidade de pulso ultrassônico; ensaios não destrutivos.

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1. Introduction

Concrete compressive strength is the main mechanical property used in the design of concrete structures. Project criteria, construction scheduling, and load capacity of a concrete structure depend upon the specified compressive strength, which is usually determined as the compressive strength at 28 days in a controlled temperature and relative humidity environment [1, 2].

Sometimes, however, it is necessary to assess concrete compressive strength on site in ages other than 28 days. Form removal, shoring, reshoring, the application of construction and service loads, and prestressing forces are only scheduled to take place after a certain level of strength or elastic modulus is reached. In some cases, compressive strength must also be estimated at later ages to determine the actual load capacity of the structural member.

Compressive strength like most of the mechanical and physical properties of concrete mixtures is continuously changing over time due to the hydration of cement particles. As the microstructure develops the mixture changes from a fluid to a solid state. It loses its initial workability, and starts to develop its mechanical properties. This continuous process can be indirectly followed by monitoring the development of either chemical, electrical, physical, or mechanical properties of the concrete mixture.

One option is to use wave propagation methods to gather information on the development of the microstructure. The most important parameters of this non-destructive method are the propagation velocities and the elastic properties, as well as the derived quantities [3]. Wave velocities depend on the modulus of elasticity, poison ratio, and density of the material.

The longitudinal or compression wave (P-wave) velocity can be easily obtained when testing a concrete sample. Portable ultrasound equipment is widely available and affordable. In order to continuously monitor changes in physical and mechanical properties, it is necessary to record transient ultrasound waves transmitted through the mixture. There have been several examples of the application of such a technique to monitor the development of the microstructure of cementitious materials, as well as to assess the effects of chemical admixtures on the development of the microstructure [4, 5].

Lin [6] presented a mathematical method to predict concrete UPV values based on the mixture proportions and on the UPV of each concrete phase, defined as cement paste, fine aggregate, and coarse aggregate. According to them, concrete UPV can be obtained by using a simple rule of mixtures, examining the volume fraction of each phase with its individual UPV, in accordance with Eq. 1.

$$\frac{1}{v_c} = \frac{1}{v_p} \frac{V_p}{V_c} + \frac{1}{v_{fa}} \frac{V_{fa}}{V_c} + \frac{1}{v_{ca}} \frac{V_{ca}}{V_c} \quad (1)$$

Where:

- V_c - UPV in concrete;
- V_p - UPV in cement paste;
- V_{fa} - UPV in fine aggregate;
- V_{ca} - UPV in coarse aggregate;
- V_p/V_c - Volume ratio of cement paste to concrete;
- V_{fa}/V_c - Volume ratio of fine aggregate to concrete;

V_{ca}/V_c - Volume ratio of coarse aggregate to concrete;

Although the volume fraction of each individual phase is given directly by the mixture proportions, in order to estimate UPV in concrete from Eq. 1, it is necessary to have previously established the UPV in the different individual concrete constituents. Lin [6] obtained UPV values directly from cement paste mixtures, and from cores of the coarse aggregate stones. The UPV in the fine aggregate, on the other hand, was indirectly obtained by comparing the UPV of cement pastes to that of mortar mixtures, using Eq. 2. Mortar was considered to be a two-phase composite material consisting of fine aggregate and cement paste.

$$\frac{1}{v_m} = \frac{1}{v_p} \frac{V_p}{V_m} + \frac{1}{v_{fa}} \frac{V_{fa}}{V_m} \quad (2)$$

Where:

- V_m - UPV in mortar mixture;
- V_p/V_m - Paste volume to mortar volume;
- V_{fa}/V_m - Fine aggregate volume to mortar volume;

Lin [6] concluded that Eq. 1 can be used to estimate the UPV in concrete with an error of 2.5% at ages later than 7 days. For early ages, of less than three days, the authors believed that their model would not take into account possible free water inside the concrete mixture.

When using the ultrasonic pulse velocity (UPV) method to estimate the compressive strength of concrete mixtures, it is necessary to demonstrate that there is a relationship between compressive strength and UPV. Both concrete compressive strength and ultrasonic pulse velocity in concrete are a consequence of the extent of cement hydration. Pinto et al [7] found a correlation between UPV in concrete and the non-evaporable water content of some mortar mixtures for UPV values greater than 2000 m/s. Although not a direct measure of the chemically combined water, the non-evaporable water content is still related to the extent of cement reaction, and can be used to assess the degree of cement hydration [8]. Similarly, Byfors [9] presented a linear relationship between compressive strength and degree of hydration for concretes with w/c ratios of 0.40 to 1.0, for degree of hydration values greater than 15%. For degree of hydration values smaller than 15%, Byfors [9] believed that compressive strength grows non-linearly with an increase of the degree of hydration values.

However, it has been well established that there is not a unique relationship between the UPV and compressive strength that can be applied to any concrete mixture [10, 11, 12]. Many factors affect the relationship between compressive strength and the UPV. Some of them are directly related to the concrete mixture, such as aggregate type, size, and content; cement type and content; and water-cement ratio. Thus, if the UPV method is used to estimate the compressive strength of concrete, the correlation curve between those two parameters for the particular concrete mixture must be previously determined.

Nevertheless, according to Equation 1, there is a direct relationship between the UPV in the cement paste phase to the UPV in concrete. For a given mixture with known volume fractions of each concrete phase (paste, fine aggregate and coarse aggregate) together with the UPVs values in the fine and coarse aggregates, the

development of UPV in concrete would be given by the development of UPV in the cement paste. UPV in the aggregates should be constant over time. Therefore, one could directly relate UPV in the cement paste phase to compressive strength of concrete.

This new relationship could, in theory, be applicable to various concrete mixtures. It would depend solely on the type of cement. The influence of aggregate type, and its proportions in the concrete mixture would be suppressed. Thus, a relationship between the UPV in cement paste and concrete compressive strength could be applied to a family of concrete mixtures expanding the use of the ultrasound to estimate concrete compressive strength.

This relationship, nonetheless, would still not be applicable to concrete mixtures in which the aggregates play an important role in concrete strength, such as for mixes with lightweight coarse aggregates or even high strength mixes. For normal strength concrete mixtures, on the other hand, such a relationship would allow a much broader use of the ultrasound to estimate concrete compressive strength. It would still be necessary to have previously obtained the UPV in cement paste and in the aggregates, as well as, the correlation relationship between the UPV in cement paste and concrete compressive strength for one mixture. Such a relationship could then be used to estimate the compressive strength on site for concrete mixtures with the same cement type, but made with any type of aggregate and with various mixture proportions.

This work presents an experimental investigation in which the relationship between concrete compressive strength and the UPV in cement paste was investigated for concrete mixtures with same type of cement. The main goal of this study was to correlate compressive strength with UPV in cement paste regardless of the type of aggregate and its proportions. Therefore, the UPV and compressive strength of concrete mixtures with three different water-cement ratios made of various aggregate proportions and two types of coarse aggregate (gravel and basalt) were monitored. The results indicated that there seems to be a unique relationship between the UPV in cement paste and concrete compressive strength for a given type of cement used in normal-strength concrete mixtures.

2. Experimental program

Concrete mixtures with water-cement ratios of 0.48, 0.55, and 0.64 were prepared in the laboratory. For each water-cement ratio, different paste volumes were chosen among the values of 28%, 32% or 35% of the total mixture volume. Table 1 shows the concrete mixture proportions. Brazilian cement Type CP V-ARI-RS was used. The fine aggregate was made of a combination of 30% river fine sand and 70% medium gravel sand, crushed from gravel coarse aggregate. Coarse aggregate with a nominal size of 19 mm was used for all mixtures. Two types of coarse aggregates were chosen, gravel and basalt. A water reducer admixture was also added to the mixture in order to maintain workability.

Each concrete mixture was named according to the following rule: the first letter identifies the mixture as a concrete mixture (C); the numbers that follow indicate the water-cement ratio and paste volume; and finally the last letter indicates the type of coarse aggregate in the concrete mixture, either gravel (G) or basalt (B). For instance, mixture C5532G represents a concrete mixture with water-cement ratio of 0.55, paste volume of 32%, and gravel coarse aggregate.

The materials were mixed in the laboratory in a 0.4 m³ drum mixer. For each concrete mixture, several 100 x 200 mm cylinders were cast. These cylinders specimens were kept inside their steel molds for the first 24 hours, after which they were demolded, and wrapped with a thin plastic film to prevent loss of moisture. All cylinder specimens were kept in laboratory conditions before tested for UPV and compressive strength.

Compressive strength and ultrasonic pulse velocity were evaluated according to Brazilian Standards at various ages from 0.75 to 28 days after casting. The calculated compressive strength was the average of four individual tests performed on the cylinder specimens. Measurements of the UPV were performed on all cylinder specimens just before compressive strength testing. Commercial ultrasound equipment was used along with 54 kHz cylindrical transducers.

The ultrasonic pulse velocity in the fine aggregate was indirectly obtained by applying Equation 2. Concrete mixture C5532G was

Table 1 - Mixture proportion, kg/m³

Mixture	Cement	Fine aggregate	Coarse aggregate	Water	Admixture	w/c	Paste volume (%)
C4828G	327	906	1009	155	1.6	0.48	0.28
C4832G	374	828	984	177	1.9	0.48	0.32
C4835G	426	761	972	203	2.1	0.48	0.35
C5528G	302	921	1001	164	1.5	0.55	0.28
C5532G	350	749	981	191	1.7	0.55	0.32
C5535G	392	776	957	214	2.0	0.55	0.35
C6428G	272	936	989	175	1.4	0.64	0.28
C6432G	310	859	956	199	1.5	0.64	0.32
C4832B	373	879	1024	180	1.9	0.48	0.32
C5532B	344	894	1012	190	1.7	0.55	0.32
C6432B	312	917	1005	204	1.6	0.65	0.32

Table 2 – Ultrasonic pulse velocity in the prismatic specimens, m/s

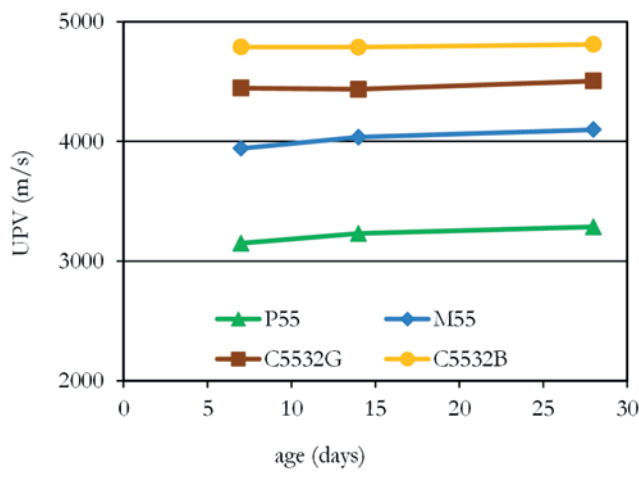
Mixture	Age (days)		
	7	14	28
P55	3149	3231	3285
M55	3942	4036	4098
C5532G	4446	4436	4505
C5532B	4789	4788	4811

chosen as the basic mixture from which mortar and cement paste mixture proportions were calculated. Thus, a cement paste mixture and a mortar mixture with water-cement ratio of 0.55, (P55 and M55) were also prepared in the laboratory. Prismatic specimens of 100 x 200 x 200 mm size were prepared for the paste and mortar mixtures. The UPV in each specimen was obtained at 7, 14 and 28 days. The ultrasonic pulse velocities in the gravel and basalt coarse aggregates were obtained by a similar approach. Two concrete prismatic specimens of the same size as for the paste and mortar mixtures were prepared for C5532G and C5532B mixtures. UPV was also measured at 7, 14 and 28 days. UPV in the basalt coarse aggregate and the gravel coarse aggregate was calculated using Equation 1 together with the obtained values of pulse velocity in fine aggregate and in the paste mixture.

3. Experimental results and discussions

Table 2 and Figure 1 show the UPV results for the prismatic specimens used to obtain the ultrasonic pulse velocities in the paste, mortar and coarse aggregates. It can be observed that the ultrasonic pulse velocities in both concrete mixtures were always higher than the UPV in the mortar, which was always higher than the UPV in cement paste. Such behavior was expected, since with the

Figure 1 – Development of the UPV over time for paste, mortar, and concrete mixtures with the same w/c ratio



introduction of greater volumes of aggregates in the mixes, there was a consequent reduction of paste volume, and therefore an increase on the UPV values. Figure 1 also depicts the influence of aggregate type on the value of UPV, since concrete mixture C5532B, with basalt coarse aggregate, presented a much higher UPV than mixture C5532G, with gravel coarse aggregate at the same volume content.

Table 3 shows the average UPV results over time for all concrete mixtures measured in the cylinder specimens, the accompanying average compressive strength results for such specimens are presented in Table 4. These data can be graphically seen in Figures 2 to 4 where the relationship between the UPV in concrete and concrete compressive strength for all mixtures are presented. The

Table 3 – Ultrasonic pulse velocity in the cylinder specimens, m/s

Mixture	Age (days)							
	0.75	1	2	3	5	7	14	28
C4828G	4099	4361	4422	4484	4549	4581	4604	4683
C4832G	4010	4131	4305	4393	4424	4477	4492	4618
C4835G	-	4157	4307	4325	4359	4383	4511	4548
C5528G	4121	4249	-	4386	-	4490	4543	4576
C5532G	3577	4038	4340	4409	4366	4470	4590	4583
C5535G	3658	-	4221	4307	-	4347	4428	4450
C6428G	3874	4135	4332	4342	4372	4413	4496	4521
C6432G	3528	3854	3991	4211	4140	4201	4283	4345
C4832B	4313	4566	4737	4766	4858	4884	4910	4956
C5532B	4142	4394	4580	4638	4703	4716	4732	4823
C6432B	3939	4240	4395	4640	4562	4600	4639	4728

Table 4 – Compressive strength results, MPa

Mixture	Age (days)							
	0.75	1	2	3	5	7	14	28
C4828G	12.8	18.4	27.6	32.4	34.2	37.7	41.8	42.9
C4832G	13.8	18.8	27.8	30.3	32.2	35.3	38.7	44.3
C4835G	-	19.5	27.8	31.7	33.9	35.0	39.0	43.3
C5528G	10.7	15.8	-	26.6	-	31.4	35.0	36.1
C5532G	4.4	11.2	24.0	26.7	30.2	33.3	38.6	40.6
C5535G	6.5	-	21.3	26.9	-	29.6	34.9	38.2
C6428G	6.5	10.5	17.1	20.3	22.3	23.4	26.9	29.6
C6432G	5.2	9.6	15.3	18.2	18.7	20.5	23.3	26.4
C4832B	13.2	20.5	27.4	30.6	33.1	35.6	40.3	45.7
C5532B	9.8	14.0	19.2	20.8	25.2	26.5	27.4	35.5
C6432B	6.2	9.9	16.2	20.7	21.6	22.2	25.4	28.0

behavior pattern of such a relationship was the same for all mixtures, since for given water-cement ratio, mixtures with greater paste volumes, and therefore smaller aggregate volumes, displayed smaller UPV values at the same level of compressive strength. On the other hand, mixtures with basalt coarse aggregate showed greater values of UPV at the same level of compressive strength. These results reinforce the influence of aggregate proportions and aggregate types on the relationship between compressive strength and UPV in concrete mixtures.

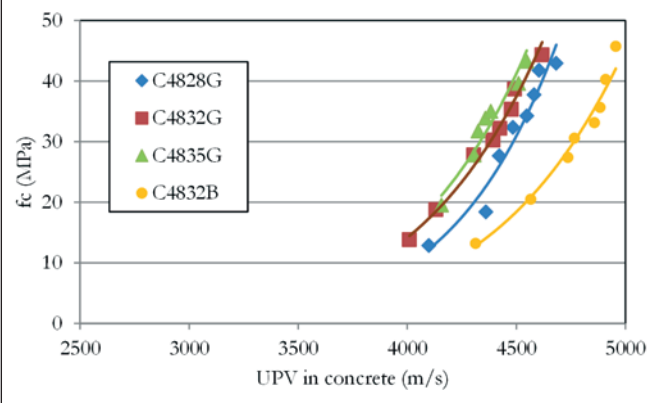
The UPV in the fine and coarse aggregates were obtained from Equations 1 and 2 along with the UPV values in the prismatic samples. Table 5 presents the calculated UPV values in the fine aggregate, as well as in the gravel and basalt coarse aggregates. The results indicated that the UPV in the basalt coarse aggregate was approximately 36% higher than the one in the gravel coarse aggregate, explaining the higher UPV observed for the concrete mixtures made with basalt coarse aggregates.

Since the objective of this study is to evaluate the relationship between UPV in cement paste phase and the compressive strength of concrete, it is necessary to estimate the UPV in the cement paste for each mixture. Even though, the value of UPV for M55 mixture was obtained from the M55 prismatic specimen, such a specimen is more than twice the volume of the cylinders, in which compressive strength was obtained. Moreover, paste specimens for 0.48 and 0.64 water cement ratio mixtures were not prepared. Therefore, it was decided to calculate the UPV in the cement paste phase of the cylinders themselves. This approach would allow to

Table 5 – UPV of aggregates, m/s

Fine aggregate	5346
Gravel coarse aggregate	5444
Basalt coarse aggregate	7397

Figure 2 – Comparison among UPV values for concrete mixtures with w/c of 0.48



directly relate compressive strength and UPV in paste phase of the same specimen.

Eq. 1 permits to estimate the UPV in the cement paste phase for each cylinder tested by knowing the UPV in the aggregates, in the concrete cylinder, as well as the volume fractions of each component. By rearranging the terms in Eq. 1, it is possible to mathematically describe the direct dependence of UPV in the cement paste with the aforementioned variables, as presented in Eq. 3.

$$\frac{1}{v_p} = \frac{1}{v_c} \frac{V_c}{V_p} - \frac{1}{v_{fa}} \frac{V_{fa}}{V_p} - \frac{1}{v_{ca}} \frac{V_{ca}}{V_p} \quad (3)$$

Thus, for each cylinder tested, the UPV in the cement paste phase was calculated according to Eq. 3. The results are presented in Table 6 for the various concrete mixtures at all ages.

Figure 3 – Comparison among UPV values for concrete mixtures with w/c of 0.55

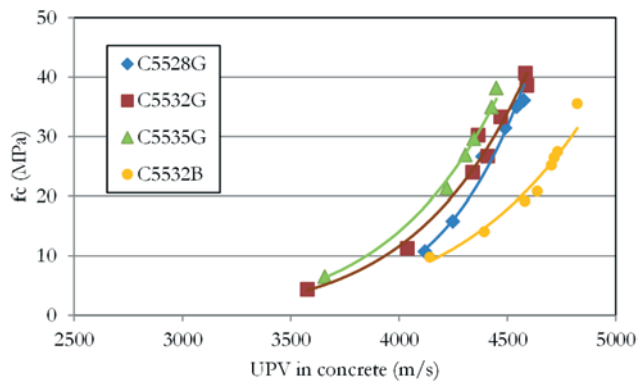
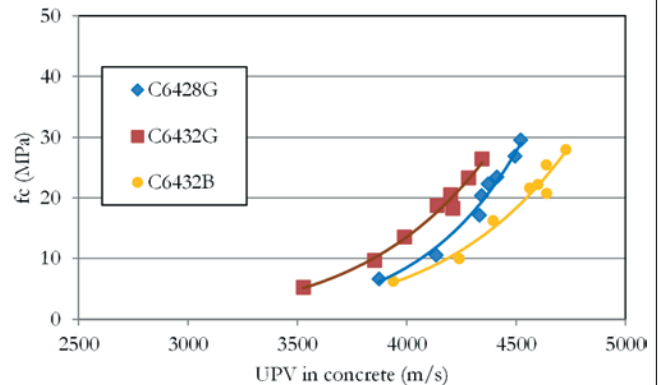


Figure 4 – Comparison among UPV values for concrete mixtures with w/c of 0.64



Figures 5 to 7 show the correlation between concrete compressive strength and UPV in cement paste phase for mixes with the same water-cement ratio. It can be noticed that for a given water-cement ratio, there seems to be a unique relationship between concrete strength and UPV in cement paste, which does not depend upon the aggregate proportion or aggregate type.

In order to assess the effect of different water-cement ratio on the relationship between UPV in cement phase and concrete compressive strength, all data were analyzed together, being presented in Figure 8. It can be observed that by using the UPV in the cement paste phase instead of the UPV in concrete as an indicator of the compressive strength acquired by the concrete mixture, concrete mixtures with different aggregates, aggregate proportions and water cement ratios may be grouped together as having the same relationship.

An analysis of variance procedure was performed to assess whether the relationship between UPV in cement paste phase and concrete compressive strength is affected by the water-cement ratio [14]. Initially, the best fit power regression curve was obtained for each water-cement relationship. The best fit curves are presented in Figures 5 to 7. It was verified that the error term variances of each best fit power regression curve were not significantly different, confirming the aptness of the regression model considering all data together. Then, with a risk level α of 0.01, it was

concluded that there is not a significant difference among the three best fit power curves. Therefore, it was possible to obtain the best fit power curve for all data, as presented in Figure 8 along with the obtained coefficient of determination.

This mathematical expression was used to compare strength prediction given by the UPV in cement paste for the mixtures studied. Figure 9 presents the results of the estimated and the predicted strength values for all mixtures.

The absolute error of the predicted strength to the measured strength was calculated for each testing age. The calculated errors for all mixtures at the various ages are shown in Figure 10. The mean of the absolute errors was on the order of 1.6 MPa, with a maximum absolute error of 4.2 MPa. However, it is possible to note that the absolute errors seem to be heteroscedastic, since the scatter band increases over strength values. The variance of the absolute errors therefore does not remain constant [15]. It depends upon the strength level.

Due to the time-dependent behavior of the strength data, the normalized error, as given by Equation 4, is a more appropriate parameter to compare approaches, as suggested by Bazant and Panula [16]. This approach equally weights the effect of differing strengths at early ages versus those at later ages. The normalized errors versus age for all mixtures are shown in Figure 11. It can be observed that the normalized errors seem to be homoscedastic,

Table 6 – Calculated UPV in the paste phase, m/s

Mixture	Age (days)							
	0.75	1	2	3	5	7	14	28
C4828G	2552	2940	3039	3145	3258	3318	3359	3512
C4832G	2603	2766	3019	3158	3207	3296	3321	3543
C4835G	-	2919	3137	3165	3216	3255	3461	3524
C5528G	2568	2753	-	2966	-	3141	3235	3295
C5532G	2067	2612	3046	3157	3087	3257	3467	3454
C5535G	2295	-	3011	3137	-	3198	3326	3360
C6428G	2247	2584	2876	2892	2940	3006	3147	3192
C6432G	2038	2404	2574	2877	2775	2863	2983	3078
C4832B	2607	2912	3137	3178	3308	3346	3383	3453
C5532B	2415	2699	2929	3004	3091	3108	3131	3257
C6432B	2184	2499	2677	2984	2883	2932	2983	3103

with the scatter band being constant over various strength levels. The mean of the relative errors was around 6.9%, with only three individual values above 15%.

$$\overline{\Delta}_i = \frac{(S_i)_{pred} - (S_i)_{obs}}{(S_i)_{obs}} \quad (4)$$

Where, $\overline{\Delta}_i$ = normalized error at test i (unitless);

$(S_i)_{pred}$ = value of predicted strength at test age i (MPa);

$(S_i)_{obs}$ = observed value of strength at test age i (MPa).

4. Conclusions

Based on the work presented in this paper, the following conclusions may be drawn:

- For the mixtures studied here, the use of UPV values in the paste phase of concrete mixes, as calculated by Eq. 3 allowed to find a unique relationship between the UPV in cement paste and the concrete compressive strength for a given type of

cement regardless the water-cement ratio, aggregate content and aggregate type.

- The relative errors of predicted to actual strength from the best fit power equation seemed to follow a homoscedastic assumption, and thus were not dependent on the strength levels. The mean value of the relative errors was on the order of 6.9%.
- This study indicated that for a given type of cement, it is possible to establish a unique relationship between the UPV in cement paste phase and the concrete compressive strength. This unique relationship could then be used to estimate concrete compressive strength on site for any concrete mixture with the same type of cement, regardless of the type of aggregates, their volume proportions in the mixture, and the water-cement ratio of the mixture. It would be necessary, however, to have previously defined UPV values in the aggregates. This could be accomplished by comparing UPV values in cement paste, mortar, and concrete mixtures using Eq. 1 and Eq. 2.
- The use of UPV in cement paste rather than in concrete to estimate concrete compressive strength could increase the use of this non-destructive test method to estimate concrete strength. Once a relationship has been established, it could be applied to

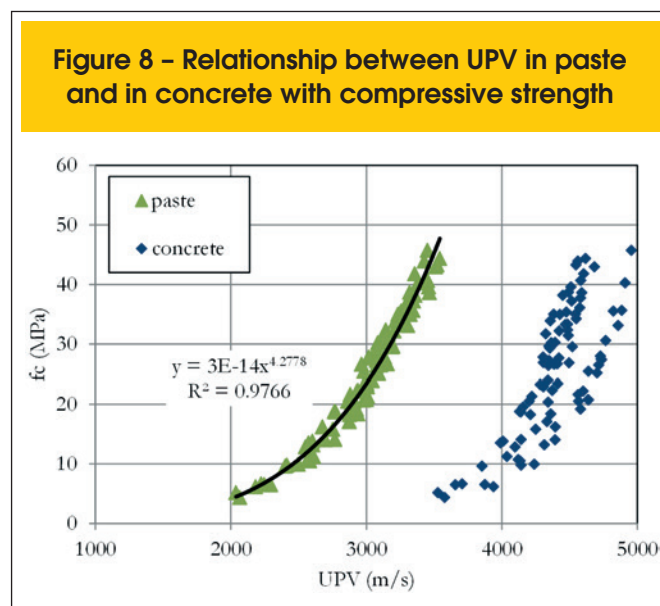
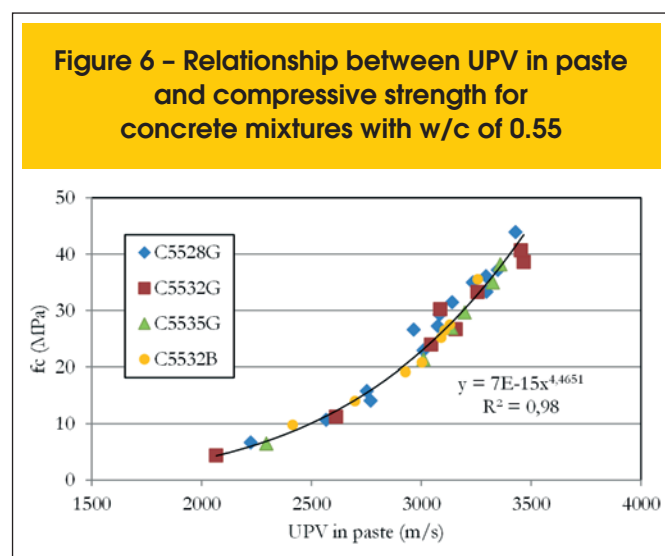
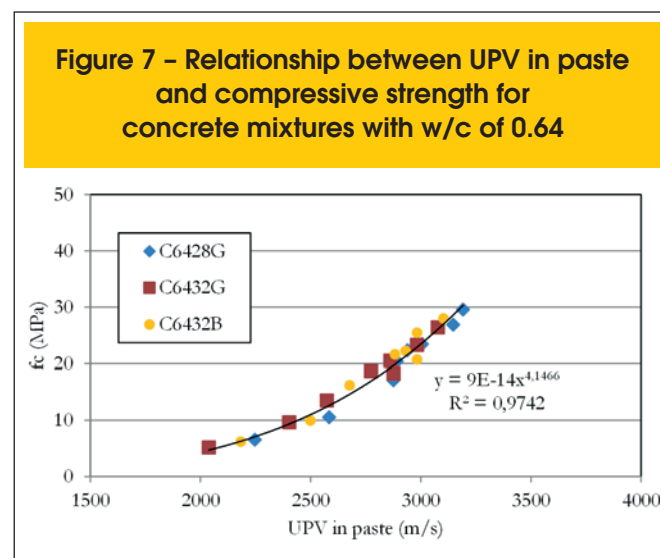
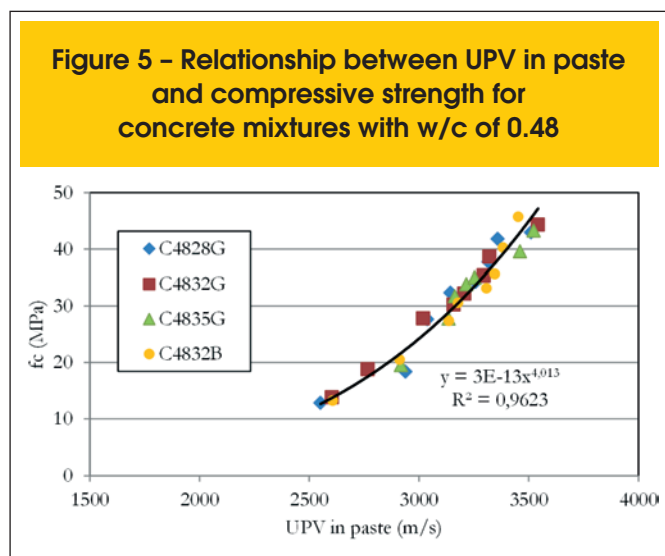


Figure 9 – Comparison between predicted and observed compressive strength

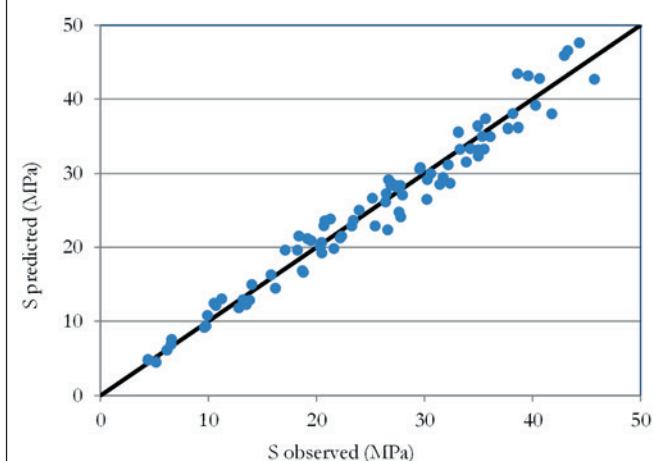


Figure 10 – Absolute errors for predictions of compressive strength

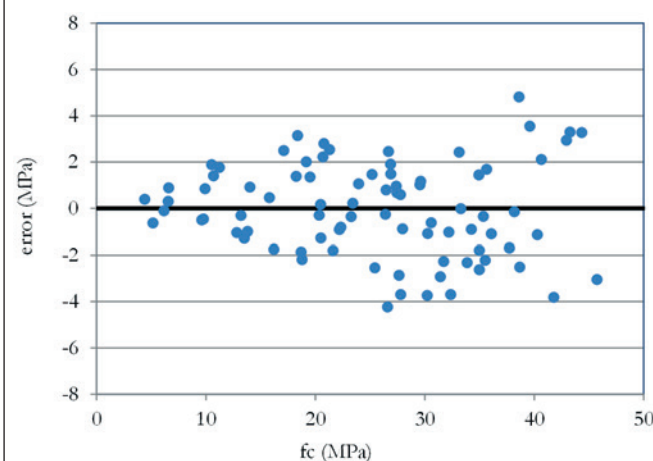
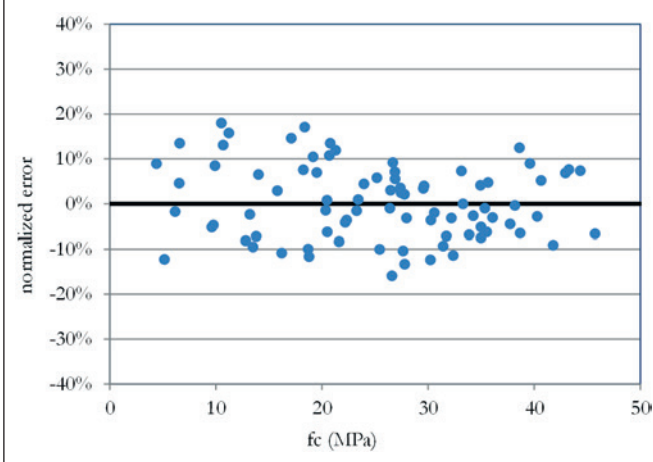


Figure 11 – Normalized errors for predictions of compressive strength



a family of concrete mixtures of the same type of cement. This conclusion is limited to the range of w/c studied here and to concrete mixtures with normal weight aggregates.

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