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Sonic Auscultation and Mechanical Characterization of Metallic & Synthetic Fiber-Reinforced Self-Compacting Concrete

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ABSTRACT

This experimental study focuses on the relationship between ultrasonic velocity measured by sensors of 50 mm diameter and 54 kHz frequency and elastic modulus and compressive strength of concrete. Samples (prismatic: 10x10x40cm and cylindrical: 16x32cm) are made with five different concrete mixtures (metallic and synthetic fiber-reinforced self-compacting concrete). The ultrasonic velocity measurements were determined with direct, semi-direct and indirect transmission mode. This methodology is based on European standard EN 12504-4. The results showed that sonic auscultation can be very useful to study the homogeneity of fiber-reinforced concrete and a beneficial supplement to characterize the quality of the concrete. Based on these experimental results, an analytical formula was set up to evaluate the compression strength of concrete by determining the velocity of sound in concrete. The resulting calibration curves for strength estimation were compared with others from previous published literature.

Keywords: *ultrasonic velocity, transmission mode, homogeneity, fiber-reinforced self-compacting concrete.*

1. INTRODUCTION

Study of wave propagation in concrete is complex because it involves various coupled phenomena: porosity, heterogeneities of different types (cement, sand, aggregates, and fibers) and ranging in size from nanometers to centimeters.

Methods using wave propagation and interaction of these waves with concrete are among the methods that have the greatest potential for non-destructive evaluation of concrete. Indeed, wave propagation properties are directly related to the material in which they propagate. These waves are sensitive to mechanical properties such as elastic modulus and Poisson's ratio, or the rate of porosity. The most common method used to date is sonic auscultation.

The measurement of wave velocity in concrete is classically used in both laboratory and on site (Malhotra and Carino, 1991) [1]. This method is also normalized by the French standards NF-EN-12504-4, 2005 [2] and American standards ASTM-C597-02, 2003 [3], and there are complete commercial devices to achieve such measures (type PUNDIT).

The principle of measurement consists in determining the time of propagation of sound waves through an element. This is done using a pair of transducers: transmitter and receiver (Fig. 1).

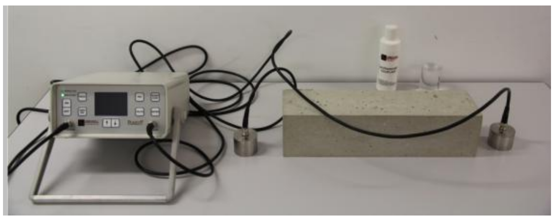

Fig. 1. Ultrasonic test equipment - PUNDIT

The system is provided with a sensor and a transmitter nominal frequency of 54 kHz, i.e. the standard in the industry. This nominal frequency limits the depth of auscultation as well as the minimum thickness of the concrete that can be probed.

After a distance of course L and a propagation time t in the material, the wave reaches a second transducer. We can thus determine the velocity of propagation of the sound wave in the material: V = L/t.

When a wave interacts with heterogeneity of the material, it undergoes diffraction. One part of its energy is deflected and redistributed in any space (Fig. 2). The wave that propagates in the same direction as the incident wave after diffraction by heterogeneity has a lower amplitude [4].

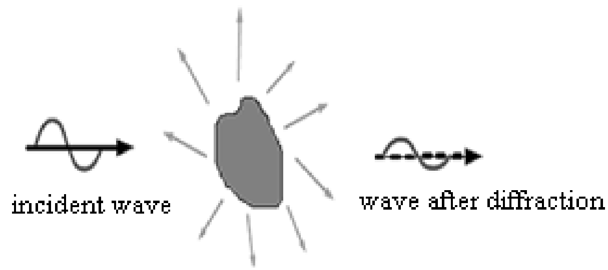

Fig. 2. Diffraction of a wave by a heterogeneity.

In the case of concrete, the heterogeneities can be the porosity of cement paste or inclusions such as sand and aggregates. These heterogeneities are very numerous, of different types and sizes. They affect the spread at different scales [4]. This is referred to as multiple diffraction (Fig. 3).

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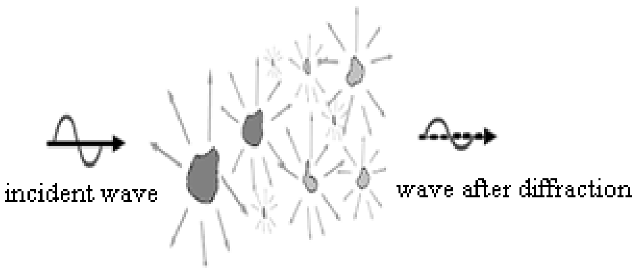

Fig. 3. Multiple diffraction of waves by heterogeneities.

2. ULTRASONIC VELOCITY MEASUREMENT

According to the European standard EN 12504-4, there are three methods (Fig.4)

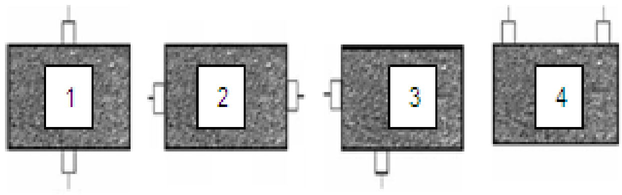

Fig. 4. Positions of the transducers: Transmission mode: 1) et 2) direct, 3) semi-direct, 4) indirect.

The transducers are brought into contact with the sides of the samples through the coupling layer, usually a gel.

The method gives users an efficient way to determine the strength of the concrete in situ or precast. A correlation between the speed of the sound wave and the strength of the concrete is necessary to make an assessment on the construction site. The estimation of strength on the construction site must be made only as a result of a correlation obtained as a result of laboratory tests on concrete specimens of the same type as those found on the site. RILEM standards [5], ASTM [6] and the British Standard Association [7] suggest procedures to establish these correlations.

3. MATERIALS AND EXPERIMENTATION

3.1. Materials

Different concretes were prepared using cement CEM I 52.5 R from Calcia-Beaucaire Cement Plant (Marseille, France). The cement "CEM I 52.5 R" is designed for building works and civil engineering works requiring high strength both in the short-term and the long-term. Limestone fillers were also used for the preparation of mixtures. The physicochemical characteristics of the materials are presented in Tables 1 and 2.

Table1: Physicochemical Composition of Cement (average values in %).

Description of Product		**CEM I 52.5 R CE CP2 NF**
Clinker $\geq$ 95%	C_3A	8.9
	C_3S	68.5
	C_2S	11
Mechanical strength mortar (MPA)	1 day	28
	2 days	39
	28 days	69
Initial setting		2h10
Blaine ($cm^2.g^{-1}$)		4810
SO_3		3.6
Na_2O Equivalent		0.41

Table 2: Physical characteristics of limestone Filler - CARMEUSE society

TESTS	Value	Standard
Blaine Surface	540 $m^2.Kg^{-1}$	NF EN 196-6
Absolute density	2.70 $g.ml^{-1}$	NF P 18-558
Blue value of fillers	0.66 $g.Kg^{-1}$	NF EN 933-9
Humidity	0.11%	NF EN 1097-5
Index of activity	0.76	NF EN 196-1

The gravel used is crushed limestone from the Marseille region. It is class 5/10 gravel and has a density of 2,600 Kg/m3, a humidity of 1% with a Los Angeles coefficient of 23.2%. The sands also come from the Marseille region, they have a specific gravity of 2.7, a fineness modulus of 2.63 and a sand equivalent ratio of 62.53. The superplasticizers used are TEMPO 16 and KRONO 20 produced by SIKA France. Technical data is provided in Table 3. TEMPO 16, according to its technical data sheet, gives the concrete a high rheology.

Table 3: Physicochemical Characteristics of the Superplasticizers used

Superplasticizer	**TEMPO 16**
Notation	T 16
Density	1.055 ± 0.015
pH	3 ± 1
Dry extract (%)	24 ± 1.2%
Cl^- content	$\leq$ 0.1 %
Na_2Oeq content	$\leq$ 1 %

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Four different fibers were used. The characteristics of these fibers are presented in Table 4 and figure 5.

Table 4: Geometrical characteristics of the fibers used in our study

Fibers	ESF 25	RC 80/50	Macro-synthetic	Micro-synthetic
Length (mm)	25	50	54	12 to 20
Diameter (mm)	2.5	0.62	-	34 µm
Slenderness λ= L/d	10	80	-	353-588
Density	7.2	7.9	0.92	0.91
Tensile strength (MPa)	1100	1270	580	Anti-cracking

Fig. 5. Geometrical characteristics of the fibers used in our study: 1) Metallic Fibers RC80/50. 2) Metallic Fibers ESF 25. 3) Macro-synthetic Fibers. 4) Micro-synthetic Fibers.

3.2. Concrete Mixtures

Self-compacting concrete is the tangible blend of special combinations of performance and of uniformity requirements that cannot always be obtained with the systematic use of the conventional constituents of ordinary concrete. The rheological property of SCC should be: "easier placement and compaction without affecting strength" [8]. It is also very interesting to consider the coupling of SCC and fibers. SCCs are fragile and require the contribution of reinforcements for durability. Fibers, on the other hand, need a very adherent matrix to function effectively. It thus seems natural that these two materials should be combined.

The objective of this paper is to characterize fiber-reinforced self-compacting concrete mechanically and by sonic auscultation.

The selected formulations of fiber-reinforced self-compacting concrete as a result of our preliminary tests are shown in Table 5. After several rheological tests [9], we then decided on five formulations. For further information, the reader may refer to [10].

Table 5: Composition of SCCs with metal and synthetic fibers

SCCs	Compositions							
	Fibers		Cement ($Kg.m^{-3}$)	Water ($l.m^{-3}$)	Sand (0/2) ($Kg.m^{-3}$)	Gravel (5/10) ($Kg.m^{-3}$)	Limestone fillers ($Kg.m^{-3}$)	W/B
	Type	($Kg.m^{-3}$)						
SCC ref.	-	-	350	170 .7	830	830	170	0.33
SCC FM1	ESF 25	100	350	170 .7	810	810	170	0.33
SCC FM2	RC 80/50	100	350	170 .7	780	780	170	0.33
SCC FS3	Micro- synthetic	5	350	170.7	815	830	170	0.33
SCC FS4	Macro- synthetic	5	350	170.7	830	830	170	0.33

The responses of the mechanical characterization tests (compressive and flexural strength, Elastic modulus and Poisson's ratio) conducted on prepared concrete are presented in the following table (Table 6).

Table 6: Mechanical characteristics of fiber-reinforced SCC

SCCs	Compressive strength (MPa)				Flexural strength At 7 days	Elastic modulus	Poisson's ratio	Density
	1 day	3 days	7 days	28 days	(MPa)	(GPa)	-	($Kg.m^{-3}$)
SCC ref.	34.6	42.8	42.63	52.20	5.69	39.05	0.421	2440
SCC FM 1	29.3	46.2	47.3	73.53	7.02	58.80	0.281	2434
SCC FM 2	41.3	48.4	56.4	70.92	6.47	55.89	0.231	2512
SCC FS 3	32.8	36.7	42.8	52.92	6.28	48.30	0.321	2373
SCC FS 4	30.4	40.2	41.5	64.35	14.46	51.28	0.361	2403

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The compression behavior is only slightly influenced by the presence of synthetic fibers. The cracks created do not allow the fibers to be involved sufficiently to improve the behavior of the concrete significantly. However, steel fibers develop an extra anchor in addition to the adhesion with the matrix, which explains the increase of 26% in the compressive strength of SCC FM2 and of 30% in the case of SCC FM1 compared with that of the reference SCC. However, the behavior of fiber-reinforced concrete, regardless of the type of solicitation, depends heavily on their distribution and orientation [11].

The effectiveness of the fiber relies on a mastery of its orientation. The precise knowledge of fiber orientation would be a factor that would ensure the proper dimension of structures, thus allowing the optimization of the quantity of fiber to be included in the formulation. On this point, the dimensioning of fiber-reinforced concrete is based on the assumption of a random distribution of fibers and homogeneous in mass (Dupont and Vandewalle, 2005) [12]. Figure 6 includes the distribution of fibers in concrete in the hardened state.

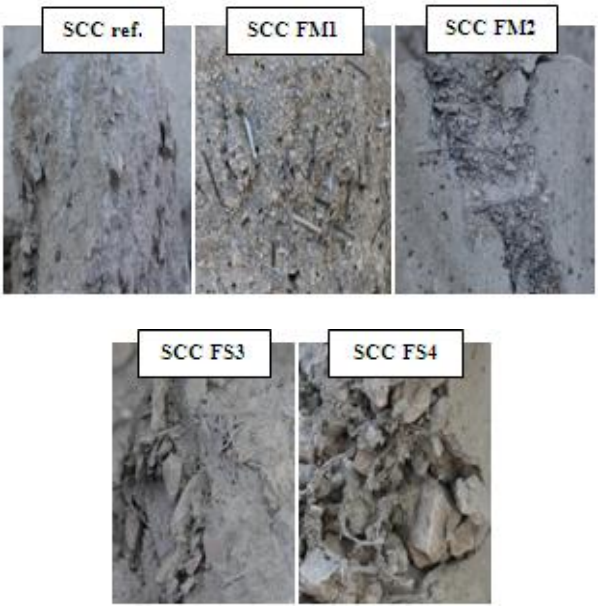

Fig. 6. Fiber distribution in the specimen after the compression test.

It is possible to make qualitative comparisons of this type of concrete (the study of homogeneity and of the quality of concrete) by sonic auscultation. In general it is a case of measuring local physical quantities (speed of sound), and then of deducing the mechanical properties that are directly related (compressive strength and elastic modulus).

3.3. Ultrasonic Velocity Measurement

The distance (path length) between the sensors must be measured as accurately as possible. It is very important to ensure a proper coupling of the transducers to the surface under test. A thin layer of coupling medium should be applied to the transducer and to the test surface. In some cases, it may be necessary to prepare the surface by smoothing it.

The transducers used for non-destructive testing can have variable dimensions adapted for different applications. In this study, we used sensors of diameter D = 50 mm.

After a travel distance L and a propagation time t in the material, it is thus possible to determine the speed of propagation of the sound wave in the material: $V = L / t$.

The measured velocities characterize the quality of concrete from the point of view of its physical characteristics (homogeneity, density). Many experimental data and correlation between the strength and the sound speed have been proposed. Table 7 suggested by Whitehurst, 1951 [13], shows the use of the speed obtained to classify the quality of concrete.

Table 7: Quality of concrete based on sound velocity

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Sound speed (m/s)	Concrete quality
> 4500	Excellent
3500 - 4500	Good
3000 - 3500	Poor
2000 - 3000	Bad
<2000	Very bad

4. RESULTS AND DISCUSSION

These methods are applicable to non-destructive controls of materials [14-19]. Thanks to these methods the mechanical properties of the auscultated medium can be determined, the homogeneity can be assessed (by detecting voids and micro-cracks) and concrete that has an incorrect W/C ratio, or that has undergone a structural change can be characterized. It is possible to make qualitative comparisons of concrete (the study of homogeneity and quality) in situ or in laboratory. All results obtained are grouped in Table 8.

According to experiments conducted at the CEBTP research center, regarding uncertainty, if the measurement conditions are highly satisfactory (satisfactory surface state, no noise), the uncertainty typically varies from 50 to 100 m/s, but in poor conditions, it is greater than 300 m/s. If an element has a low average velocity and a high standard deviation (example: velocity of 2,500 m/s and standard deviation of 400 m/s) it means that it is in poor condition, probably cracked, or has had a poor implementation. To calculate the uncertainty on an average of velocity sound measurements in a specimen, we choose a confidence level of 95% for the Student coefficient $t_{N,x}$. The values of the standard deviation and the uncertainty of each mixture are given in Table 8.

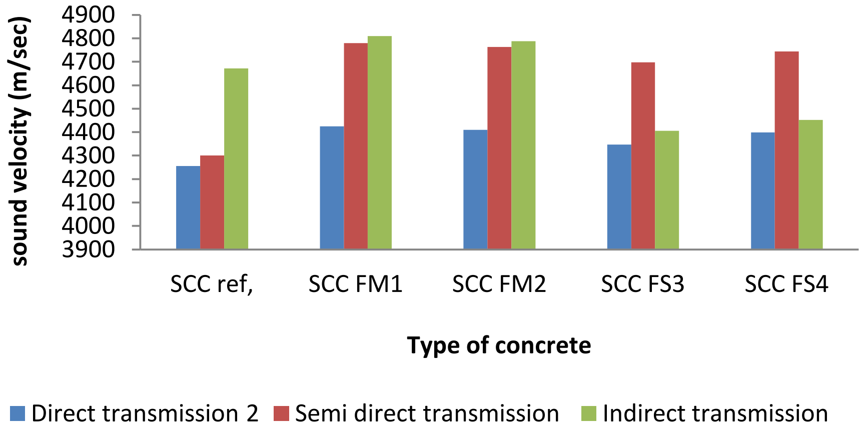

Fig. 7. Sonic auscultation of concrete according to the 3 types of transmission.

Table 8: Sonic auscultation of different concretes used (in m/sec).

Concretes		SCC ref.	SCC FM1	SCC FM2	SCC FS3	SCC FS4
Direct transmission 1	Sonic velocity	4354	4675	4613	4532	4584
	Standard deviation	138	48	124	28	25
	Uncertainty	343	120	308	70	62

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Direct transmission 2	Sonic velocity	4255	4425	4410	4347	4399
	Standard deviation	28	30	25	36	40
	Uncertainty	69	74	62	89	99
Direct transmission 3	Sonic velocity	4301	4442	4422	4337	4347
	Standard deviation	68	130	44	102	82
	Uncertainty	169	323	109	253	204
Semi-direct transmission	Sonic velocity	4300	4780	4763	4697	4744
	Standard deviation	122	88	141	38	66
	Uncertainty	303	218	350	94	164
Indirect transmission	Sonic velocity	4672	4810	4788	4405	4452
	Standard deviation	98	64	102	38	72
	Uncertainty	243	159	253	94	179

We noticed that the sound speed measured in the case of SCC FM1, regardless of the mode of transmission, is higher than that of other concretes. It is obvious to relate this speed increase to use of steel fibres. Mechanically, the fibers, ensuring the transfer of stress through the crack, limit its opening and its spread. The location of the macro-cracking is thus delayed, and therefore limits the fragility of the material. The confirmation of these concepts is provided by increasing the speed of sound in the material. Concerning the hardness or the strength on the surface of material, we can see that reference SCC, SCC FM1 and SCC FM2 are of excellent quality. Sound speeds, indirect transmission mode, exceed the value of 4,500 m/sec (Figure 7). Generally, all concrete manufactured during our research work is of good quality. The minimum value of the speed is 4,255 m/sec.

Sonic auscultation provides users with an effective way to characterize the intrinsic behavior of the material by measurement of Young's modulus and to determine the strength of the concrete in situ or prefabricated. A correlation between the propagation velocity and the strength of the concrete is necessary to make an assessment on the site. The estimation of strength on the site must be made only as a result of a correlation obtained by means of laboratory tests on concrete samples of the same type as those found on the site. Figure 8 presents the evolution of compressive strength and of elastic modulus based on sound velocity measured in direct, semi-direct and indirect transmission mode.

The graph (Fig. 8) shows that the propagation velocity of sound in the specimens can be used in the correlation: strength (Rc)-sound velocity (V) and Elastic modulus (E)-sound velocity (V). Correlations V-E seem similar to V-Rc. In the case of direct or semi-direct transmission, we can see that the sound velocity increases with the increase of compressive strength and of the elastic modulus of the samples. On the other hand in indirect transmission mode, this property is not respected because this transmission mode gives an idea of the surface hardness of each material while the elastic modulus and the compressive strength indicate the rigidity of a specimen. Therefore, to characterize the deformability or the internal behavior of the specimen, we can use sonic auscultation with a direct or semi-direct transmission mode without using a destructive test.

Overall, the higher the velocity and the lower the uncertainty, the better the quality of the material, i.e. hmogeneous and therefore presents with a significant improvement of its strength.

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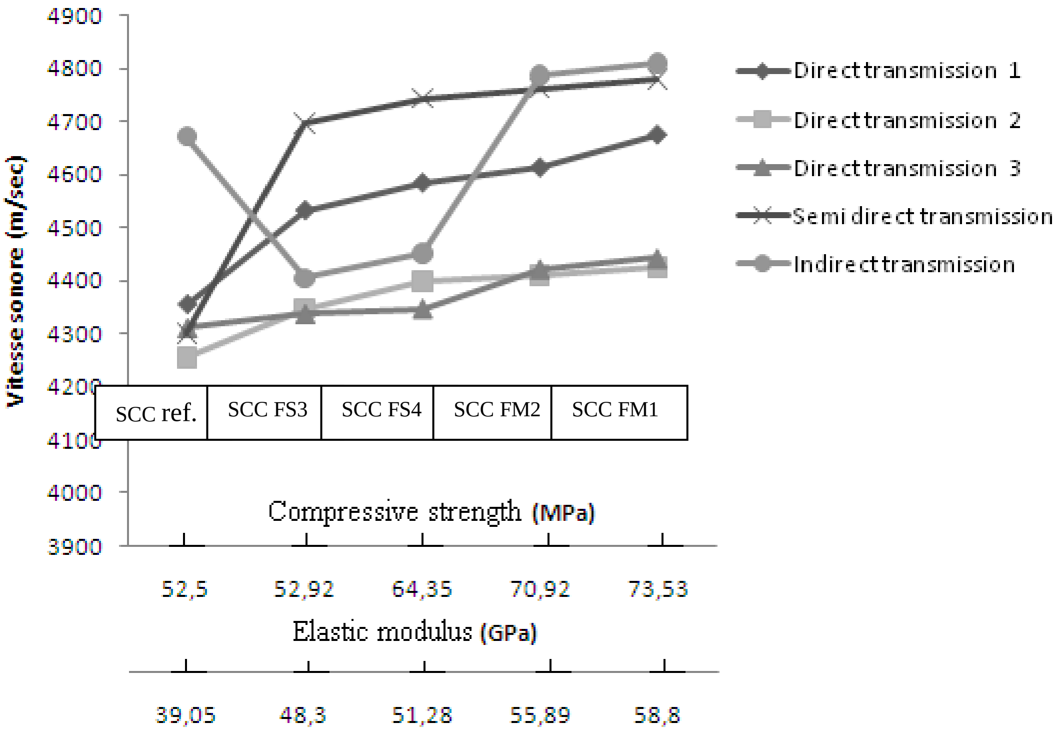

Fig. 8. Compressive strength and elastic modulus of concrete based on sound velocity.

5. ULTRASONIC VELOCITY REGRESSION MODEL

Many attempts to use ultrasonic velocity V [m/s] as a measure of the compressive strength of concrete RC [MPa] were made because of the obvious advantages of non-destructive testing methods. Manufacturers usually provide such relationships for their own test systems, which are not suitable for all types of concrete. Therefore, they must be calibrated for different mixtures. The classical approach to derive these mathematical relationships by using regression analysis did not have much success [20]. Many reports and correlation data between the velocity and strength of concrete have been proposed [21-24]. The most popular formula is: RC = a exp (b V), with (a, b) as coefficients.

Subsequently, we tried to relate the experimental values found in this study with analytical models proposed in the literature. After an extensive analysis of these models, we found that the model that is best adapted to our case is that of P.Turgu [21], but for larger strength values, exceeding 60 MPa, the model gives smaller values. To correct this difference, we proposed individual analytical relationships (Table 9).

Table 9: Statistical analysis of regression models for individual relationships sonic Velocity - Compressive Strength (V-RC).

Concrete	Sonic velocity (m/sec)	measured RC (MPa)	RC –P. Turgut (MPa) ***RC=1.146 exp(0.77 V)***	RC – individual analytical relationship (MPa)
Ref. SCC	4,672	52.20	41.83	RC= 1.146 exp(0.8174 V)
SCC FM1	4,810	73.53	46.52	RC= 1.146 exp(0.8907 V)
SCC FM2	4,788	70.92	45.74	RC= 1.146 exp(0.88297 V)

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SCC FS3	4,697	52.92	42.69	RC= 1.146 exp(0.8203 V)
SCC FS4	4,744	64.35	44.22	RC= 1.146 exp(0.86217 V)

On the basis of experimental results presented in Table 9, an analytical model was established to evaluate the compressive strength of concrete by determining the sound velocity in the concrete. In our case, we are not able to generalize this model because the study was conducted on concrete with different fibers (metal and synthetic), which is why the individual analytical formula varies according to the type of fiber used.

Figure 9 shows that the estimated concrete strength by the resulting calibration curve is higher than the others. It is the furthest from the calibration curve proposed by the manufacturer. However, this does not mean that it is less confident than others but that the differences between them are due to the influence of different factors such as the type of aggregate used and/or proportions, original water/cement ratio, curing conditions, level of compaction and moisture content where each curve is used to predict the strength for a specific concrete mix.

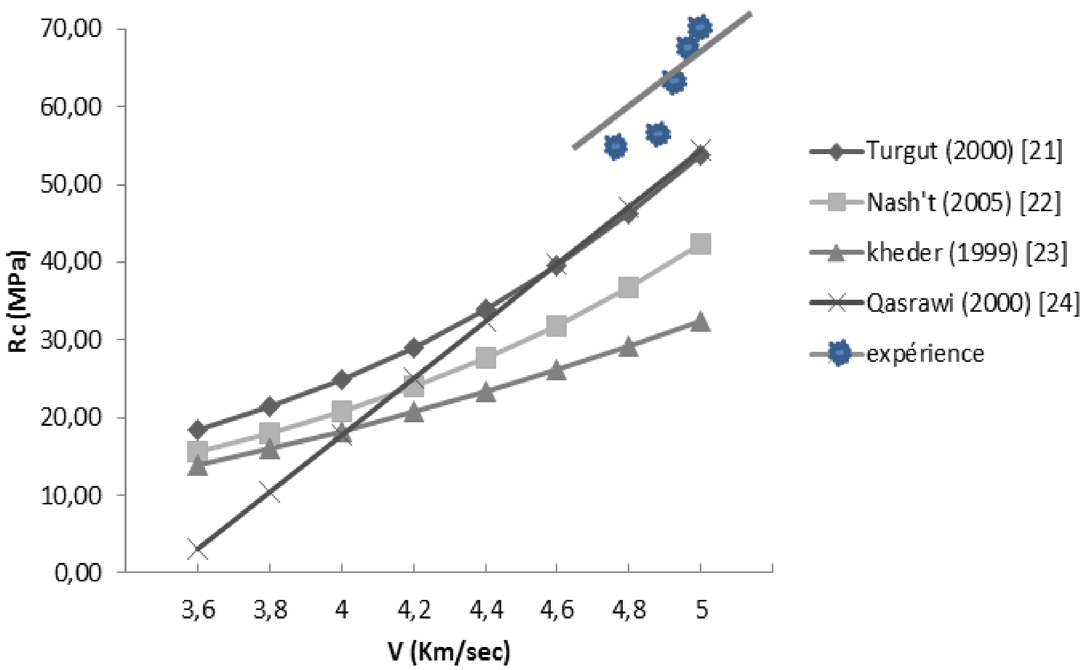

Fig. 9: Comparison of the resulting calibration curve from the Ultrasonic velocity test with others from previous research

Various regression models proposed by different investigators and others proposed by the author were tried for the data obtained from the current experimental work. The results show that the regression model defined by Eq. [RC=1.146 exp(0.77 V)] (proposed by P. Turgut [21]) is the best representation for the data obtained from the experiment.

6. CONCLUSION

The use of ultrasound is a very suitable tool for non-destructive evaluation of concrete.

The wave propagation depends directly on the mechanical and structural properties of concrete. This method consists in measuring the velocity of propagation of an ultrasonic wave in the concrete. We can link this velocity to Young's modulus, but the numerical results of the measure are not totally reliable.

The highly heterogeneous and random character of concrete also raises the problem of the repetitiveness of measurements in different parts of the concrete. A particular configuration of disposition / nature / shape of heterogeneities encountered during the propagation will provide parameters of specific propagation that are not representative of the material.

The use of the velocity of sound propagation as a measure of the compressive strength of concrete was made on the basis of conventional techniques of calculation such as multiple regression analysis but unfortunately these studies do not

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consider or did not assess the effect of parameters of concrete mixtures on relationships: sound velocity - compressive strength.

This document is a qualitative way to assess the homogeneity of fiber-reinforced concrete and to compare the velocity of sonic auscultation of a material with the presence of metal or synthetic fibers. Depending on the type of concrete tested, an analytical model allows us to obtain the compressive strength of the concrete easily by using only the value of the velocity of sound. The higher the velocity of sound propagation, the greater the rigidity and the less the specimen is deformable.

For comparison, (direct transmission mode 1) a self-compacting concrete with a density of 2,440 kg/m3 and a Poisson's ratio of 0.421 has a sound velocity of about 4,300 m/s. It is however essential to notice that the velocity of propagation in concrete varies depending on the mixture. The presence of metal fibers in concrete increases the wave velocity to a value of 4,600 m/s, while with the presence of synthetic fibers, the value of the velocity is around 4,500 m/s.

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