Correlation between the Compressive Strength of Concrete and Ultrasonic Pulse Velocity; Investigation and Interpretation

الارتباط بين مقاومة الانضغاط للخرسانة وسرعة الذبذبات فوق الصوتية،تحري وتفسير

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Abstract:

The literatures on ultrasonic pulse velocity (UPV) as a nondestructive test for evaluating the properties of concrete have been reviewed. Many researchers attempted to correlate compressive strength of concrete to (UPV) and they suggested many equations for this purpose. In this study the reliability of these equations has been investigated. It seems that none of these equations is reliable enough to be recommended to be used in practices. This conclusion may be interpreted on the basis that some properties of composite material, such as compressive strength, are a function of the weakest component, while the UPV through the composite is a function of UPV in all components. Griffith theory is also used to interpret this phenomenon.

الخلاصة:

في هذا البحث تم استعراض النشريات السابقة التي تخص استخدام فحص الذبذبات فوق الصوتية في تحديد مقاومة الانضغاط للخرسانة . وتم اختبار عدد من المعادلات الموضوعة سابقا إحصائيا لتحديد مدى معوليه هذه المعادلات في استخراج مقاومة الانضغاط . لقد تم التوصل إلى أن أي من المعادلات التي تم اختبارها لاتمتلك معوليه عالية . وقد تم تفسير ذلك على ضوء ان بعض خواص المواد التركيبية مثل مقاومة الانضغاط هي دالة للمادة الاضعف بينما سرعة الذبذبات الصوتية هي دالة لسرعتها في كافة مكونات الماده التركيبية كما تم الاستفادة من نظرية (اغرفث) في تفسير هذه الظاهرة .

1-Introduction:

The ultrasonic pulse velocity method is one of the oldest nondestructive tests (NDT) methods for concrete. It is based on measuring the travel time over a known path of ultrasonic compressional waves. This test is described in ASTM C597 and BS 1881-203. The ultrasonic pulse velocity (UPV) is a function of the density and dynamic elastic constants of the concrete [1]. The wave velocity depends upon the mass of the medium, and hence if the mass and velocity of wave propagation are known it is possible to assess the elastic properties. For an infinite, homogeneous, isotropic elastic medium, the compression wave velocity is given by [2]:

$$V = \sqrt{\frac{K \cdot E_d}{\rho}} \qquad \text{..........(1)}$$

Where V = compression wave velocity (km/s)

$$K = \frac{(1-\nu)}{(1+\nu)(1-2\nu)} \qquad \text{..........(2)}$$

E_d =dynamic modulus of elasticity (kN/mm^2)

ρ =density (kg/m^3)

And ν = dynamic Poisson's ratio.

The ultrasonic pulse velocity method has been widely used to evaluate the quality of concrete and assess the structural integrity of concrete structures. It can be used to determine cracks, honey-combs, voids, and homogeneity of concrete. But its use for predicting strength is still limited since there are many variables affecting the relationship between strength and pulse velocity of concrete [3]. The determination of the modulus of elasticity of concrete from the pulse velocity is normally recommended. It can be added that the value of Poisson's ratio over the full range of possible value (from 0.16 to 0.25) reduces the computed value of modulus by only a bout only 11 percent [4].

Popovics stated that UPV is truly nondestructive and has been successful for testing materials other than concrete [5].

The development of field instruments to measure the pulse velocity occurred nearly simultaneously in the late 1940s in Canada and England[6]. In Canada there was a desire for an instrument to measure the extent of cracking in dams. In England the emphasis was on the development of an instrument to assess the quality of concrete pavement. This method has been, also, suggested for measuring the fire-damaged surface layer having a lower wave speed than the underlying sound concrete [7].

It has been claimed that knowing the modulus of elasticity of the concrete, other mechanical properties can be estimated from empirical correlations. That is the basic idea of the ultrasound pulse velocity (UPV) test. The method is based on the determination of the time required for a pulse of vibration at an ultrasonic velocity and generated by a transducer on the concrete surface to travel through the concrete [8]. The velocity is calculated as:

$$V = \frac{L}{T} \qquad \text{..........(3)}$$

Where V = pulse velocity (km/s)

L = length (m) and T = effective time (10^{-6}s)

Many of experimental data and the correlation relationship between strength and pulse velocity of concrete have been presented and proposed. Some numbers suggested by Whitehurst for concrete for concrete with a density of approximately (2400 kg/m^3) are given in (Table1) for classification of quality of concrete on the basis of pulse velocity [4].

In Iraq, where buildings were affected by war processes, UPV is wildly used to evaluate the concrete structures. Certain equation has been used to determine the compressive strength from UPV results. This equation was applied for all cases regardless of the mix proportions and aggregate types.

Neville [4], however, reported that there is no unique relation between UPV and compressive strength of concretes. He, also, reported that is no physical relation between the strength of concrete and the value of the ultrasonic pulse velocity. ACI 318M-05[9], suggested that modulus of elasticity for normal concrete Ec can be taken as $4700\sqrt{fc'}$.

Neville [4], however, reported that it may be recalled that the modulus of elasticity is related to strength, but this relation, too, has no physical basis.

(Table 1)

Classification of the quality of concrete on the basis of pulse velocity

Longitudinal pulse velocity (km/s)	**Quality of concrete**
>4.5	excellent
3.5-4.5	good
3.0-3.5	doubtful
2.0-3.0	poor
<2.0	very poor

2-Literature review:

Rouf [10], suggested the following experimental relation between compressive strength and (UPV):

$$C = 2.8 e^{0.53v} \qquad \text{..........(4)}$$

Rouf,et al., [11], however, suggested another relation for assisting the compressive strength:-

$$C = 2.016 e^{0.61v} \qquad \text{..........(5)}$$

They recommended that the surface of concrete should be wetted before testing, and the average at least 30 tests should be taken for each portion of the structure. They, also, suggested that the compressive strength of this portion can be calculated as shown:

$$fc = f'c - K \cdot S \qquad \text{..........(6)}$$

Where fc = the predicted compressive strength.

fc' = average of at least 30 test.

S=standard deviation.

K= constant depend on the degree of confidence.

J .Keating,et al., [12], have examined four types of cement slurries used in cementing oil well casings to determine whether strength build-up during the first 24 hours after mixing can be predicted from measurements of ultrasonic pulse velocity and volume change. The pulse velocity method was found to be a useful predictive technique.

Ward, et al., [13], used the nondestructive testing consist of ultrasonic velocity and rebound hammer techniques to establish a correlation with compressive strength of core tests. They reported that ultrasonic pulse velocity is primarily used to establish concrete uniformity. They, also, found that the rebound hammer/core correlation formed the basis of recommendation on the acceptance or rejection of the in-situ concrete.

Sharad and Akash[14] , reported that there is no simple correlation between cube strength and pulse velocity test, but the correlation is affected by type of aggregates, age, aggregate cement ratio, size and grading, of aggregate and curing condition. They reported that UPV method of NDE can be accepted only when supporting standards are developed to facilitate its introduction into professional practice.

Ramazan, et al., [15], presented a relationship between (UPV) and compressive strength which was exponential for FA (high- volume fly ash), BFS (blast furnace slag) and FA+BFS. However, constants were different for each mineral admixture and each level of replacement of Portland cement (PC).

P.Turgut [16], used the data obtained from many cores taken from different reinforced concrete structures having different ages and unknown mix proportions of concrete to find a relationship between concrete strength and UPV. He concluded that the value of UPV increases as the concrete strength increases. He stated that UPV tests on high strength concrete are more reliable. He suggested the following equation to find the approximate value of compressive strength of concrete regardless the mix proportions of concrete through using only longitudinal velocity variable:-

$$S_{Lab} = 0.3161 e^{1.03 v_n} \qquad \text{..........(7)}$$

E. Proverbio, et al., [17], studied a laboratory testing program undertaken to evaluate the reliability of (UPV) and rebound hammer tests for evaluation of compressive strength of concrete. They concluded that a poor correlation between (UPV) and concrete strength was evidenced not with standing the well controlled laboratory conditions. Better results were obtained for rebound hammer test. It was evidenced that a preliminary knowledge of concrete characteristics is of great importance to optimize regression model.A coefficient of determination higher than 0.9 was obtained by using a combined method.

Zoubeir,et al.,[18], proposed a simple model to relate ultrasonic pulse velocity with porosity and permeability of concrete.

Panesar,et al., [19], evaluated the potential use of ultrasonic pulse velocity (UPV) for determining the early age compressive strength of dry-cast concrete containing varying percentages of ground granulated blast-furnace slag (GGBFS). They stated that there is a good agreement between the strengths determined using (UPV) with the aid of the formulae suggested in ACI-363 and the measured strength.

Md. Safiuddin, et al.,[20], concluded that the ultrasonic pulse velocity of the concrete increased with increasing age for all curing methods. But it had shown that the velocity increases about 1.2 Km/s (0.75 mi./s) during three years, an increase of 33 percent. The increase in the compressive strength during the same period is from 10 to 62 MPa (1450 to 8992 psi), an increase of more than 500 percent.

Popovics [5], attempted to contribute to the development of a pragmatic method for the improved nondestructive determination of concrete strength in structures. Two approaches are adopted. In both approaches the velocity of ultrasonic waves in concrete is used. He concluded that there is no acceptable method at present for the nondestructive determination of concrete strength. The novelty of this article is the recognition that concrete strength can not be calculated with acceptable accuracy from the longitudinal pulse velocity V_L alone-supplementary tests are needed. It also showed that the supplementary test (s) should measure material characteristics of the concrete. He presented the following equation:

$$f = 0.0096\, e^{0.0018 V_L} \qquad \text{……….(8)}$$

Fairs[21], suggested the following relation to assist the compressive strength of high performance concrete :

$$f_c = 0.0011 e^{(2.315v)} \qquad \text{……….(9)}$$

Where S_{Lab} , f , C , f_c represent the compressive strength in MPa.

V : velocity km/s

3-The present work:

In this study the reliability of some relations suggested by Rouf [10&11], P.Turgut [16], Popovics[4] ,and Fairs [21] has been investigated.

Data have been collected from previous researches for this purpose. They were:

1. Work done by A.M. Abdullatif [22] which represents concrete with constant w/c ratio, the same aggregate, variable gypsum content in sand, and different cement types.
2. Work done by Al jalwe N.M.F [23] which represents concrete with constant cement content, different w/c ratio and light weight aggregate.
3. Work done by Moter S.K [24] which represents fiber reinforced concrete with different (SO3) content in sand and same type of cement.

4. Data available in the laboratory of Kerbala University.

These data are shown in Fig. (1). It is clear that this data cover a wide rang of concrete.

These data are summarized in (Table 2)

Table (2)

Summary of the selected data

Number of cases	Compressive strength (MPa)				Velocity (km/s)			
	Min.	Max.	The Mean	The standard deviation	Min.	Max.	The Mean	The standard deviation
131	0.63	52.20	23.0945	13.6874	1.63	6.00	4.2103	1.0749

4- Result and discussion:

It is obvious from Fig. (1) that for any value of (UPV) there is a wide range of compressive strength . For example for value of UPV equals to 4.5 the values of compressive strength are ranging from (10MPa) to (50 MPa). This may be considered as a primary indicator for the correlation between (UPV) and compressive strength of concrete. The theoretical compressive strength for these five relations was obtained against the experimental compressive strength**.** Equation 8 and equation 9 give strange and unreasonable results some of these results are shown in Table (3), so they were neglected**.** .The results of the rest four relations were plotted in Figs. (1) to (4). It is obvious that there is high scatter of results from the line y=x for all these relations. Selected results were shown in Table (4). It is very clear that the residuals of all these cases are very high. This indicates the low reliability of these relations.

(Table 3)
Experimental and theoretical of compressive strength based on Popovics and Fairs

Case No.	Experimental results		Theoretical results	
	Compressive strength (fc') MPa	Velocity $(\boldsymbol{V})$ km/sec	(fc') according to Equation [8]	(fc') according to equation [9]
1	25.2	5.15	0.0097	165.6
2	38.7	5.16	0.0097	169.5
3	23.9	5.69	0.00969	578.2
4	27.6	4.94	0.00968	101.9
5	33.8	5.08	0.00969	140.9
6	3.40	2.63	0.00965	0.48
7	30.8	5.84	0.0097	818.2
8	2.50	2.35	0.00964	0.25

(Table 4)
Experimental and theoretical of compressive strength for selected cases

Case No.	Reference	Experimental results		Theoretical results		
		Compressive strength (fc') MPa	Velocity (V) km/sec	(fc') according to Rouf [10]equation	(fc') according to Rouf [11]equation	(fc') according to P.Turgut [16]equation
1	A.M. Abdullatif [22]	33.6	3.8	20.9	20.5	15.8
2		10	4.02	32.5	23.4	19.9
3		12.5	4.2	25.9	26.1	23.9
4		15.4	4.21	26.1	26.3	24.2
5		11	4.27	26.9	27.3	25.7
6		13	4.44	29.5	30.3	30.6
7		15	4.52	30.7	31.8	33.2
8		21.7	4.82	36	38.1	45.3
9		25.2	5.15	42.9	46.6	63.6
10		38.7	5.16	43.1	46.9	64.3
11	Al Jalwe N.M.F [23]	1.34	2.0	8.1	6.8	2.5
12		1.8	2.23	10.9	7.9	3.1
13		1.5	2.16	8.8	7.5	3.0
14		1.96	2.32	9.6	8.3	3.4
15		2.77	2.50	10.5	9.3	4.2
16		2.90	2.52	10.6	9.4	4.2
17		3.40	2.63	11.3	10.0	4.7
18		2.70	2.43	10.2	8.9	3.9
19	Moter S.K [24]	13.2	4.1	24.6	24.6	21.6
20		30.0	4.6	32.1	33.4	36.1
21		22.4	4.47	29.9	30.8	31.6
22		28.4	4.27	26.9	27.3	25.7
23		14.3	4.2	25.9	26.1	23.9
24		24.7	4.39	28.7	29.3	29.1
25		32.6	4.29	27.2	27.6	26.2
26	Data available in Kerbala University	33.33	5.88	63.2	72.8	134.9
27		26.5	5.74	58.7	66.9	116.8
28		31.51	5.69	57.1	64.9	110.9
29		28.1	5.84	61.9	71.1	129.5
30		23.97	5.85	62.2	71.5	130.8
31		23.93	5.69	57.1	64.9	110.9

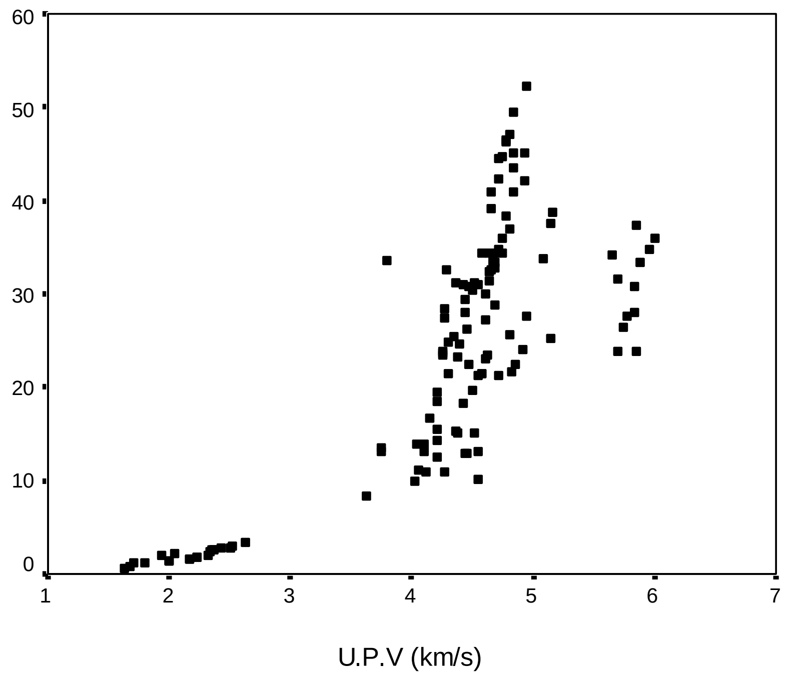

Fig. (1)
Compressive strength against the plus velocity

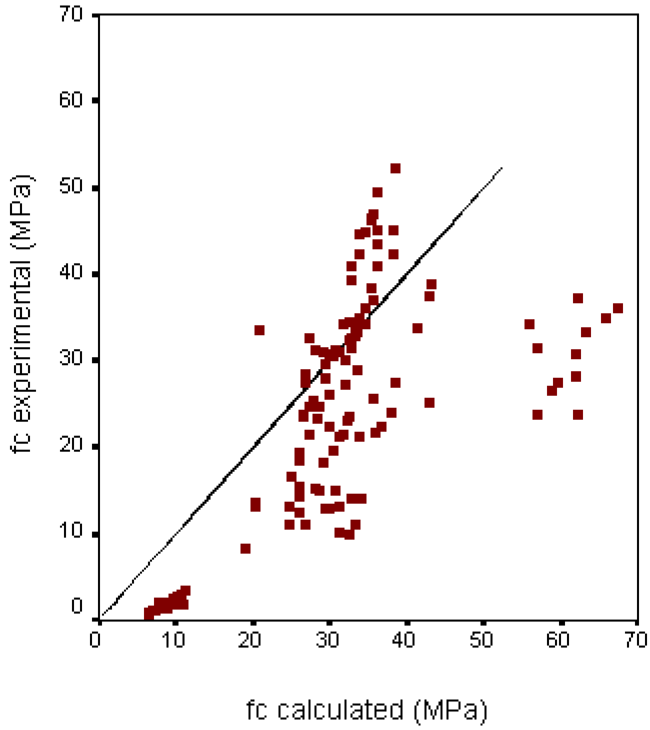

Fig. (2)

Experimental and theoretical compressive strength for Rouf[10] eq.

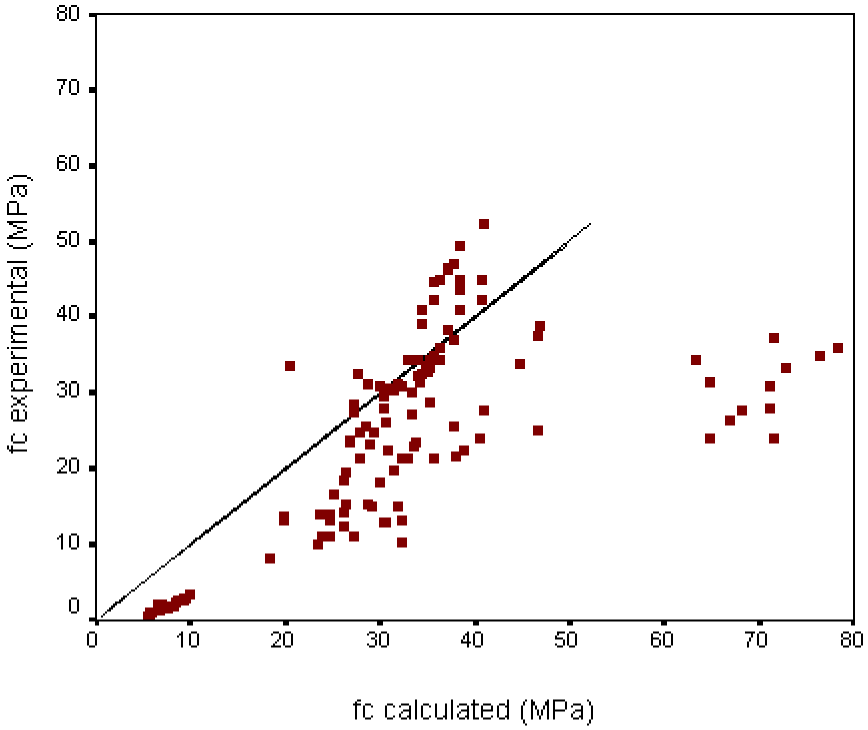

Fig. (3)

Experimental and theoretical compressive strength for Rouf[11] eq.

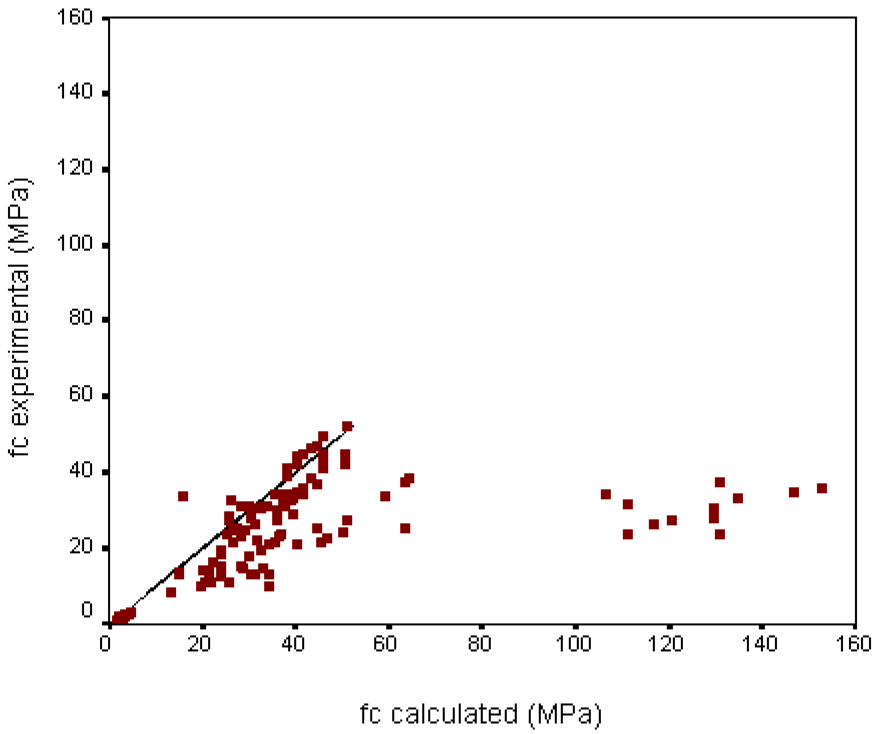

Fig. (4)

Experimental and theoretical compressive strength for P.Turgut [14] eq.

Statistical analysis of the results obtained was, also, applied by using chi square test (goodness-of-fit tests) to ensure the previous conclusion.

The chi-square test is the more interesting statistical tests in the engineering field so that it can be used in this analysis.

The equation of chi-square known as the following [25]:

$$\chi^2 = \Sigma_{j=1}^{r} \frac{(fo_j - fe_j)}{fe_j} \qquad \text{.......... (10)}$$

fo_j :observed values.

fe_j : expected values.

r: number of rows.

The application of results the chi-square equation on the collected data using level of significance ($\alpha = 0.05$ and $\alpha = 0.1$) is shown in (Table 5):

(Table 5)
Simulated of chi- square values

Reference	(χ^2) for Rouf [10] equation	(χ^2) for Rouf [11] equation	(χ^2) for P.Turgut [16] equation	(χ^2_α) tabulated use $\alpha = 0.05$	(χ^2_α) tabulated use $\alpha = 0.1$
[22]	267.81	252.42	316.696	100.7442	95.4729
[23]	132.36	102.61	10.07	14.067	12.017
[24]	16.319	17.229	15.156	23.685	21.064
Data available in Kerbala University	185.18	269.6	875.3	19.675	17.275

It is shown from the above analysis, that for about 60% of the cases, the chi-square values (χ^2) are greater than the chi-square values (χ^2_α) obtained from table for level of significance ($\alpha = 0.05$ and $\alpha = 0.1$).

From this result we can conclude that all these proposed relations did not approximate the experimental results and have poor correlation between the (UPV) and compressive strength.

This result may be interrupted according to the following points:

1. The compressive strength of concrete depended mainly on the properties of its cement paste because it's the weakest point, but it is not the case for the modulus of elasticity since it is depended mainly only on aggregate according to the theory of composite materials.
   The ultrasonic pulse velocity in concrete media is the average of its velocities in concrete components (*i.e* depends mainly on aggregate) .Accordingly (UPV) can give a good indicator about the modulus of elasticity rather than compressive strength.

2. Furthermore, failure of concrete can be explained by the presence of flaws postulated by Griffith. Cement paste is known to contain numerous discontinuities-pores, fissures and voids. These affect the compressive in such a manner not similar to its effect on UPV. Although Griffith's hypothesis applies to failure under the action of a tensile force, but it can be extended to fracture under biaxial and triaxial stress and also under uniaxial compression [4].
3. The factors that affect the strength may affect the pulse velocity differently, especially since the strength of a typical structural concrete is controlled by the strength of the cement paste, whereas the pulse velocity is controlled by the properties of the aggregates.
4. The insensitivity of the longitudinal pulse velocity to small but important changes in the internal structure of concrete.
5. The fact that the attenuation of ultrasonic waves in concrete is high, higher than in most other solids.
6. The present methods for ultrasonic testing of concrete require direct contact between the concrete surface and the transducers. Since the contact is not always perfect, the air trapped in between may cause variable errors in the measurements.
7. The effect of wetting concrete before testing on the strength and the pulse velocity is different. This reduces its compressive strength but increases the pulse velocity [26].
8. Popovics [5] reported that no theoretical relationship between strength f and pulse velocity V exists even for homogeneous, linearly elastic materials .He, also, reported that the accuracy of ± 20 percent under laboratory conditions if reliable parameters are available. Since this is usually not the case, the potential error in the strength determination is significantly greater.
9. There is an objection relating the use of combined method (UPV and rebound number).The aggregate in the concrete, has the decisive influence on both the pulse velocity and the rebound number. Thus, the combination of these two tests cannot provide additional meaningful information, especially since the concrete strength is controlled by the hardened cement paste, not by the aggregate.

5- Conclusions:

It is difficult to apply any proposed equation for assessing compressive strength from (UPV) for all cases.

6- Recommendation:

Because it seems that when the type and quantity of aggregate in concrete is kept constant the correlation between (UPV) and compressive strength is sufficiently good, it is recommended to establish equations for these cases.

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