Ultrasonic Pulse Velocity – Strength Relationship for Concrete Subjected to Sulfate Attack

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Abstract

The purpose of this paper is to investigate the relationship between the Ultrasonic Pulse Velocity (UPV) and the compressive strength and the flexural strength of hardened concrete when subjected to different concentrations of sulfate attacks. The specimens used in the studies were made of concrete with different water-cement ratios (w/c). The UPV measurement and compressive and flexural strengths tests were carried out for concrete specimens of ages (4-40) days.

The experimental results show that the relationship between UPV and the compressive and the flexural strengths of concrete is significantly influenced by age and the concentration of sulfate attack. The UPV and the compressive strength of concrete grow with age, but the growth rate varies with w/c ratio. It is found that with the same concentration of sulfate attack, a clear relationship curve can be drawn to describe the UPV and compressive and flexural strengths of hardened concrete. This paper presents the UPV-strength relationship curves for concrete having different (w/c) ratios subjected to different concentrations of sulfate attack. These curves are thought to be suitable for prediction of hardened concrete strength with a measured UPV value when sulfate attack is considered.

It is concluded that the UPV increases with the increase of the compressive and flexural strength. The observed range for UPV was (3.5 to 4.75 km/sec) corresponds to (24 to 28.5 N/mm2) for compressive strength and to (4.6 to 6.5 N/mm2) for flexural strength.

The UPV decreases with the increase of the concentration of sulfate exposure. The obtained maximum reduction in UPV was 31.6% with respect to the control spacemen at age of 40 days.

Key Words: Compressive Strength, Flexural Strength, Ultrasonic Pulse Velocity, Sulfate Attacks

العلاقة بين سرعة الموجات فوق الصوتية و مقاومة الخرسانة المعرضة الى هجوم الاملاح الكبريتية

فراس لطيف خليف

الخلاصة

ان الغرض من هذا البحث هو دراسة العلاقة بين سرعة الموجات فوق الصوتية مع مقاومة الانضغاط ومقاومة الانثناء للخرسانة المتصلبة والمعرضة الى تراكيز مختلفة من الاملاح الكبريتية. تم استخدام عينات كونكريتية ذو نسب محتوى مائي (w/c) مختلف وتم فحصها لا اتلافيا بجهاز موجات فوق الصوتية وباعمار من ٤ الى ٤٠ يوم.

تبين من خلال التجارب في هذا البحث مدى تاثير العمرو تركيز الاملاح الكبريتية على مقاومة الانضغاط ومقاومة الانثناء. وتبين ايضا بزيادة العمر تزداد الموجات فوق صوتية والمقاومة وبنسب مختلفة حسب المحتوى المائي (w/c).

يتبين من خلال المنحنيات المرسومة علاقة تركيز الاملاح الكبريتية مع سرعة الموجات فوق صوتية ومقاومة الانضغاط ومقاومة الانثناء للخرسانة المتصلبة ولمختلف نسب المحتوى المائي (w/c).

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ان هذا البحث يقدم علاقة سرعة الموجات فوق الصوتية ومقاومة الخرسانة بنسب محتوى مائي مختلفة ولتراكيز مختلفة من الاملاح الكبريتية حيث يمكن اعتماد هذه المنحنيات المرسومة كدليل لقراءة المقاومة من خلال سرعة الموجات عند حالة الهجوم بلاملاح الكبريتية.

وتم استنتاج بان سرعة الموجات الفوق صوتية تزداد بزيادة مقاومة الانضغاط والانثناء. حيث كانت لانتاج المستخلصة لسرعة الموجات الفوق صوتي بـ(٣,٥-٤,٧٥)كم\دقيقة مقابل (٢٤-٢٨,٥) نت\ملم٢ لمقاومة الانضغاط و (٤,٦-٦,٥) نت\ملم٢ لمقاومة الانثناء.

ويلاحظ ايظا بان سرعة الموجات الفوق صوتية تقل بزيادة تركيز الاملاح الكبريتية المهاجمة. حيث ان اعلى تركيز تقليل لسرعة الموجات الفوق صوتية بـ(٣١,٦%) للعينات المفحوصة بعمر ٤٠ يوم.

1. Introduction

Nondestructive test (NDT) methods are used to determine hardened concrete properties and to evaluate the condition of concrete in deep foundations, bridges, buildings, pavements, dams and other concrete construction. Nondestructive testing is defined as testing that causes no structurally significant damage to concrete.

Nondestructive test methods are applied to concrete construction for four primary reasons(1):

- Quality control of new construction;
- troubleshooting of problems with new construction;
- Condition evaluation of older concrete for rehabilitation purposes; and
- Quality assurance of concrete repairs.

Nondestructive testing technologies are evolving and research continues to enhance existing methods and develop new methods.

2. Ultrasonic Through Transmission Method

One of the oldest NDT methods for concrete is based on measuring the travel time over a known path length of a pulse of ultrasonic compression waves. The technique is known as ultrasonic through transmission, or, more commonly, the ultrasonic pulse velocity (UPV) method(1).

The principle is that the speed of propagation of stress waves depends on the density and the elastic constants of the solid.

In a concrete member, variations in density can arise from non-uniform consolidation, and variations in elastic properties can occur due to variations in materials, mix proportions, or curing. Thus, by determining the wave speed at different locations in a structure, it is possible to make inferences about the uniformity of the concrete. The compression wave speed is determined by measuring the travel time of the stress pulse over a known distance(1).

3. Instrumentation

The main components of the device for measuring the ultrasonic pulse velocity are shown in Plate (1) which is used in this work. A transmitting transducer is positioned on one face of the member and a receiving transducer is positioned on the opposite face. The transducers contain piezoelectric ceramic elements. Piezoelectric materials change dimension when a voltage is applied to them, or they produce a voltage change when they are deformed. A pulser is used to apply a high voltage to the transmitting transducer (source), and the suddenly applied voltage causes the transducer to vibrate at its natural frequency. The vibration of the transmitter produces the stress pulse that propagates into the member. At the same time that the voltage pulse is generated, a very accurate electronic timer is turned on. When the pulse arrives at the receiver, the vibration is changed to a voltage signal that turns off the timer, and a display of the travel time is presented. The transducers are coupled to the test surfaces using a viscous material, such as grease, or a non-staining ultrasonic gel couplant if staining of the concrete is a problem.

4. Previous Works

Some work in previous literature made use of the Ultrasonic Pulse Velocity (UPV) of concrete to predict compressive strength [(1-6)] At early age of concrete, the pulse velocity increases rapidly relative to strength[(7,8)].

Pulse velocity is influenced by many variables, however, including mixture proportions, aggregate type, age of concrete, moisture content, and others[(1)]. The factors significantly affecting the concrete strength might have little influence on UPV. As a result, a strength estimate made with the pulse velocity method is not reliable if a pre-established calibration curve is not available[(2)].

No clear rules have been presented to describe how the relationship between UPV and the compressive strength of concrete changes with its mixture proportion. Therefore, there exists a high uncertainty when one tries to make use of UPV to predict the strength of concrete in different mixture proportions[(9)].

This paper uses certain mixture proportion of concrete and varies in water/cement ratio (w/c). The UPV measurement and compressive strength tests were carried out at the age from 4 to 40 days. The influence of three factors: age, w/c, and sulfate concentration-on UPV and the compressive strength of concrete is studied and used to determine how these factors affect the relationship between UPV and the compressive strength of concrete[(10)].

5. Research Significance

Currently, the influence of the concentration of sulfate attack on the relationship between UPV and the compressive strength of concrete is unclear. This study uses concrete subjected to different concentrations of sulfate attack and study the relationship between UPV and the compressive strength of concrete and to clarify its influence. Furthermore, this paper presents clear relationship curves between UPV and the compressive strength of concrete under such attack to improve the application of the UPV method on nondestructive evaluation of concrete strength.

6. Experimental Details

All the experimental work was carried out at the laboratory of construction materials in the Civil Engineering Department - College of Engineering - University of Al-Anbar.

7. Materials

Materials used for making specimens include cement, fine aggregate (FA), and coarse aggregate (CA). The cement used was Portland Type I. The chemical and physical properties of the cement are given in tables (1 & 2) respectively. River sand with a saturated-surface dry (SSD) with specific gravity of 2.62 and gravel with an (SSD) specific gravity of 2.60 were used as fine and coarse aggregates, respectively. Sand was brought from a quarry in 70-km area in Ar-rumadi City/Al-Anbar Governorate. 25mm size gravel was brought from the Jarayish area in Ar-rumadi City/Al-Anbar Governorate. The grading curves for fine and coarse aggregates are shown in figures (1 & 2), respectively.

The sulfate used is Calcium sulfate $CaSO_4$ with ratios of 0%, 3% and 6% (by weight) of the FA. Tap water was used in concrete mixtures and for curing of specimens.

Table (1) Chemical Composition of Cement

Compound Composition	Chemical Composition	Percentage by Weight	Limit of IOS: 1984
Lime	CaO	61.27	-
Silica	SiO_2	21.63	-
Alumina	Al_2O_3	5.05	-
Iron Oxide	Fe_2O_3	3.12	-
Magnesia	MgO	2.06	5% max.
Sulfate	SO_3	2.07	2.8% max.
Loss on Ignition	L.O.I	3.12	4% max.
Insoluble residue	I.R	1.32	1.5% max.
Lime Saturation Factor	L.S.F	0.88	0.66-1.02

Table (2) Physical Properties of Cement

Physical Properties	Test Results	Limit of IOS 5:1984
Specific surface area (m2/kg)	4810	> 2300
Setting time using vicat's instrument Initial (hrs. : min.) Final (hrs. : min.)	 3:20 4:40	 > 45 min < 10 hr.
Compressive strength for cement paste cube (70.7 mm) at: 3 days (MPa) 7 days (MPa)	 33.4 42.2	 > 15 > 23

8. Experimental Specimens

The concrete was mixed according to a volumetric proportion of (1:2:4) (C:F.A.:C.A.). Two w/c ratios of 0.45 and 0.65 were used in this study.

All the specimens were cast in steel molds of (150×150×150) mm for cubes and (150×150×600) mm for prisms, and kept in their molds for approximately 24 hours in the laboratory. After removing the molds, the specimens were tested at ages of 4 days to 40 days for all control and sulfate attacked specimens. At each age, the pulse velocity and compressive strength of three SSD specimens (air-dry) were measured according to the specification of ASTM C 597 and ASTM C 39, respectively.

9. Experimental Equipment

Ultrasonic Pulse Velocities were measured by a commercially available pulse meter with an associated transducer pair. The transducer pair had a nominal frequency of 54 kHz. The principle of Ultrasonic Pulse Velocity measurement involves sending a wave pulse into concrete and measuring the travel time for the pulse to propagate through the concrete. The pulse is generated by a transmitter and received by a receiver. In the experimental studies, the transmitter and receiver were placed at the top and bottom surfaces of a cube or a prism specimen, respectively. As a result, the traveling length of the ultrasonic pulse was the length of the specimen, which was measured by using a vernier with a minimum reading of 0.01 mm.

Knowing the path length, the measured travel time (Δt) can be used to calculate the pulse velocity (υ) as follows

$$\upsilon = D/\Delta t \tag{1}$$

where D is the travel path length of ultrasound in the specimen. The concrete surface must be prepared in advance for a proper acoustic coupling. Light pressure is needed to ensure firm contact of the transducers against the concrete surface.

10. Experiment Results

The experimental data presented in the figures discussed in this paper are from individual tests.

To address the relationship between UPV and the compressive strength of concrete, this section first analyzes the development of UPV and strength of concrete along with age.

Subsequently, the influence of sulfate exposure and w/c ratio on the UPV-strength relationship of concrete is investigated. In the end, the relationship curves between UPV and strength of hardened concrete are developed.

11. Results and Discussion

11.1. Pulse Velocity and Compressive Strength Development of Concrete

Six different mixes were used in this work. The w/c ratios were 0.45 and 0.65. The sulfates percentages were 0%, 3%, and 6% by weight of FA. The sulfates were added in the curing water thus represent the practical sulfate attack.

Destructive tests were performed to obtain compressive and flexural strengths. Nondestructive tests were also performed to obtain the corresponding UPV.

Table (٣) and figures (3 & 4) show the destructive test results namely compressive and flexural strengths. It can be seen that both strengths reduced with the increase in sulfate content. Maximum percentage of reduction was 11.4% in compressive strength and 20% in flexural strength both at 6% sulfate exposure.

For the nondestructive test, tables (٤ & ٥) and figures (5 & 6) show the corresponding UPV related results. Reduction in the Ultrasonic Pulse Velocity (UPV) is observed with the increase in sulfates content. Furthermore, the reduction is also observed with the age. At 20 days of age, the maximum percentage of reduction in UPV is shown 16.3% corresponds to 31.6% at 40 days of age.

Figures (7, 8, 9, & 10) indicate the relation of the UPV with the various parameters investigated in this work. It can be seen that the range of UPV was (3.5-4.75) km/sec corresponding to 150mm-cube compressive strength (24-28.4) N/mm2 and to (4.6-6.5) N/mm^2 flexural strength range.

It is found that the lower w/c ratio, the higher UPV, compressive strength, and flexural strength (see figures 7, 8, 9, & 10). . Both the UPV and strength of concrete grow along with the advancement of age. At the same age, both UPV and strength of concrete with low w/c are higher than those with high w/c mainly because of the denser structure of concrete with a lower w/c (11).

As age increases the UPV and strength increases for control specimens. However, as the sulfate content increases the UPV decreases in manner shown in figures (7 & 8) for compressive strength and in figures (9 & 10) for flexural strength.

It is clear that sulfate exposure is influential factor of the relationship between UPV and strength of hardened concrete. For a given sulfate exposure, figures (7, 8, 9, & 10) can be used to acquire the UPV and strength values of hardened concrete having w/c of 0.45 and 0.6 subjected to sulfate exposures of 0%, 3% and 6%.

As a result, it is feasible to simulate the UPV-strength relationship curve for concrete with a particular sulfate exposure from Figures (7, 8, 9, & 10).

Table (3): The results of Destructive Tests (at age 28 days)

w/c Ratio	Sulfate %	Compressive Strength (N/mm2)	Flexural Strength (N/mm2)
0.45	0	28.61	6.45
	3	27.13	5.25
	6	25.36	5.15
0.65	0	26.88	5.05
	3	26.05	4.80
	6	23.96	4.65

Table (٤): The Results of UPV for Compressive Specimens (km/Sec.)

w/c Ratio		0.45			0.65		
Sulfate %		0	3	6	0	3	6
Age (days)	4	4.39	4.37	4.30	3.95	3.97	3.92
	8	4.41	4.35	4.26	4.03	3.92	3.89
	12	4.49	4.31	4.26	4.16	3.86	3.80
	16	4.53	4.28	4.17	4.23	3.78	3.72
	20	4.61	4.23	4.10	4.33	3.73	3.67
	24	4.80	4.16	3.86	4.42	3.69	3.57
	28	4.80	4.16	3.86	4.48	3.61	3.49
	32	4.92	4.03	3.76	4.52	3.33	3.30
	36	4.95	4.00	3.65	4.57	3.25	3.23
	40	5.05	3.89	3.57	4.65	3.16	3.10

Table (٥): The Results of UPV for Flexural Specimens (km/Sec.)

w/c Ratio		0.45			0.65		
Sulfate Ratio		0	3	6	0	3	6
Age (days)	4	4.1	4.17	3.87	4.00	4.11	3.98
	8	4.21	4.05	3.82	4.20	3.99	3.96
	12	4.28	4.0	3.71	4.28	3.98	3.88
	16	4.38	3.97	3.70	4.31	3.93	3.84
	20	4.41	3.89	3.69	4.40	3.80	3.79
	24	4.44	3.80	3.61	4.41	3.73	3.72
	28	4.65	3.73	3.54	4.60	3.60	3.61
	32	4.71	3.68	3.45	4.66	3.54	3.53
	36	4.82	3.59	3.44	4.73	3.45	3.40
	40	4.93	3.52	3.37	4.88	3.40	3.37

12. Further Research

In this paper, an experimental approach to establishing the relationship between UPV and the strength of hardened concrete was presented and verified to be suitable for application. Although a wide variety of mixture proportions of concrete had to be considered in further studies.

13. Conclusions

The objective of this paper is to investigate the relationship between the ultrasonic pulse velocity (UPV) and the compressive strength and the flexural strength of concrete under the influence of the w/c ratio, the sulfate exposure and the age of concrete. Specific conclusions are as follows:

1. The UPV increases with the increase of the compressive and flexural strength. The observed range for UPV was (3.5 to 4.75 km/sec) corresponds to (24 to 28.5 N/mm2) for compressive strength and to (4.6 to 6.5 N/mm2) for flexural strength.
2. The UPV decreases with the increase of the concentration of sulfate exposure. The obtained maximum reduction in UPV was 31.6% with respect to the control spacemen at age of 40 days.
3. For control specimen, the UPV increases with age. The % increase of 40 days spacemen to 4 days ones was 17.7%.

4. The UPV is shown to decrease with the increase in w/c ratio. For control specimens with w/c of 0.45 the maximum UPV was 5.05 km/sec while for those with w/c ratio of 0.65 the maximum UPV was 4.65 km/sec at age of 40 days.
5. The UPV test is shown effective in detecting the effects of sulfates on concrete specimen.

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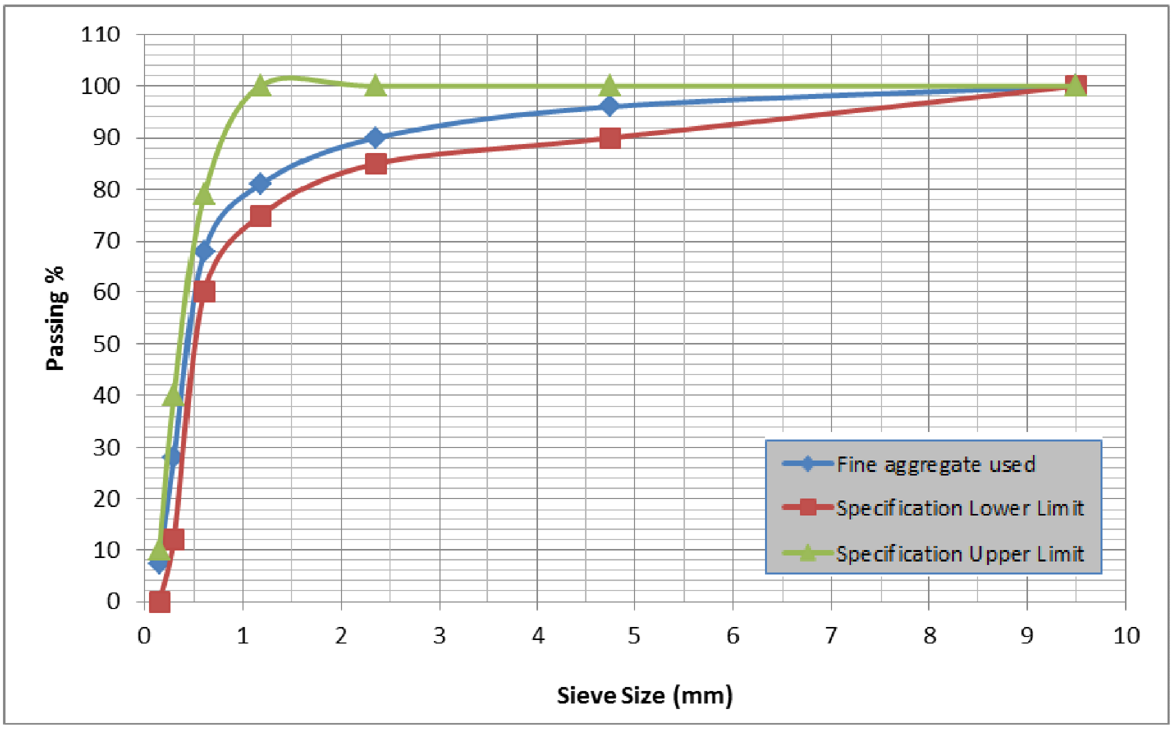

Figure 1. Sieve Analysis for Fine Aggregate (According to B.S. 882:1992).

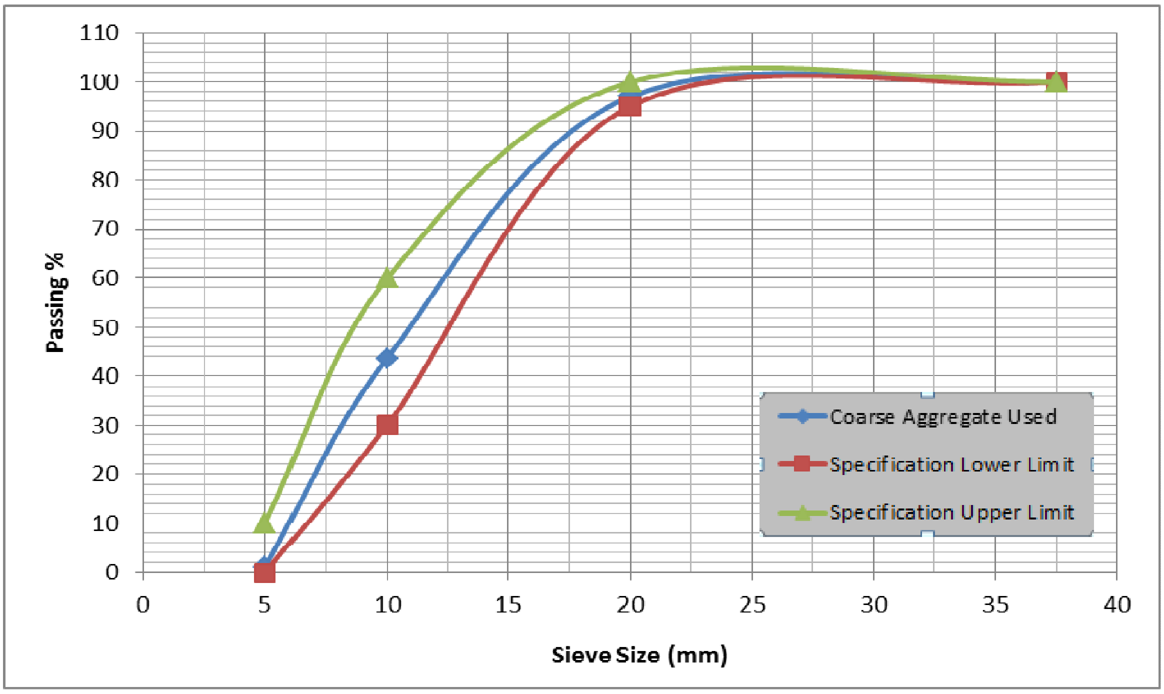

Figure 2. Sieve Analysis for Coarse Aggregate (According to B.S. 882:1992).

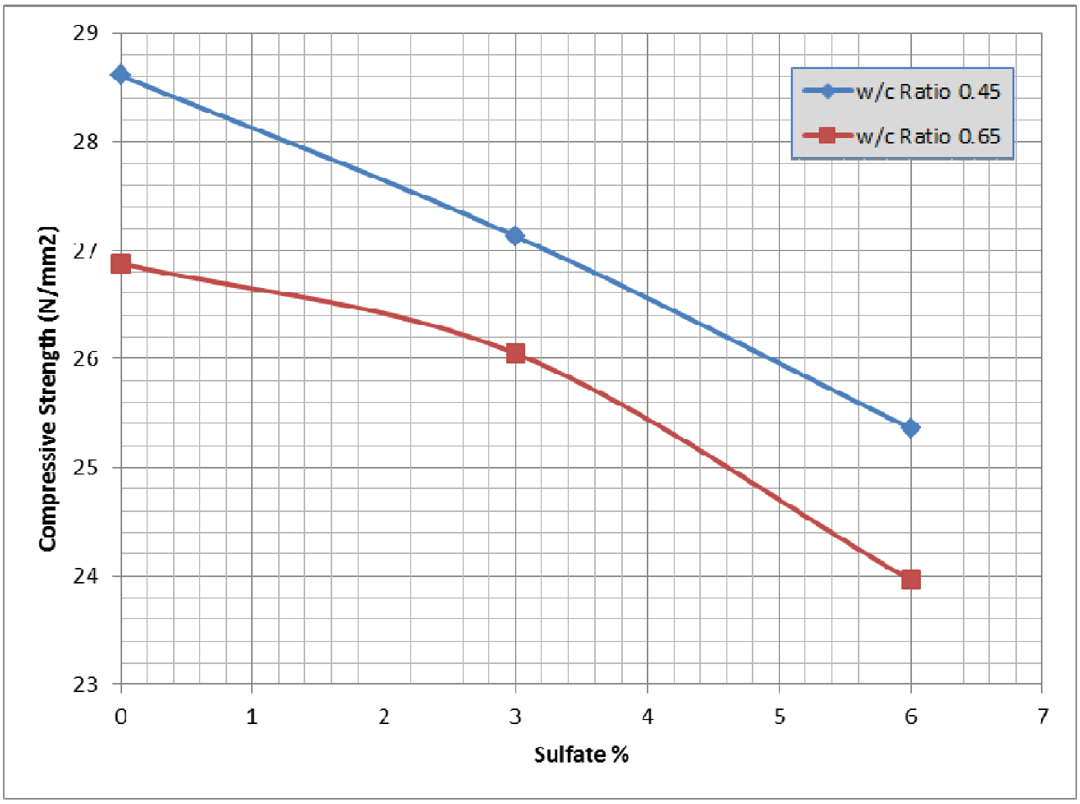

Figure 3. The Relationship between Sulfate Ratio and Compressive Strength at Age 28 Days.

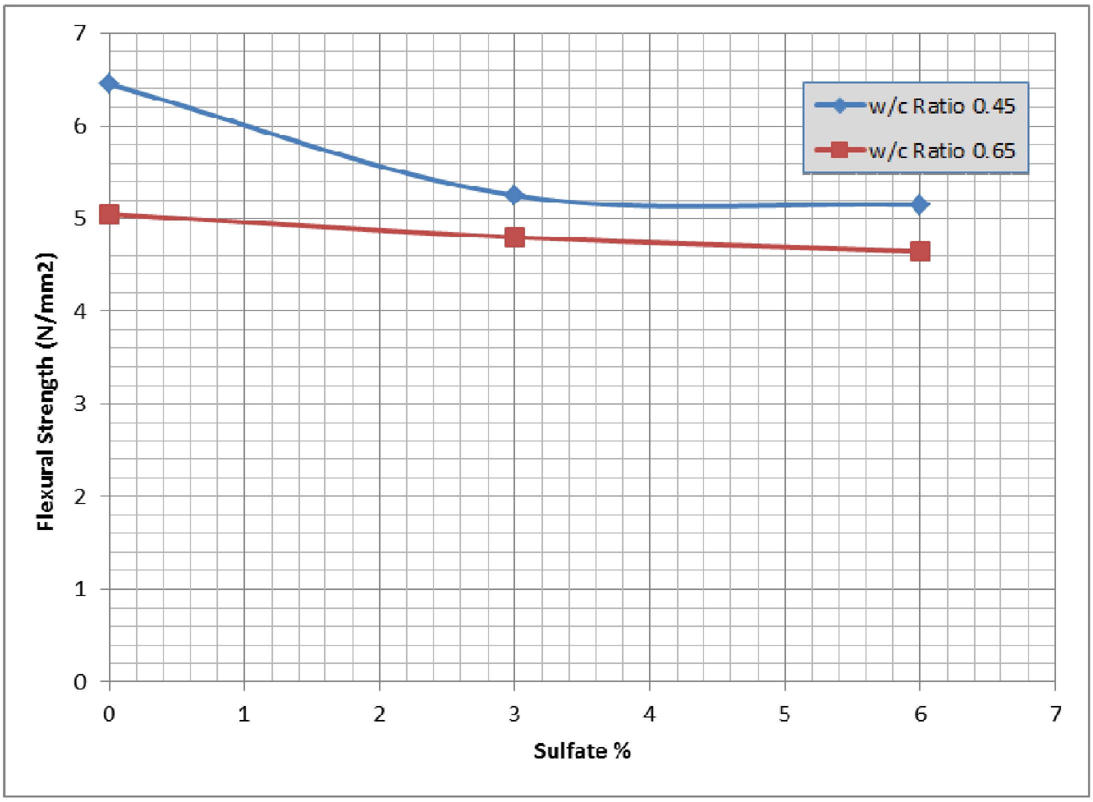

Figure 4. The Relation between Sulfate Ratio and Flexural Strength at Age 28 Days

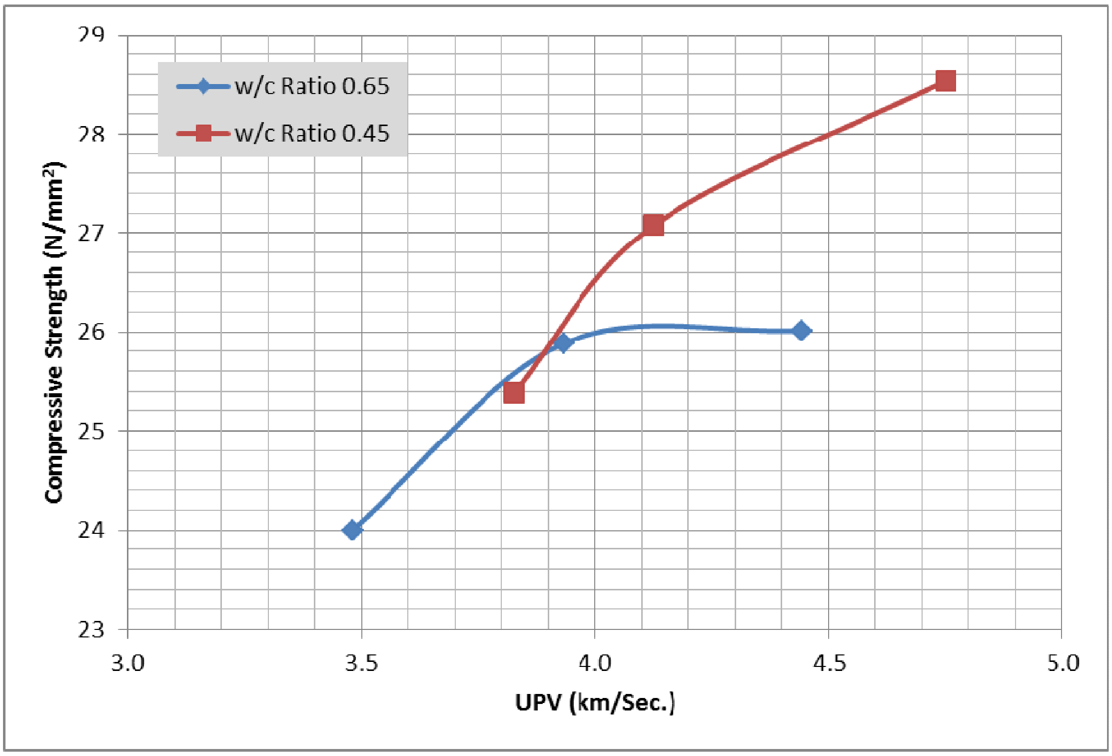

Figure 5. UPV-Compressive strength Relationship of the Hardened Concrete at Age 28 Days

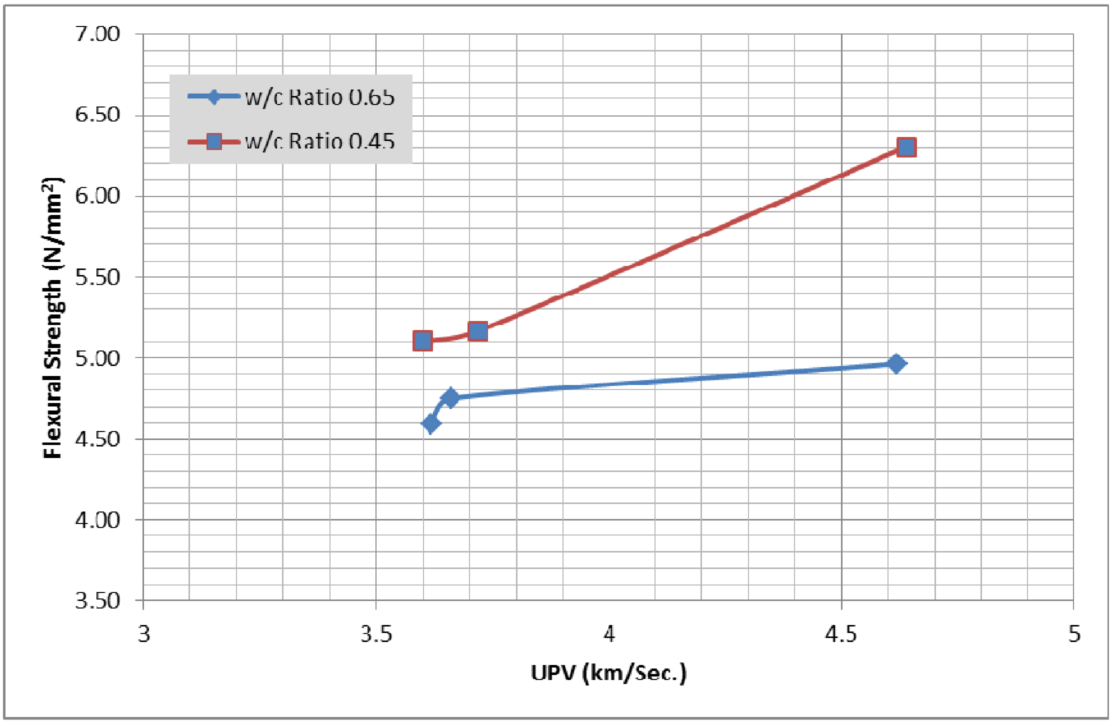

Figure 6. UPV-Flexural strength Relationship of the Hardened Concrete at Age 28 Days

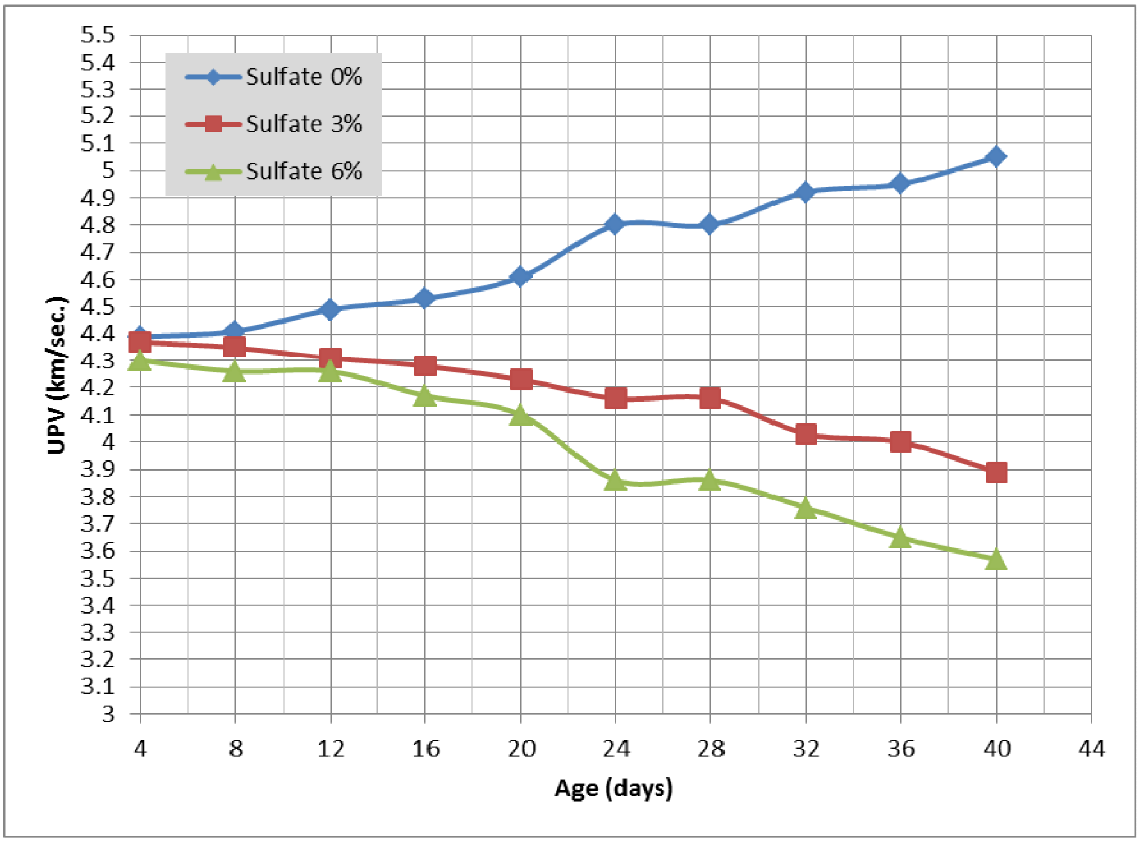

Figure 7. The Relation between Age and UPV for Compressive Specimens (w/c Ratio 0.45)

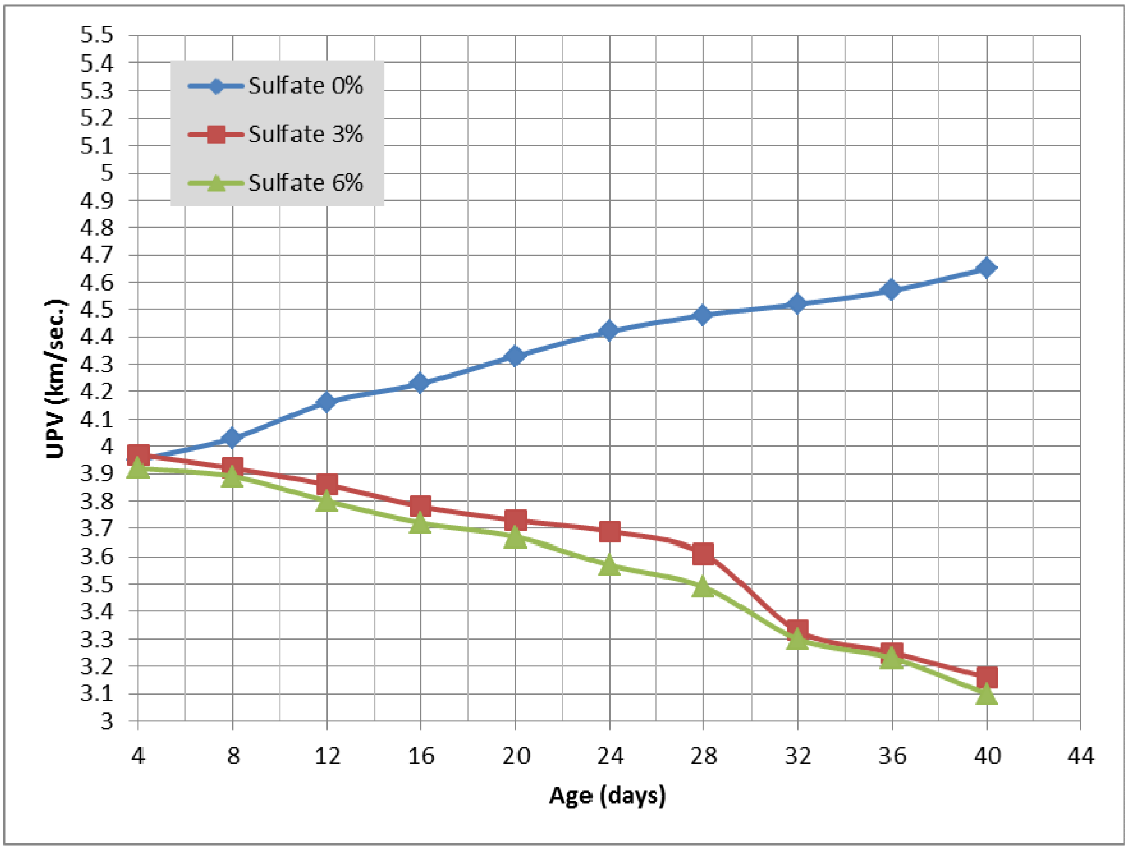

Figure 8. The Relation between Age and UPV for Compressive Specimens (w/c Ratio 0.65)

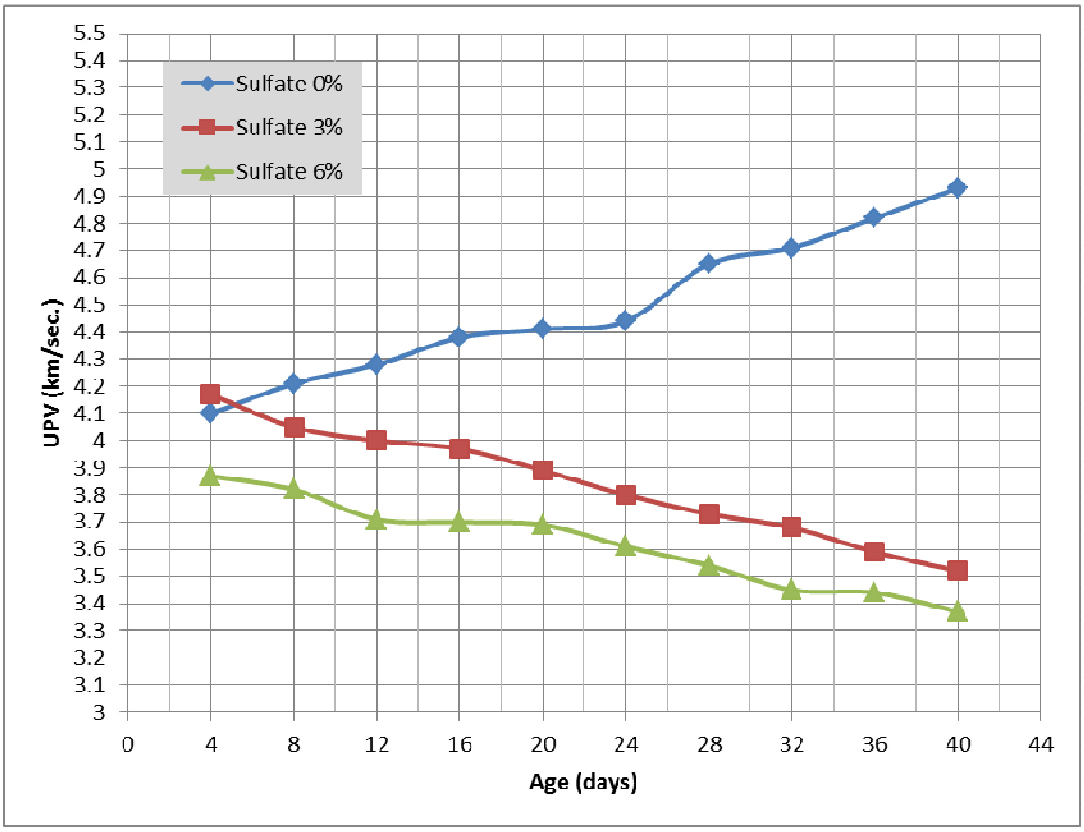

Figure 9. The Relation between Age and UPV for Flexural Specimens (w/c Ratio 0.45)

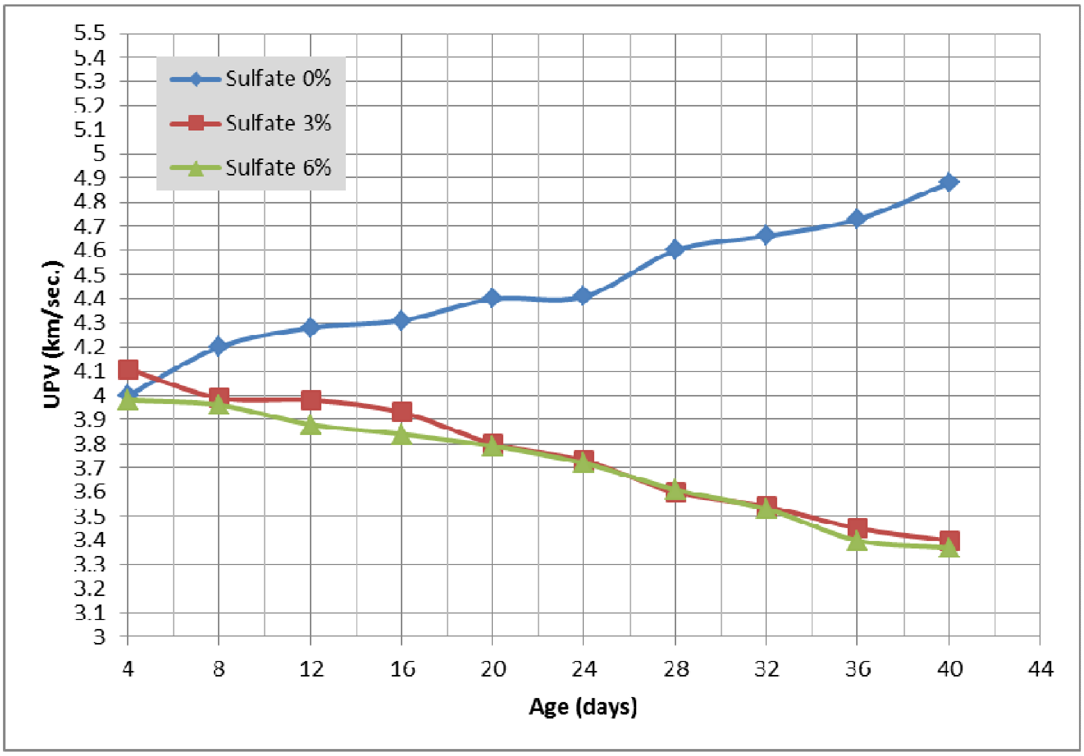

Figure 10. The Relation between Age and UPV for Flexural Specimens (w/c Ratio 0.65)

Plate 1. The UPV Instrumentation