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Non-Destructive Evaluation of Concrete using Ultrasonic Pulse Velocity

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Abstract: Ultrasonic pulse velocity is one of the most popular non-destructive techniques used in the assessment of concrete properties. This article investigates the relationship between Ultrasonic Pulse Velocity (UPV) and the compressive strength of concrete. The specimens used in the studies were made of concrete with a paste content of 18% and the constituents of the specimens varied in different water-cement ratios (w/c). The UPV measurement and compressive strength tests were carried out at the concrete age of 2, 7, 15 and 28 days. The UPV and the compressive strength of concrete increase with age, but the growth rate varies with mixture proportion. A relationship curve is drawn between UPV and compressive strength for concrete having different w/c from 0.35 to 0.7.

Key words: Compressive strength, concrete properties, non-destructive evaluation, testing concrete, ultrasonics, water cement ratios

INTRODUCTION

Concrete is a complex composite material, which begins its life as a mixture of graded stone aggregate particles suspended in a fluid of cement and water and admixtures. Nominally, aggregate occupies 75% of the volume, cement about 15% and water content 10%. The priority when choosing a mix design is strength, which along with permeability of the concrete is governed by the water-cement ratio. For high strength and low permeability the water-cement ratio should be low. The that describes the ease of placing and compaction, for a fixed water-cement ratio, is adjusted by choice of aggregate quantity, grading and shape, and also by the assistance of chemical plasticizers. Larger, rounded aggregate tends towards greater workability. It is usual for the coarse aggregate used in structural concrete to have a nominal maximum size of 20mm. Concrete reaches half its strength after about 3 days and 90% after 28 days. Concrete is a very versatile, potentially durable composite material, which is strong in compression but about 90% weaker in tension such that structural members subject to tensile stress are reinforced with steel bars. The setting of concrete is not a drying out process but a chemical reaction called hydration, where the calcium silicates in the cement react with the water to form hydrates and is accompanied by the evolution of heat. In the early stages of hydration, water rises and aggregate settles, such that the surface concrete is not representative of the overall volume. The structure of the cement hydrate to a large extent determines the durability of the concrete. There are inherent pores of a few nm, and pores 50 to 100 times larger as a result of the presence of excess water above that required to complete hydration. Additionally there may be air pockets or volumes of lower density due to inadequate compaction. It is also likely that all concrete has an extensive crack system induced by shrinkage, thermal movements, loading and a number of other causes. Concrete in service is exposed to a wide variety of environments and, because of its physical and chemical nature, may deteriorate as a result (Perkins, 1997). The pores and the crack system provide passage ways by which acidic moisture and gases that attack the alkaline concrete can penetrate. Once deterioration is apparent, its classification and extent need to be appraised so that appropriate remedial action can be specified. Routine testing of concrete is primarily concerned with assessing current adequacy and future performance (Bungey and Millard, 1996). An initial visual inspection of the site can prove valuable in locating deterioration and aid the choice of an appropriate method of test. Although standard control cubes and cylinders are used to determine the strength of concrete produced on site, they cannot be truly representative of the insitu concrete strength of a structure. However, extraction of cores is expensive and might weaken the structure. Various NDE methods which

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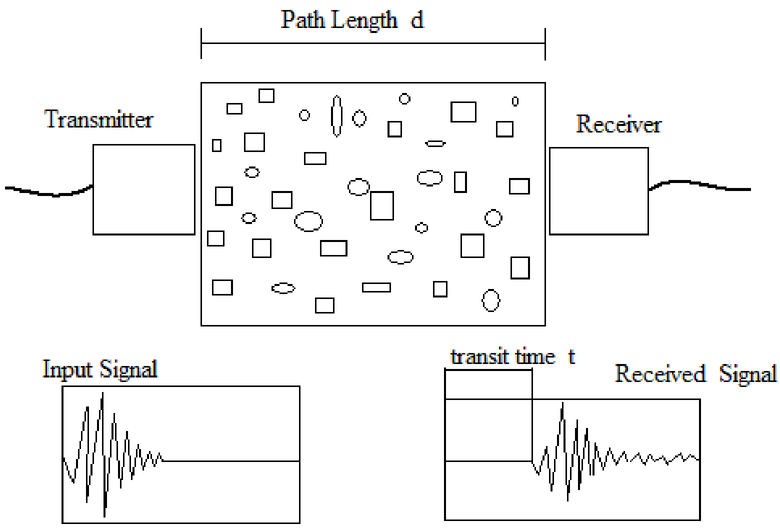

Fig. 1: Ultrasonic pulse velocity testing

Fig. 2: The PUNDIT plus set

enable certain properties of concrete to be measured in-situ, from which concrete strength is estimated, have been devised. Of the non-destructive techniques, the ultrasonic pulse velocity technique offers the lowest cost of use and is convenient as well as rapid to employ.

MATERIALS AND METHODS

Ultrasonic pulse velocity: When the surface of a semi-infinite solid is excited by a time varying mechanical force, energy is radiated from the source as three distinct types of elastic wave propagation. The fastest of these waves has particle displacements in the direction of travel of the disturbance and is called the longitudinal, compression or P-wave. The compression wave velocity V_p is a function of the dynamic Young's modulus E, the Poisson's ratio υ, and the mass density ρ, (Krautkramer and Krautkramer, 1969; Marsh, 2000), and is given by:

$$V_p = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}}$$

Table 1: Quality of concrete given by IS code (BS, 1881, 1983) as a function of UPV

UPV(m/s)	Concrete quality
Above 4500	Excellent
3500 to 4500	Good
3000 to 3500	Medium
Below 3000	Doubtful

It is clear from the above equation that velocity is independent of geometry of material and depends only on elastic properties of the material through which it passes. Hence the principle of assessing quality of concrete is that comparatively higher velocities are obtained when the quality of concrete in terms of density, homogeneity and uniformity is good. In case of poorer quality, lower velocities are obtained (Table 1).

In the test described in BS (1881): Part 203 (BS, 1881, 1986), the time the pulses take to travel through concrete is recorded. Then, the velocity is calculated as:

$$V = L/T \tag{2}$$

where V = pulse velocity (m/s), L = length (m), and T = effective time (s), which is the measured time minus the zero time correction. The zero time correction is equal to the travel time between the transmitting and receiving transducers when they are pressed firmly together.

The UPV results can be used:

- To check the uniformity of concrete
- To detect cracking and voids in concrete
- To control the quality of concrete and concrete products by comparing results to a similar made concrete
- To detect the condition and deterioration of concrete
- To detect the depth of a surface crack
- To determine the strength if previous data are available

Since strength is the major property in structural concrete, measured velocity was related to strength, and plots of velocity vs. strength were obtained.

Experiments: The experimental set-up is shown schematically in Fig. 1. The apparatus (Fig. 2) which is manufactured by CNS Farnell, London, derives its name from the initial letters of the full title of "Portable Ultrasonic Non-Destructive Digital Indicating Tester" (PUNDIT). The dimensions of the unit are 185 mm × 130 mm × 185 mm, and it weighs in at 3 kg. The ambient temperature range to which the equipment may be operated is 0 to 45ºC. The test equipment provides a means of generating a pulse, transmitting this to the concrete, receiving and amplifying the pulse and measuring and displaying the time taken.

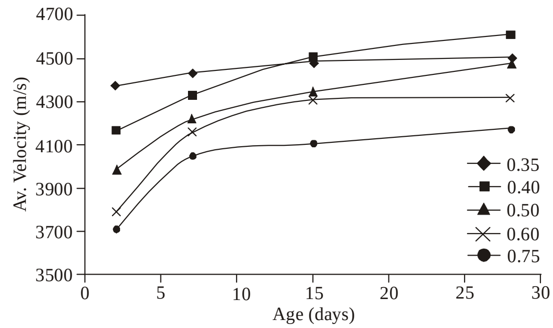

Fig. 3: UPV of concrete cubes against age

Materials used for making specimen include ordinary Portland Limestone type 2.5N, standard sand, Coarse Aggregate (CA) of 10 mm grain size and water.

The water-cement ratio (w/c) used in this study ranges from 0.35 to 0.75. The cement paste occupies approximately 18% of the total concrete volume.

Five concrete specimens were produced for each mixture proportion. All the specimens were cast in steel moulds and kept in their moulds for approximately 24 h in the laboratory. After removing the moulds, three concrete cubes were tested at an age of 2 days and all other concrete cubes were cured in water at 20ºC (68ºF) and tested at ages 7, 15 and 28 days, respectively. At each age, the pulse velocity and compressive strength of the five specimens were measured according to the specification of the British standard (Qasrawi, 2003). Five simulation curves of the relationship between UPV and compressive strength of hardened concrete are proposed for concrete with w/c of 0.35, 0.4, 0.5, 0.6 and 0.75. These curves were verified to be suitable for prediction of hardened concrete strength with a measured UPV value.

RESULTS AND DISCUSSION

Figures 3 and 4 shows the UPV and strength development, respectively, with the age of concrete having different w/c. Both the UPV and strength of concrete increase 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 as shown in Fig. 3 and 4 mainly because of the denser structure of concrete with lower w/c.

Figure 3 indicates that concrete with high w/c (w/c = 0.75) at the age of 2 days has a UPV of about 89% of that of 28 days, but the strength is only about 60%. Figure 3

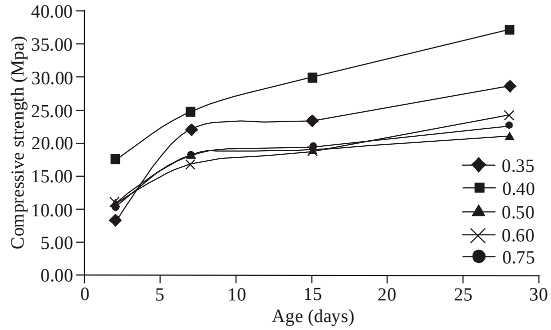

Fig. 4: Compressive strength of concrete cubes against age

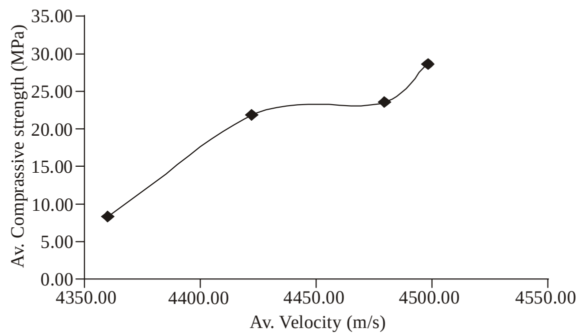

Fig. 5: Comparison of Av. Velocity and compressive strength with 0.35 w/c

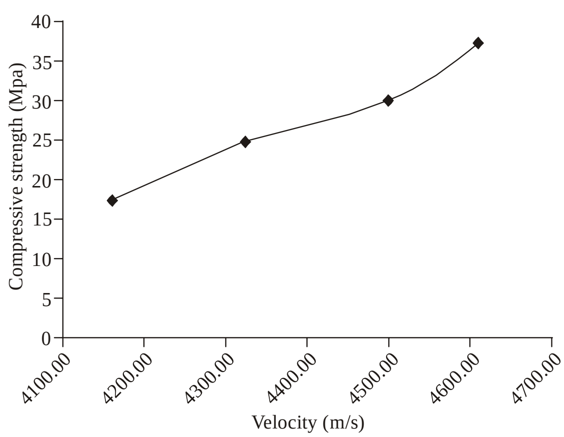

Fig. 6: Comparison of Av. Velocity and compressive strength with 0.40 w/c

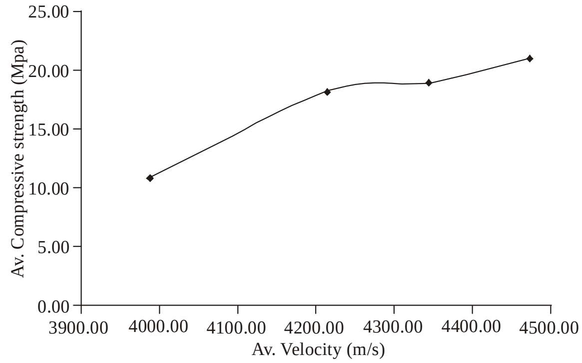

Fig. 7: Comparison of Av. Velocity and compressive strength with 0.50 w/c

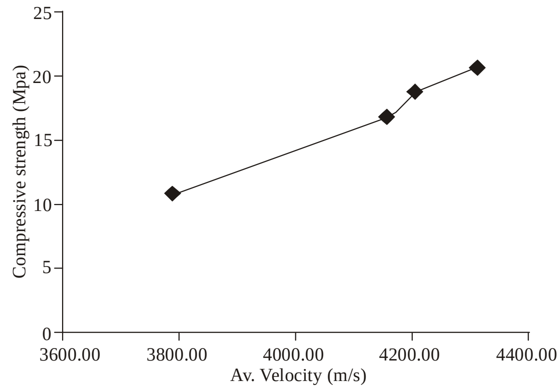

Fig. 8: Comparison of Av. Velocity and compressive strength with 0.60 w/c

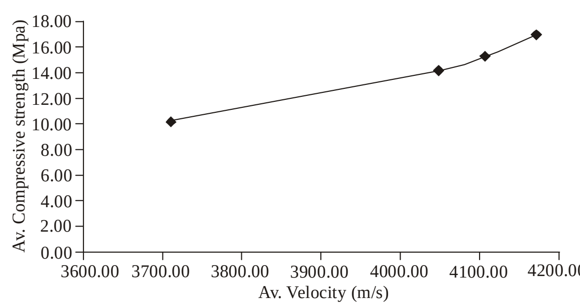

Fig. 9: Comparison of Av. Velocity and compressive strength with 0.75 w/c

also indicates that at the age of 2 days, concrete with low w/c (w/c = 0.35) has a UPV that is approximately 97% of that at 28 days and the strength is about 30%. To sum up, the UPV and strength growth rates of high and low w/c concrete are significantly different at an early age. As a result, the relationship between UPV and strength of concrete becomes unclear when age and mixture proportion is taken into consideration simultaneously. This observation suggests that it is be better to separately consider the effect of age and mixture proportion on UPV and strength relationship. For the given mixture proportion, Figure 5 to 9 are used to acquire the UPV and strength values of hardened concrete having w/c of 0.35, 0.40, 0.50, 0.60, 0.75.

Table 2: Concrete mix proportion for verification of UPV-strength relationship curves

w/c	Cement/kg	Sand/kg	C.A (10 mm)/kg	Water/L
0.35	15.4	30.9	61.7	4.6
0.40	15.4	30.9	61.7	6.2
0.50	15.4	30.9	61.7	7.7
0.60	15.4	30.9	61.7	9.2
0.75	15.4	30.9	61.7	11.6

Table 3: Comparison results of UPV-strength relationship

w/c	Av.velocity/ms	Theoretical C.S/MPa	Experimental C.S/MPa
0.35	4755.00	33.15	32.25
0.40	7505.60	40.30	41.00
0.50	6305.00	29.00	30.40
0.60	5446.60	22.50	21.40
0.75	4529.20	19.00	20.65

In this study, five curves of the relationship between UPV and compressive strength are drawn for concrete with the given w/c.

The equations for the curves of these five w/c are as follows:

$$\sigma\ (0.35) = 1E\text{-}15\ e^{0.008v} \quad (3)$$
$$\sigma\ (0.40) = 0.022\ e^{0.001v} \quad (4)$$
$$\sigma\ (0.50) = 0.053\ e^{0.001v} \quad (5)$$
$$\sigma\ (0.60) = 0.097\ e^{0.001v} \quad (6)$$
$$\sigma\ (0.70) = 0.205\ e^{0.001v} \quad (7)$$

where σ and v represent the compressive strength (MPa) and the ultrasonic pulse velocity (m/s), respectively. For the five w/c (0.35, 0.40, 0.50, 0.60 and 0.75) the relationship between UPV and strength of concrete is pretty good for this particular mixture proportion with a very high coefficient of determination, R^2 of 0.866, 0.981, 0.888, 0.994 and 0.989, respectively. This indicates relevance between data points and the regression curves.

Verification of proposed UPV - strength relationship curves: To verify the validity of the proposed UPV - strength relationship, additional specimen were constructed with different concrete having a different mixture proportion of w/c 0.40, 0.50, 0.60, as listed in Table 2. The cement paste also occupies 18% of the total concrete volume. The specimen were prepared and cured in water and then tested at the age of 28 days. The measured pulse velocity, v of each specimen was used to predict its compressive strength by using the suitable UPV - strength equation that is representative of the w/c of the specimen.

The predicted strength was compared with the compressive strength obtained from the destructive tests on the specimen. The comparison results are shown in Table 3. Almost all the comparison results are within the recommended ±10% deviation from the true value. This verifies the suitability of the proposed relationship curves for prediction of hardened concrete strength with a measured UPV value.

CONCLUSION

The main objective of this paper is to investigate the relationship between the Ultrasonic Pulse Velocity (UPV) and compressive strength of concrete as well as to understand the influence of the mixture proportion and the age of concrete on the relationship between UPV and compressive strength. Specific conclusions are as follows:

- The UPV and strength growth rates of high and low w/c concrete have a significant difference at an early age. As a result, to clearly define the relationship between UPV and the strength of concrete with different mixture proportions, it is necessary to eliminate the interference caused by the different UPV and strength growth rates of concrete at early ages.
- The equations obtained from the simulation curves can be used to determine the concrete strengths of the concrete mix proportions.

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REFERENCES

Bungey, J.H., and S.G. Millard, 1996. Testing of Concrete Structures. Blackie Academic and Professional, London.

BS 1881: Part116, 1983. Method for Determination of Compressive Strength of Concrete Cubes. British Standards Institution, London.

BS 1881: Part 203, 1986. Recommendations for Measurement of Velocity of Ultrasonic Pulses in Concrete. British Standards Institution, London.

Krautkramer, J. and H. Krautkramer, 1969. Ultrasonic Testing of materials, G. Allen & Unwin. J. Sound Vibration, 11(1): 157-158.

Marsh, B., 2000. The European Classification of Exposure Environmental for Concrete. Concrete, 34(6).

Perkins, P.H., 1997. Repair, Protection and Waterproofing of Concrete Structures. E & FN Spon, London.

Qasrawi, H.Y., 2003. Concrete strength by combined non-destructive methods. Simply and reliably predicted, pergamon.