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A Preliminary Study on Ultrasonic Non-Destructive Testing of Concrete in Maritime Environment

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Abstract. This paper describes an experimental study in which non-destructive testing (NDT) of concrete in marine and a non-marine environment was performed. Nine (150mm x 150mm x 150mm) cubic specimens from three batches of concrete with w/c of 0.40, 0.50, and 0.60 and with appropriate variations in cement and sand were prepared.

The hardened concrete specimens were cured under controlled laboratory conditions for 28 days. In the first stage the cubic specimens were tested using through-transmission NDT technique lying simply on laboratory floor, representing a typical of non-marine environment. Afterwards, for simulating marine-like environment, the cubic specimens were retested lying in a water tank. The underwater through-transmission of the specimens was performed.

The results obtained from both ways of testing were recorded and plotted in time and frequency domains. P-wave velocities and attenuation of the wave signals were measured and compared. Additionally, the wave reflection factor (WRF) was calculated and compared for specimens tested under water.

The results show that the wave attenuation, the P-wave velocities in concrete, and the WRF are highly influenced by the w/c ratio. The outcomes of this study can be useful in conducting research on testing actual maritime concrete structures.

1 INTRODUCTION

The growing concern of the present day engineers is to effectively inspect the deteriorated concrete infrastructure [1,2]. Their priorities are increasingly shifting away from building new structures towards inspection, assessment and maintenance of the existing infrastructure [3]. Before appropriate rehabilitation can be prescribed, it is therefore necessary that the condition of a structure should be assessed. Non-destructive test (NDT) techniques that can detect, localize and characterize damage and flaws in the infrastructure are of great interest for this purpose [4].

The concrete infrastructure is comprised of a wide range of structure types including bridges, beams, columns, pavements, piers and pipes. Each of these structures, some of which are also constructed in marine environment, may contain damage or embedded flaws. Elastic wave-based non-destructive test (NDT) methods are useful for detecting flaws or defects in all kinds of concrete structures [5]. However the application of elastic wave-based NDT methods for concrete structures is severely limited by the physical coupling between sensors and concrete surface, which reduces testing efficiency [1].

Most NDT techniques require good contact between the sensor and tested concrete surface to obtain reliable data. But the surface preparation is often very time- and labor consuming due to the rough surface or due to limited access particularly in case of underwater concrete structures. The easiest approach to speed up the data collection process is to eliminate the need for physical contact between the sensor and tested structure. Commonly used non-contact techniques include radiography with penetrating radiation, RADAR with electromagnetic pulsed waves and infrared thermography [6]. However, these techniques limited safety provision and are very expansive.

In this study a special through transmission test setup is developed as a solution that enable the elastic wave-based NDT method to test the concrete not only in non-marine environment but also perform the underwater NDT of concrete. This method describes the location, size and shape of embedded damage or flaws. It provides a direct way to help engineers evaluate the condition of both surface and under water concrete structures. Additionally, the through transmission test (Figure 1) can evaluate the velocity and attenuation of an ultrasonic wave traveling through the concrete. By knowing the pulse time of flight and the thickness of the concrete member the velocity can be calculated.

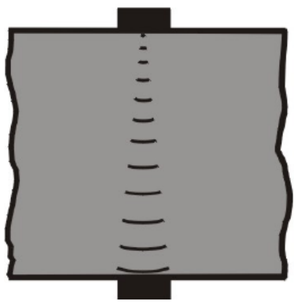


Figure 1. Ultrasonic through transmission method.

The proposed test setup was applied to evaluate the cubic specimens, prepared with different w/c, in two stages. In the first stage the specimens were tested lying simply on laboratory floor. Afterwards, for simulating marine-like environment, the cubic specimens were retested lying in a water tank. The underwater through-transmission testing of the specimens was performed. The results obtained from both ways of testing were recorded and plotted in time and frequency domains. P-wave velocities and attenuation of the wave signals were measured and compared. Additionally, the wave reflection factor (WRF) was calculated and compared for specimens tested under water. The results show that the wave attenuation, the P-wave velocities in concrete, and the WRF are highly influenced by the w/c ratio.

2 EXPERIMENTAL PROGRAM

Nine (150mm x 150mm x 150mm) cubic specimens from three batches of concrete with w/c of 0.40, 0.50, and 0.60 and with appropriate variations in cement and sand were prepared. Two sizes of coarse aggregates were used, one with size varied from 2 to 8 mm and second with size varied from 8 to 15 mm. The aggregate quantities were kept constant in all the three batches. After 24-hour of casting the steel moulds were opened and the hardened concrete specimens were kept in water tub for 28-day of curing under the laboratory controlled temperature. Details of the mix proportions are given in Table 1.

Table 1: Mix proportions and compressive strength of concrete

W/C	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Crushed stone (kg/m^3)	Air entraining agent (kg/m^3)	Water reducing agent (kg/m^3)	Slump (cm)	Compressive strength (MPa)
0.40	425	170	799	910	0.034	0.026	8.0	56
0.50	340	170	871	910	0.034	0.017	10.0	45
0.60	283	170	919	910	0.034	0.010	10.50	38

Figures 2 and 3 show the test setups for testing cubic specimens outside and inside of water. The test setup used for testing of the concrete specimens outside of water consisted of a tone burst pulsar, a broadband receiver, two sensors, an agilent (function generator), and an oscilloscope (see Figure 1). One of the sensors was connected with the pulsar for wave transmission in the specimens and the other with receiver for wave reception. Each sensor had a central frequency of 500 kHz. In the current experimental program the ultrasonic waves were generated into the concrete specimens at a frequency range of greater than 100 kHz.

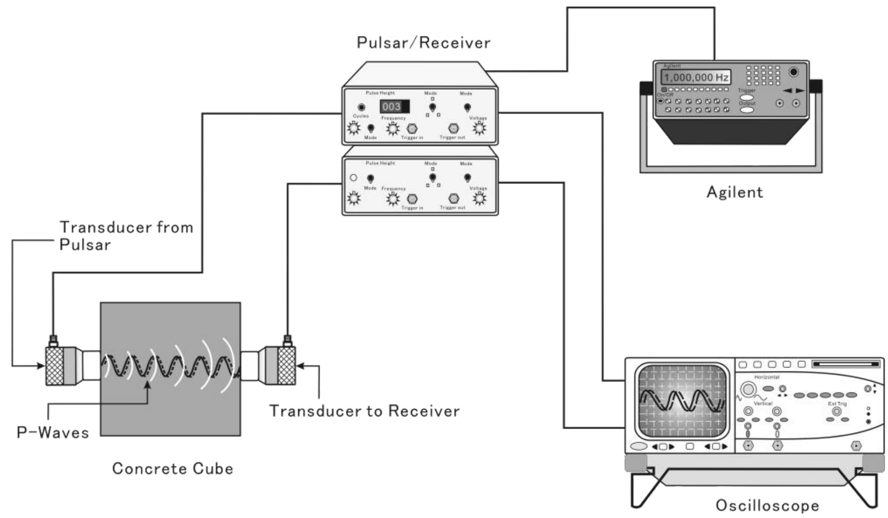


Figure 3. Ultrasonic through transmission testing of a cubic specimen outside of water

Similarly, for NDT of concrete specimens in water, the test setup consisted of a water tank, Master and Slave sensors, a loading pedestal for placement of the concrete cube, a control system, a computer and an oscilloscope (see Figure 2).

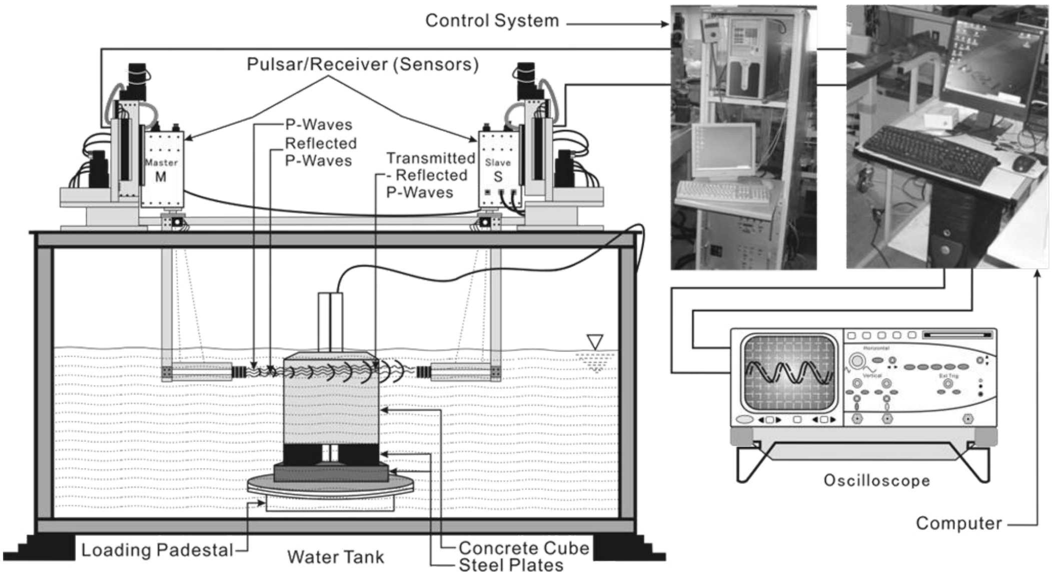
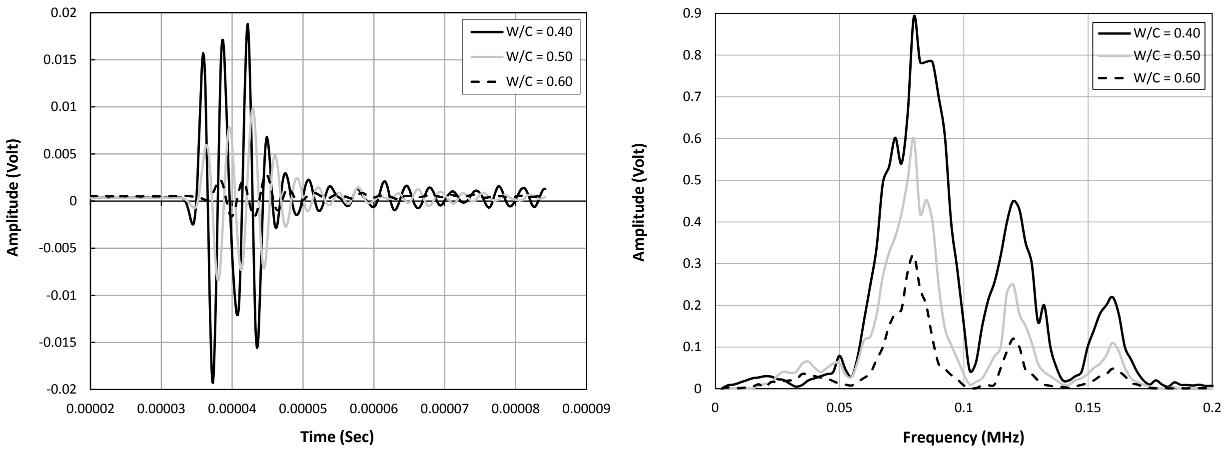


Figure 4. Ultrasonic through transmission testing of a cubic specimen inside of water

3 DISCUSSION OF TEST RESULTS

Figure 5 (a) shows the captured wave signals in time domain for the cubic specimens cast with w/c of 0.40, 0.50, and 0.50. The mean values of three specimens tested outside of water (Figure 3) at each w/c are plotted for comparison. As was expected, the effect of w/c is very pronounced in the plotted results. The experimental results illustrate that the amplitude of the waveforms decreases as w/c increases.

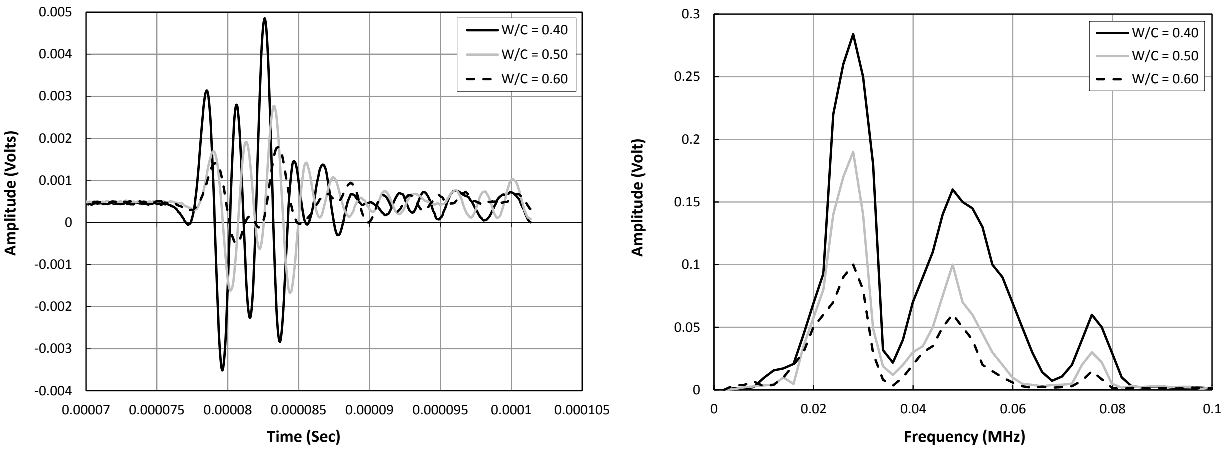


(a) (b)

Figure 5. Ultrasonic waveforms for outside of water tests (a) time domain (b) frequency spectrum

The Fourier transformed values of the time domain wave signals, as plotted in Figure 5 (a), are given in Figure 5 (b). At each w/c, the frequency spectrum appeared in three distinct peaks. The test results show that the amplitude of the ultrasonic waveforms decreases as w/c increases. The comparison of the relative amplitudes of these two frequency peaks can be used to calculate attenuation. It was observed that the wave attenuation increases as frequency level increases. The highest attenuation of the ultrasonic waveforms was observed for frequency level greater than 150 kHz.

Similar trends for the change in the ultrasonic amplitude in time and frequency domain were obtained for the underwater experimentation (Figure 4). The average results of three specimens at different w/c were used for comparison. Figures 7 and 8 show these changes graphically. It can be seen that signal amplitude decreases as w/c increases (see Figure 7). Similarly, it was noticed that signal attenuation increases as frequency level increases.



(a) (b)

Figure 5. Ultrasonic waveforms for underwater tests (a) time domain (b) frequency spectrum

The comparison of test results revealed that the magnitudes of ultrasonic waveforms in both time and frequency domains were greater for the specimens evaluated outside of water than those for inside of water. The reduction in ultrasonic amplitude for under water evaluation was because of the fact that when an ultrasonic wave traveling through a medium hits an interface, defined as a boundary between two materials (water and concrete) with different acoustic properties, it is partially reflected back and partially transmitted into the medium on the other side of the interface. Therefore, the partially transmitted waves through the concrete were more prone to attenuate and resulted into signals reduction from the outside of water state to inside of water state by about 68% for all w/c concretes.

The wave reflection factor (WRF) for specimens tested underwater was additionally calculated, which describes the amount of wave energy reflected at the interface of water and concrete. The WRF for P-waves is determined by the acoustic impedances of the two materials that form the interface. When the wave travels from Material 1 (fluid/water) into Material 2 (concrete) the WRF is

$$WRF = \frac{\rho_c v_c - \rho_f v_f}{\rho_c v_c + \rho_f v_f} \tag{1}$$

with ρ_f and ρ_c as the densities while v_f and v_c as the P-wave velocities of fluid and concrete respectively.

From the test results analysis it was found that WRF increases as w/c decreases and vice versa. Table 2 shows the P-wave velocity and WRF values for cubic specimens tested under water. P-wave velocities of cubic concrete specimens tested outside of water are tabulated in Table 3. Both tables consist of the mean values of three tests with different w/c.

Table 2: Wave velocities and WRF for cubic specimens tested in water

W/C	Volume (m^3)	Mass (kg)	Concrete Density (kg/m^3)	Fluid density (kg/m^3)	v_c (m/s)	v_f (m/s)	WRF
0.40	0.0016	3.67	2370	1000	2851	1479	0.764
0.50	0.0015	3.64	2360	1000	2827	1479	0.763
0.60	0.0015	3.60	2350	1000	2817	1479	0.762

Table 3: P-wave velocities of cubic specimens tested outside of water

W/C	v_c m/s
40	4688
50	4615
60	4451

The tabulated results (tables 2 and 3) show that in each case concrete wave velocity decreases as w/c increases. However, the wave velocity values for specimens tested outside of water were found higher than those for inside of water, independent of w/c. This is perhaps because of the fact that underwater the non-contact NDT sensors generated weaker ultrasonic wave signals. It was, therefore, difficult to identify the onset, which resulted in a decreased pulse velocity. It might be an interesting finding towards evaluating concrete behavior applying through transmission testing technique to under water concrete structures. However, to validate this finding future research based on extensive experimentation in this direction is strongly recommended.

4 CONCLUSIONS

This research is focused on conducting an experimental study in which the through transmission NDT of concrete in marine and a non-marine environment was performed in order to examine the P-wave velocity and signal attenuation. Nine cubic specimens were cast. Three batches of concrete with w/c of 0.40, 0.50, and 0.60 and with appropriate variations in cement and sand were prepared.

The test results show that the testing technique appears to be reliable in both surface and underwater NDT evaluation of concrete. In both cases the results obtained for testing cubic specimens are reasonable and satisfactory. The P-wave velocities, however, for concrete specimens tested outside of water are greater than the specimens tested inside of water.

As the w/c decreases, the amplitude, the peak frequency levels, the P-wave velocity in concrete, and the wave reflection factor (which is a measurement of attenuation) increase. As a result for the specimens tested underwater high attenuation of ultrasonic signals at frequency levels higher than 50 kHz was observed.

On the other hand, due to stronger signals for outside of water testing, the ultrasonic waves obtained at each w/c were found more prone to attenuate as soon the frequency levels exceeded 150 kHz. Additionally, attenuation can easily be calculated by comparing the relative amplitude levels of the different frequency peaks.

The research findings presented in this study can be very useful in conducting research on testing actual maritime concrete structures.

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