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ON THE STUDY OF CONCRETE HYDRATION PROCESS USING PIEZOELECTRIC BASED SURFACE WAVE PROPAGATION TECHNIQUE

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ABSTRACT

Concrete is a non-homogenous material with complex microstructure, consisting of cement, fine aggregates and coarse aggregates. In the first few hours after mixing, the fresh concrete will go through the hydration process and gradually reaches solid properties. Study shows that as the concrete changes gradually from liquid to solid, the properties such as stiffness of the concrete changes accordingly. Monitoring of concrete hydration is essential especially in in-situ construction. The concrete shall reach sufficient strength before further loading is possible. In this paper, attempt has been made to study the correlation between the velocity of surface (Rayleigh) waves and the concrete hydration process using the surface wave propagation technique employing smart piezoelectric (Lead Zirconate Titanate, PZT) transducer as colocated actuator and sensor. The PZT transducer is mechanically attached to the concrete through surface bonding. The velocity of surface waves was determined by measuring the distance between the actuator and sensor and also the time of flight (TOF). Preliminary study shows that there is a steady increase in the velocity of surface waves with time, implying that the concrete is going through a hardening process. Signal processing techniques such as cross-correlation analysis and Hilbert transform are adopted for improved accuracy.

KEYWORDS

Lead zirconate titanate (PZT), surface wave propagation, rayleigh waves, time of flight, concrete hydration.

INTRODUCTION

Concrete is the most predominant building material used in today’s construction industry. This is due to its versatility, availability, relatively low cost and ease of use in a variety of civil engineering applications. Concrete, a non-homogeneous mixture of coarse aggregate, sand and hydrated cement paste, is known to possess the ability to be moulded into limitless geometries. In the first few hours
after mixing, the fresh concrete will go through the hydration process and gradually reaches solid properties. Study shows that as concrete changes gradually from liquid to solid, the properties such as stiffness of the concrete changes accordingly.

The purpose of this study is to find a correlation between the velocity of surface waves and the concrete hydration process using the PZT based surface wave propagation technique. This method employs the smart PZT transducer, which is a collocated actuator and sensor. The PZT will generate an electric field when it is subjected to mechanical stress (direct effect). In the converse effect, a mechanical strain will be generated when an electric field is applied across the PZT.

The PZT patches are permanently bonded to the concrete specimen by using high strength epoxy at predetermined distances. One of the patches is assigned as an actuator to excite a five-peak tone burst signal. The excitations are conducted at various frequencies ranging from 10 kHz to 50 kHz. Another patch will act as sensor to pick up the wave from the actuator. As concrete hardens, it becomes stiffer and thus affecting the velocity of the wave. Consequently, the traveling time of the wave is altered, which can be measured from the electrical signatures. In general, wave velocity is expected to increase with stiffness of the medium. In short, the velocity of wave can be correlated to the elastic modulus and thus the strength of the concrete.

The data acquired was analysed using signal processing techniques such as cross-correlation analysis and Hilbert transform to achieve higher accuracy. It is worth mentioning that the elastic wave generated by the surface bonded PZT patch is assumed to be predominantly Rayleigh (surface) wave which is non-dispersive in nature.

In this preliminary study, attempt was first made on mortar to ensure the homogeneity of concrete. Further study could focus on investigating the effect of coarse aggregate on the sensor signals.

**EXPERIMENTAL TESTING**

**Experimental Setup**

One batch of mortar is mixed using cement to sand ratio of 1:2. The water to cement ratio is 0.2. Two numbers of prisms were made with dimensions of 100 mm width, 100 mm depth and 500 mm length. The PZT patches were surface bonded using two parts quick set epoxy onto the surface of first prism specimen (Prism A) 3 hours after the mortar started to harden and when there is no excessive water at the top surface of the mortar.

The distances from Patch 1 to Patch 2, and from Patch 2 to Patch 3 are 60mm and 100mm, respectively. The PZT arrangement is shown in Figure 1. The reading was taken immediately after the epoxy set and monitored continuously for the first 7 days and thereafter at 14 days and 28 days. The second specimen (Prism B) was attached with PZT after 24 hours. The PZT patches will be attached to the specimen faces that were in contact with the mould to ensure smooth surface. The spacing of PZT patches in Prism B were identical to Prism A.

The instruments used in this experiment are the Function Generator (Tektronix AFG 3021B), Digital Phosphor Oscilloscope (Tektronix DPO 2012) and a personal laptop as shown in Figure 2. A 5V Hanning windowed five-peak tone burst was applied from the function generator to the PZT actuator at designated frequency ranges from 10 kHz to 50 kHz, at 10 kHz step.

Reading was taken by the oscilloscope for various PZT patches, acting as sensors. Patch 1 was first actuated with Patch 2 and Patch 3 taking turn to be sensors. Patch 2 was later actuated with Patch 3 acting to be sensor.
Signal Processing

The sample data acquired will be averaged in the data acquisition hardware which is the oscilloscope. A 128-sample averaging was selected to reduce noise and to acquire a clear wave pattern. Since PZT transducers are very sensitive to vibrations, noise reduction is essential. Gaining clear wave packets is crucial as it carry information such as the Time of Flight (TOF), signal amplitude and other important information. As the surface waves tend to disperse, the wave packets will be distorted and the precise TOF could be difficult to identify.

In this experiment, Cross Correlation method was used to extract the exact location of the original wave packets. The TOF of the wave packets could be identified with a simple peak detection algorithm. Bao (2003) presented the cross correlation principle to determine the TOF. By calculating the cross correlation of the excitation signal and the sensor signal, the time of arrival was clearly obtained at the maximum of the cross correlation signal.

The envelope of the signal could be obtained by applying Hilbert transform to the cross correlation signal. The envelope is a curve or surface that is tangent to every one of a family of curves or surfaces. The envelope is effective in extracting the amplitude of a periodic signal and can help to simplify the process of detecting the time of arrival for the wave packets (Bao, 2003). Figure 3 shows the estimate time of arrival using the cross correlation approach.
RESULTS AND DISCUSSIONS

The results at early age (6 hours to 9 hours) from Prism A showed that the sensor signal is very weak. The sensor signal received is much clearer from day 1 to day 28 for both Prism A and Prism B. Figure 4(a), 4(b) and 4(c) shows the Actuator and Sensor response for Prism A at frequency of 30 kHz for 60 mm, 100 mm and 160 mm actuator-sensor distances after 1 day.

The figures clearly indicate that the time of arrival for 60 mm distance is shorter than the 100 mm and 160 mm distance. This also means that any distance lesser 60 mm is not advisable as the signals will be overlapping. Figure 5 depicts a sample result of the distributed cross correlation and its corresponding Hilbert Transform’s envelope for Prism A at 30 kHz with Actuator - Sensor distance of 100 mm.

Figure 4. Amplitude of actuator and sensor versus time step for Prism A at 30 kHz after 1 day
Figure 5. Distribution of cross correlation and Hilbert Transform’s envelope against time for Prism A at 30 kHz and 100 mm Actuator-Sensor distance.

The TOF evaluated from the cross correlation and Hilbert transform will be used to determine the wave speed of the surface waves. Since the actuator – sensor distance has already been fixed, the average wave speed of the wavepacket can be obtained from the ratio of distance to time.

In this experiment, ten mortar cubes has been taken from the same mixing batch to monitor the compressive strength. The dimension of the mortar cubes is 100 mm x 100 mm x 100 mm. The mortar cubes specimens were tested with the universal compression testing machine to obtain the compressive strength. In each of the compressive test done, two mortar cubes were tested at day 1, 3, 7, 14 and 28 respectively. Figure 6 shows the compressive strength of the mortar cubes specimens with time. The results show that there is a steady increase in the compressive strength with time which indicate that the mortar is going through a process of hardening and stiffening.

Figure 7(a) to (f) illustrates the velocity of the surface waves with time for Prism A and B at 30 kHz for Actuator-Sensor spacing of 60 mm, 100 mm and 160 mm. Preliminary study indicates that there is a progressive increase in the velocity of the surface waves with time. From the theory of wave propagation, the velocity of wave is proportional to the stiffness of the medium. In this case, as the concrete hardens, its stiffness and strength increases, which is reflected from the increase in velocity.

An interesting phenomenon can be observed in the beginning part of all the curves where the slope is very steep, corresponding to a sharp increasing in velocity in the first few days. This implies a high rate of hydration (hardening) in the first few days of curing. This results are in good agreement with the compressive strength at different days.

The results from both samples show that the final wave speed for Prism B is consistently higher than Prism A, despite they are produced from the same mixing batch. This could be due to the different bonding condition between the PZT patches and the variation in mortar surfaces. Since PZT patches at Prism A were bonded to the surface of mortar while it is still hardening and wet, the PZT patches may not be properly bonded and the surface was still bit rough during the PZT placement. As for Prism B, the surface has already hardened and the surface chosen is a smooth surface since it is covered by the mould. The placing of PZT patches on the smooth mortar surface ensured a better bonding condition, hence enabling the surface waves to travel smoothly. The selection of specimen surface is vital to ensure the PZT is accurately attached to the specimen and allowed the wave signal to travel efficiently.
Figure 6. Compressive Strength versus Age (Mortar Cubes)

(a) Prism A: Actuator-Sensor distance = 60 mm

(b) Prism B: Actuator-Sensor distance = 60 mm
(c) Prism A: Actuator-Sensor distance = 100mm

(d) Prism B: Actuator-Sensor distance = 100mm

(e) Prism A: Actuator-Sensor distance = 160mm
CONCLUSIONS

In this paper, we have demonstrated that by utilizing the piezoelectric based wave propagation technique, complemented with appropriate signal processing (cross correlation and Hilbert transform) methods, the TOF of the surface waves could be correlated to the hydration process of concrete. The increase of the surface wave speed with time indicates that the mortar is going through a stiffening process. Future study could focus on establishing a parametric relationship between stiffness (Young’s modulus) of concrete and wave speed for strength characterization.

REFERENCES