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Piezoelectric-based non-destructive monitoring of hydration of reinforced concrete as an indicator of bond development at the steel–concrete interface

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ABSTRACT

Advances in piezoelectric materials have attracted interests among researchers to develop new non-destructive evaluation and monitoring techniques. In this study, piezoceramic (PZT) sensors were embedded in concrete by bonding the sensors on steel reinforcing bars to perform non-destructive monitoring. To evaluate the performance of the PZT sensors and electromechanical impedance (EMI) sensing technique, a series of experiments was carried out to monitor the bond development between steel rebar and concrete by measuring the electrical response of the PZT bonded to the steel rebar using an impedance analyzer. From the EMI measurements, the gradual adhesion between the steel rebar and fresh concrete could be detected via the measured changes in the conductance spectra of the PZT sensor bonded to the steel rebar. The bond development could be attributed to the transformation of concrete from liquid to solid state controlled by the hydration of cement and by monitoring the hydration of concrete with respect to time, the status of bonding can be estimated. The results show that the early-age development of bonding between steel rebar and concrete is affected by various factors such as varying water–cement ratio, low curing temperature and poor compaction.

1. Introduction

For a new RC structure, monitoring its early-age development can serve as a check for the quality of construction. The critical aspect for effective concrete reinforcement is the bond between the rebar and concrete [1]. The destructive methods such as pull-out [2] or break off [3] tests are commonly used to assess the bond strength. It would be very useful to develop non-destructive approaches for evaluating steel–concrete bond that can be effective and practical for field application. Among the non-destructive methods that have been developed include acoustics emission (AE) [4,5] and electrical resistance [6] methods. The AE method is feasible for field application and has been adopted to monitor the onset and progression of damage on steel rebar to concrete interaction [4]. However, the application of AE is time-consuming and the results are not always unambiguous [7]. Fu and Chung [6] investigated the steel–concrete bond interface using the contact electrical resistance method. They found that at a fixed humidity, the bond strength between steel rebar and concrete increased monotonically with increasing water–cement (w/c) ratio, while contact resistivity decreased slightly. Their work was in contrast with many studies that showed bond strength increased with increasing concrete compressive strength where increasing w/c ratio would decrease the compressive strength.

Recent development in the monitoring of structural integrity or technical conditions of structures has seen an increase in the use of piezoelectric materials. Piezoelectric materials are known to have a special property that enables them to be used for actuating and sensing applications. Compared to other types of sensors, structures bonded or embedded with piezoceramic (PZT) sensors have the advantages of structural simplicity, low cost, quick response and high reliability [8]. A promising approach, which employs PZT sensors, has emerged and shown the suitability for field application. The approach, based on the electromechanical impedance (EMI) principle, has been demonstrated successfully for monitoring damages in structures [9–14] such as pipelines, composites, bridges and concrete structures, and a number of studies have been focusing on monitoring changes in structural properties over time [15–17]. The basis of this non-destructive monitoring technique is basically to monitor variation in mechanical impedance of a structural element via electrical impedance of a PZT sensor bonded to or embedded in the host structure. The PZT functions as both an actuator and a sensor; to excite the structure and also used to measure the structural impedance. Thus, by measuring the electrical impedance of the PZT, any changes in the structural properties are captured by the coupled electromechanical impedance. Interaction of the coupled relationship between electrical and mechanical impedance can be illustrated as follows [18]:

$$Y(\omega) = i\omega\, a\left(\varepsilon_{33}^{T}(1-i\delta)-\frac{Z_s(\omega)}{Z_s(\omega)+Z_a(\omega)}d_{3x}^{2}\overline{Y}_{xx}^{E}\right) \tag{1}$$

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where $Y(\omega)$ is the electrical admittance (inverse of impedance) of a PZT transducer, ω is the excitation frequency, a is the geometric constant of the PZT transducer, ε_{33}^{T} is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, $Z_s(\omega)$ is the structure's mechanical impedance, $Z_a(\omega)$ is the mechanical impedance of the PZT, d_{3x} is the PZT coupling constant in the arbitrary x direction at zero stress, and $\overline{Y}_{xx}^{E}$ is the complex Young's modulus of the PZT at zero electric field [18]. It should be noted that the coupled electromechanical admittance $Y(\omega)$ in Eq. (1) when measured using a commercial impedance analyzer, consists of real and imaginary parts as follows:

$$Y(\omega) = G(\omega) + jB(\omega) \quad (2)$$

where G is the conductance (real part) and B is the susceptance (imaginary part). Measured conductance or susceptance spectra vary over a range of frequencies. Generally, only conductance spectrum of the PZT is usually used in monitoring applications because it is less sensitive to ambient temperature change compared to the susceptance spectrum [19]. However, the susceptance spectrum could be used to evaluate the integrity of the PZT [20].

This paper presents a new adaptation of the EMI method with an embedded PZT sensor for non-destructive monitoring of hydration of reinforced concrete as an indicator of the bond development at the steel–concrete interface. The authors had conducted an initial test [21] on a steel rebar using polymeric clay as the bonding material. The initial test results show that a PZT sensor attached to the rebar can successfully detect the bonding of the polymeric clay to the rebar and as the bonding length was increased. The aim of the present study is to show that the EMI sensing principle is a feasible monitoring approach that can be used to effectively and reliably estimate the status of bonding between steel rebar and concrete for the purpose of ensuring that optimal bonding has been attained prior to loading of reinforced concrete elements. The main advantage of the non-destructive technique is that it meets the health monitoring requirements of concrete from the fresh to the hardened state.

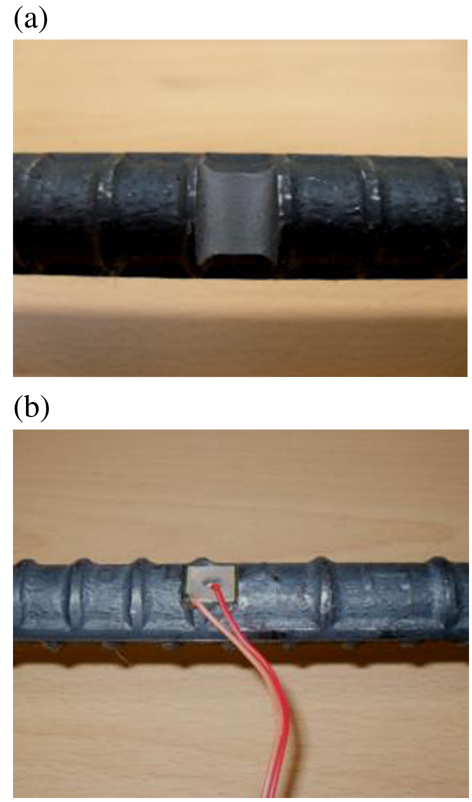

Fig. 1. (a) A flat cut on the rebar was made, (b) bonded PZT sensor.

2. Experimental setup

PZT manufactured by PI Ceramic GmbH (www.piezoceramic.com/) was used. The chosen PZT type was of “soft” materials with high permittivity, high coupling factor and high piezoelectric charge constant and the size of 10×10×0.3 mm was specifically ordered. A deformed steel rebar of 67 cm long was bonded with a PZT sensor at the mid-length as shown in Fig. 1 using epoxy adhesive and left to cure for about 24 h. After soldering the electrical wires to the PZT electrodes, the sensor was coated with epoxy putty to protect it against moisture from embedment in fresh concrete. The rebar that was attached with the PZT sensor was then installed inside a beam mold (150×150×500 mm) with the sensor positioned downwards. Fig. 2 shows the schematic diagram of the experimental setup. After mixing, fresh concrete (0.4:1.0:1.0:2.0) consisting of water, cement, fine and coarse aggregates was poured into the mold in two layers of approximately equal height with each layer consolidated by rodding. The cement used was from Ssangyong Cement as specified in KS (Korean Industrial Standards) L 5201 (Portland Cement). The measured chemical composition, physical properties and particle size of the cement are given in Table 1. The fine aggregate was river sand with specific gravity of 2.56 and water absorption of 1.37%. The coarse aggregate was crushed gravel with 19 mm maximum size, specific gravity of 2.66 and water absorption of 0.51%. The grading of fine and coarse aggregates is shown in Table 2. Immediately after concrete casting work was completed (about 10 min), the initial electromechanical (EM) admittance measurement was performed. After that, the measurements were performed at 1, 3, 6, 9, 12, 24, 72 and 168 h after casting. The specimen was only removed from the mold after 48 h. During the curing process, the specimen was covered with plastic sheet to prevent moisture loss and allowed to cure in a controlled room air (20 ± 2 °C) while additional water was provided by spraying.

3. EM admittance measurement and results

High-frequency excitation up to 400 kHz is generally used in the EM impedance or admittance measurement using PZT [19]. In this study, an impedance analyzer (Agilent 4294A) was used for providing AC voltage sweep to vibrate the PZT sensor and measure its electrical response at the same time. The impedance analyzer can be used to measure simultaneously two complimentary admittance parameters in each measurement cycle. The ‘G–B’ function was selected where G and B are the conductance and susceptance, respectively. In the experimental setup shown in Fig. 2, all data were saved in the memory of the impedance analyzer after each measurement. The data were later transferred from the impedance analyzer to a laptop computer by a simple data acquisition technique using a cross cable.

Fig. 3(a) shows the conductance spectrum of the free PZT and of the PZT after bonding to the steel rebar. The act of bonding the PZT on the steel rebar caused the conductance values to drop significantly. The selected frequency range should include the resonance peak to facilitate the detection of small structural changes. In Fig. 3(b), it is shown that the first resonance peak of PZT has shifted to 130 kHz after bonding compared to 170 kHz before bonding (free condition). The bonded PZT spectra which were acquired separately over a few days are shown to be well repeatable. This is because the measurements were taken under nominally the same environment. However, the effect of temperature on the conductance spectra have been found to be closely related to the thickness of bonding, as an increase in temperature may reduce the stiffness of the bonding layer, thus affecting strain transfer [22]. Therefore, it is important to verify the integrity of the bonded PZT from time to time during monitoring to ensure measurement reliability. In this paper, a diagnostic technique

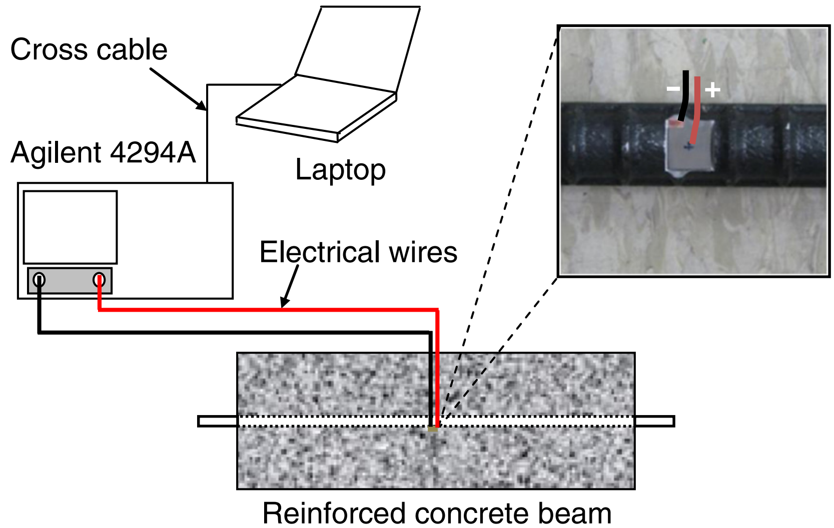

Fig. 2. Schematic diagram of the measurement system.

proposed by Park et al. [20] was used to check the performance of the embedded PZT in concrete during curing process. The results are reported in Section 5.

4. Monitoring changes in the conductance spectrum

The second term in Eq. (1) includes both the mechanical impedance of PZT and the host structure. When the properties of the host structure are altered, the mechanical impedance of the PZT will be shifted. Any changes in the conductance spectra (such as magnitude and frequency) are attributed to the changes in the structure. In order to monitor the changes in concrete during curing, the shift in the magnitude and frequency of the conductance spectra was tracked at the resonance of the peak or valley. Fig. 4 shows the acquired conductance spectra of the embedded PZT at the monitoring time, while Fig. 5 shows the magnitude and frequency shifts versus curing time. The initial conductance spectrum, which was acquired immediately after the completion of the concrete casting work, shows that the resonant frequency of the PZT has shifted further from 130 to 125 kHz. After the concrete placement, the conductance spectrum slowly changed its shape where it can be seen in Fig. 4 that the peak conductance reduced and after that the conductance spectrum moved to the right.

As far as early-age bond development between steel rebar and concrete is concerned, bonding mechanism very much depends on the concrete characteristics. In other words, the bond development can be attributed to the transformation of concrete from liquid to solid state controlled by the hydration of cement. By monitoring the hydration of concrete with respect to time, the status of bonding between steel rebar and concrete can be monitored. In Fig. 5, the magnitude reduced sharply up to the 3rd hour, while the resonant frequency remained constant. Then, a sudden change in the magnitude and frequency was observed between the 3rd hour and the 9th hour. The sudden change could suggest the onset of rigidity in the fresh concrete. It is believed that rapid bond development occurred during this period when the concrete lost its plasticity and stiffened to a certain degree. After the 3rd hour, the conductance spectrum shifted rightwards. This could suggest that the hardening of concrete has begun and the gradual increase in the resonant frequency reflects the continued bond development over time. Thus, from the observations, it is clearly shown that bond development is significantly influenced by concrete age. According to the pull-out test results reported in Ref. [23], the bond strength at 1, 3 and 7 days was 26, 57 and 68%, respectively, of that at 28 days. As shown in Fig. 4, significant changes in the conductance spectrum were noticeable up to the 72nd hour. Based on the results, it can also be said that for the concrete mix, 72 h of curing was enough for achieving a reasonable bonding between steel rebar and concrete.

Table 1
Measured chemical composition, physical properties and particle size of cement.*

Chemical composition	(%)
CaO	62.14
Al_2O_3	5.47
SiO_2	21.98
Fe_2O_3	3.38
K_2O	–
MgO	2.56
SO_3	1.80
Cr_2O_3	–
PbO	–
Physical properties	
Specific gravity	3.15
Surface area (m^2/g)	0.35 (Blaine)
Particle size	(μm)
10%	3.33
50%	16.92
90%	45.48

* Data obtained from EERC, KAIST.

Table 2
Aggregate grading.

Sieve size (mm)	Percent passing (%)	
	Fine aggregate	Coarse aggregate
25	–	100
19	–	100
12.5	–	43.7
9.50	–	4.5
4.75	100	0.4
2.36	93.5	0
1.18	75.4	–
0.6	48.7	–
0.425	26.1	–
0.3	26.1	–
0.15	5.2	–

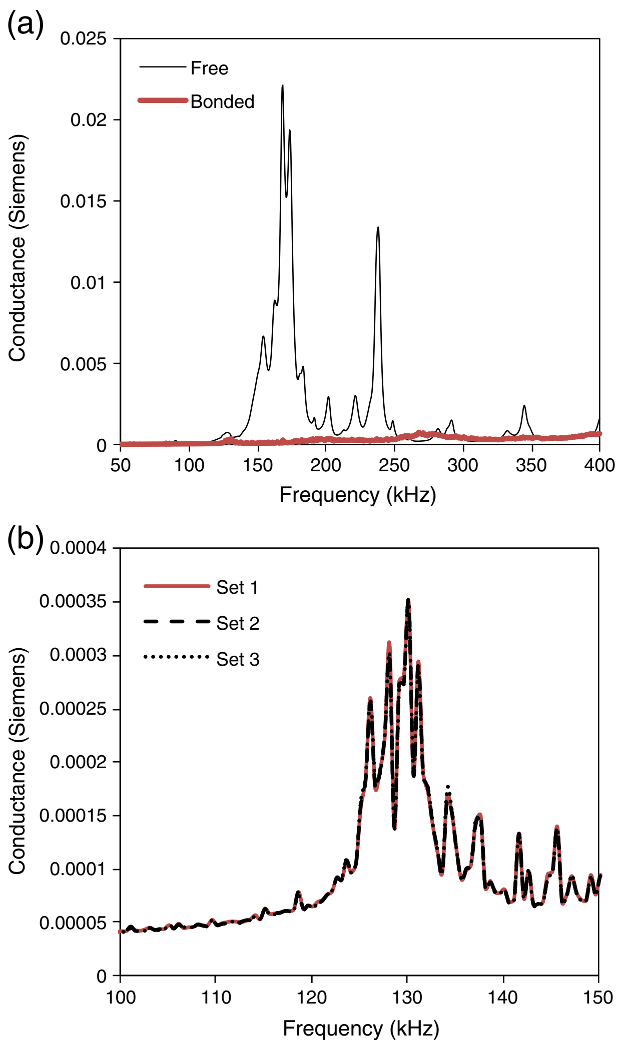

Fig. 3. (a) Comparison between free and bonded PZT, (b) repeatability of the bonded PZT spectra.

5. PZT performance assessment

The slope of the conductance spectra was used to assess the bonding condition of the PZT sensor. It can be seen from Fig. 6 that the surface bonded PZT has lower slope compared to the free PZT due to the bonding layer effect between the PZT and the steel rebar. By monitoring the slope of the conductance spectra at a lower frequency range (40–20,000 Hz), it is possible to assess bonding condition and PZT performance [20]. In Fig. 6, a large increase in the slope of the conductance spectrum signifies bonding defects, while degradation in PZT performance will cause a decrease in the slope. In the experiment, the effect of curing on susceptance slope of the embedded PZT at different curing times was investigated. Fig. 7 shows that the susceptance slopes measured during the curing process were very much the same, except at the 12th hour. A closer look at the slope values reveals that the slope decreased after the concrete placement but slowly increased and reached the peak value around the 12th hour and finally decreased close to the slope at the time before concrete placement.

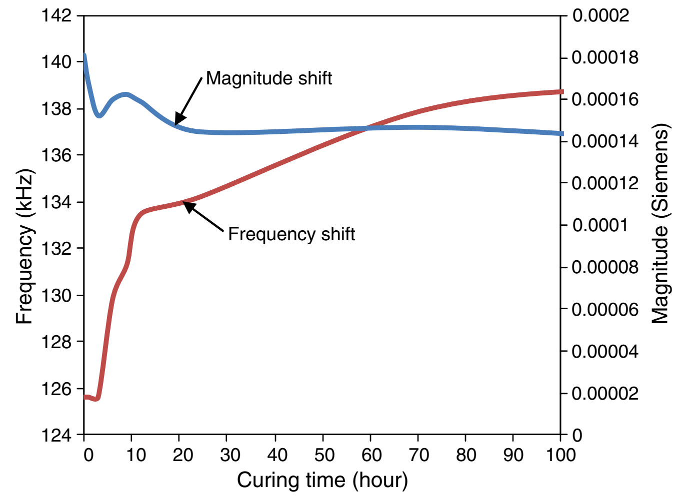

Fig. 5. Magnitude and frequency of the conductance spectra at resonance.

The slope variation during the initial curing could be due to the hydration heat from the reaction between cement and water. It is noted that the susceptance slope of PZT can be influenced by the temperature of the environment. Previous study [24] has shown that the relationship is linear if the ambient temperature is below the curie temperature of the PZT. From the findings [24], it is estimated that the slope would change by about 1% per °C due to temperature change. Therefore, based on the results of the susceptance measurements, the embedded PZT is shown to survive the curing pressure and hydration heat.

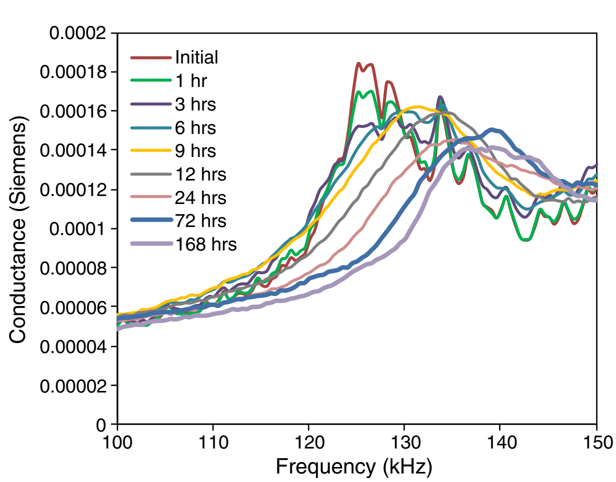

Fig. 4. Conductance spectra at different curing times (w/c ratio = 0.40, T = 20°C).

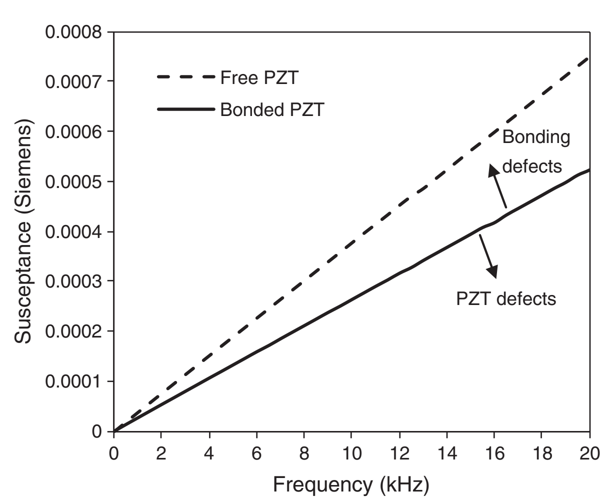

Fig. 6. Assessment of PZT performance based on susceptance spectrum.

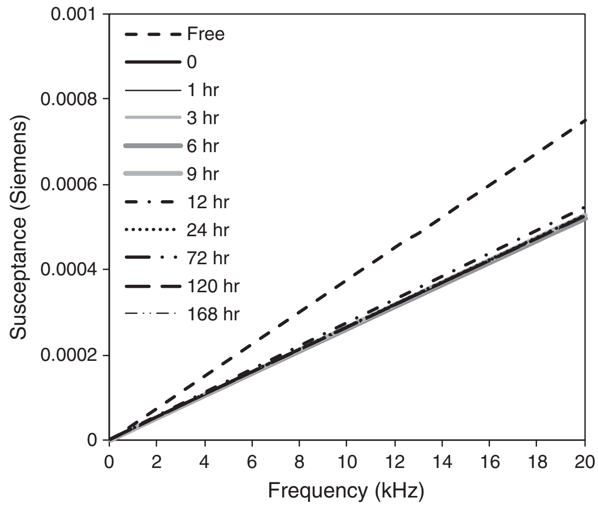

Fig. 7. Susceptance spectra at different curing times.

6. Effects of varying water–cement ratio, curing temperature and compaction

So far, the results show that the EMI approach could be a viable method for evaluating the gradual bonding between steel rebar and concrete during construction. The results reflect the importance of early-age development of concrete on bonding between steel rebar and concrete. In a further study, the aim was to investigate the effects of varying w/c ratio, curing temperature and compaction on the conductance spectra of PZT. The experimental results of the further study are presented in Fig. 8. The comparisons were made based on percentage frequency shift, which was obtained by calculating the frequency shift with respect to that of the initial resonant frequency.

Fig. 9 shows the percentage frequency shift for three different w/c ratios versus curing time. All specimens were cured at controlled air temperature of 20 °C. In Fig. 9, all three w/c ratios show a period of almost zero frequency shift initially, followed by a rapid development of frequency shift, and then slower development after that over time. The strength of concrete is known to influence the interfacial bond strength with steel rebar significantly [1], while the strength of concrete is known to decrease with increasing w/c ratio [25]. This suggests that the development of concrete strength surrounding the rebar is an important factor to the development of bond at the steel–concrete interface. It is shown that the development of frequency shift of the PZT, used as an indicator of bond development during curing, show a good correlation with varying w/c ratios. The effect of higher w/c ratio can be seen where the w/c ratio of 0.40 had a shorter period of inactivity, while a slow rise in the frequency shift for w/c ratios of 0.45 and 0.50 is observed. During concrete mixing, higher w/c ratio makes the cement particles wider apart. Due to the loose microstructure, mixes with high w/c ratios would set slower and gain lower bonding strength.

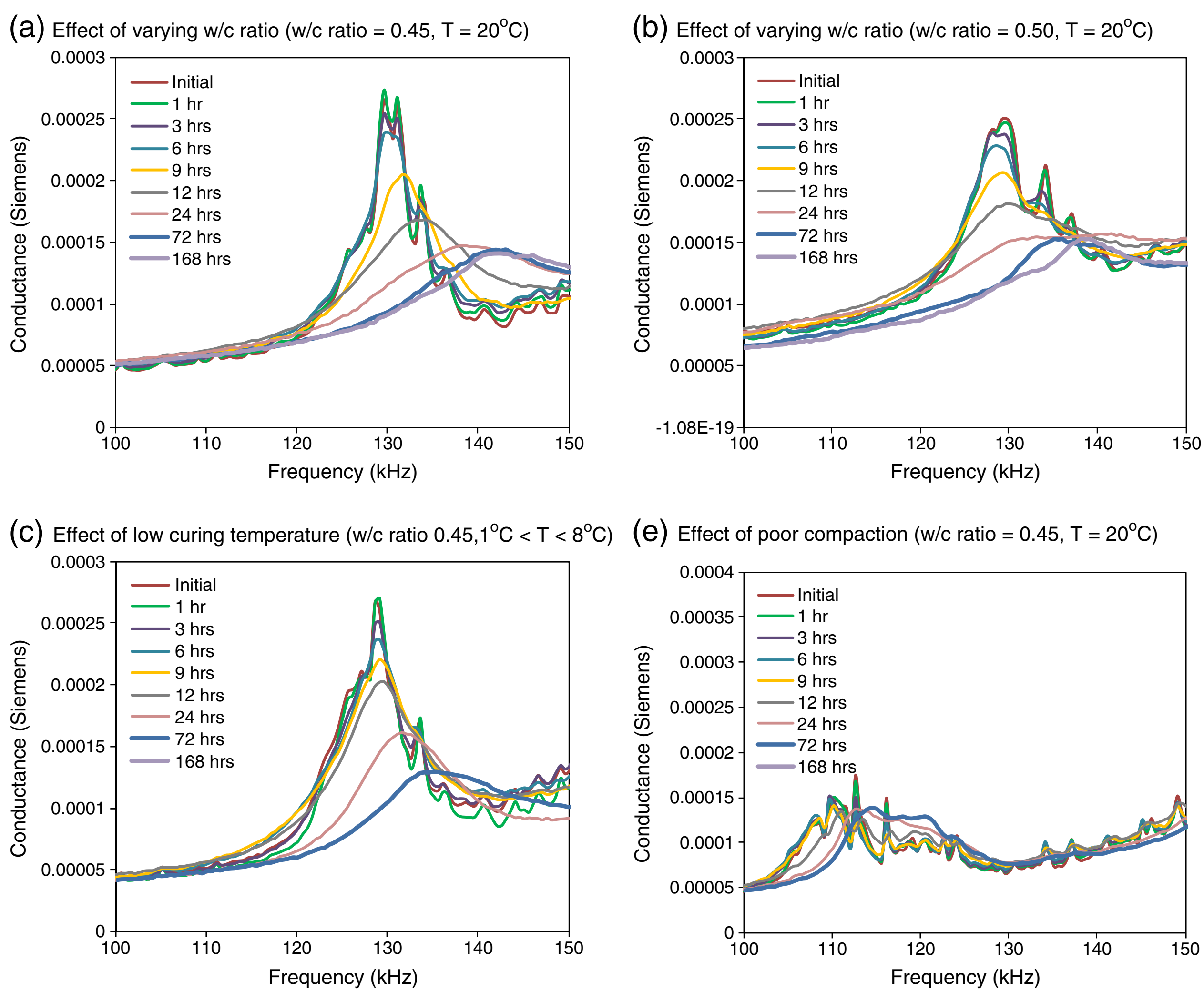

Fig. 8. Experimental results of the further study.

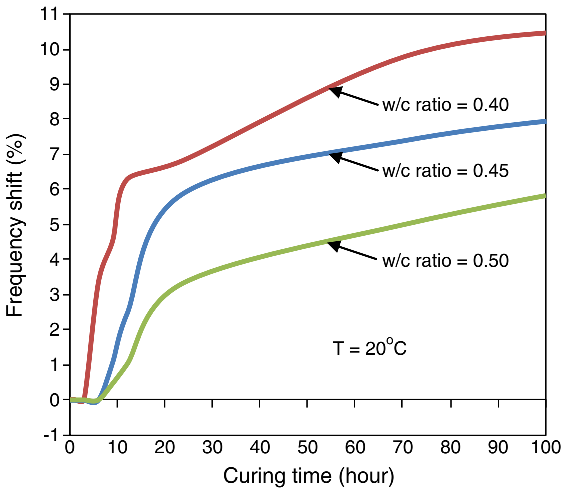

Fig. 9. Effect of varying w/c ratio.

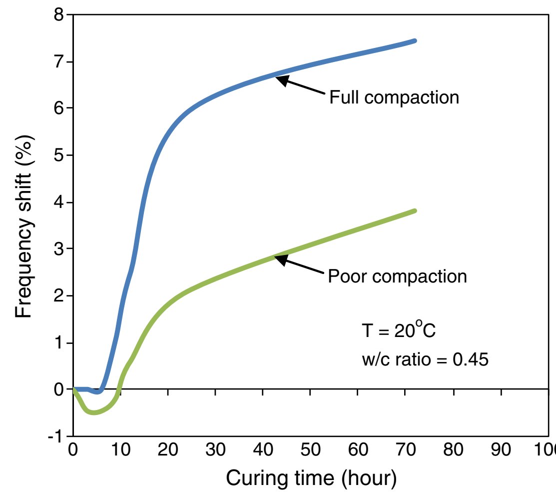

Fig. 11. Effect of poor compaction.

Fig. 10 shows the effect of curing temperature on the frequency shift of the conductance spectra of PZT. Both mixes had the same w/c ratio of 0.45. One specimen was cured at controlled air temperature of 20 °C in the curing room, while the other was exposed to cold weather during winter with the approximate temperature of not greater than 8 °C but above 1 °C. The way temperature influences bond strength between steel rebar and concrete is in much the same manner as it does to strength development of concrete [26]. In Fig. 10, it is shown that the low curing temperature affects the rate of frequency shift. Therefore, it is reasonable to assume that due to the delayed setting and strength gain of concrete the bond development was slower under the low curing temperature.

The effect of compaction was compared between two mixes of the same w/c ratio of 0.45 cured at constant air temperature of 20 °C. The difference between the two was how the concrete was placed and compacted. A fully compacted specimen followed the standard compaction and finishing procedure, while only minimal compaction was applied during concrete placing for the poor compacted specimen. Fig. 11 shows how compaction effort may influence the conductance spectra. The frequency shift development for the poor compacted specimen is interesting, where during the initial period up to the 3rd hour, the resonant frequency shifted to the left resulting in a negative rate of frequency shift. The probable reason could be due to the non-uniform distribution of fresh concrete in the mold. The lack of bonding across the interface between steel rebar and concrete was evident from the lower amount of frequency shift demonstrated by the poor compacted specimen as shown in Fig. 11.

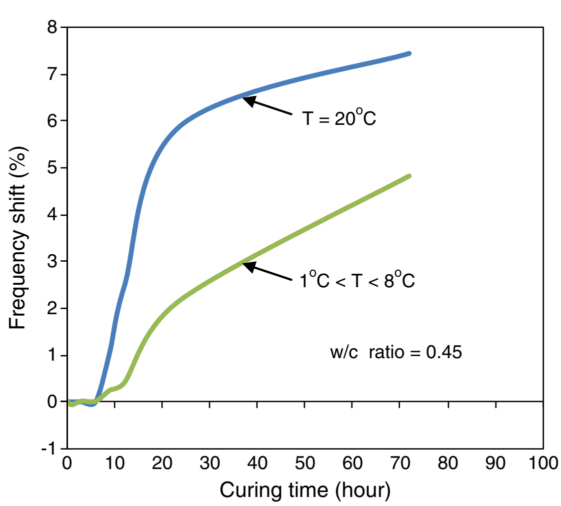

Fig. 10. Effect of low curing temperature.

7. Conclusions

In this study, an adaptation of the EMI technique with embedded PZT sensors for monitoring gradual bonding between steel rebar and concrete during early-age development has been investigated. The changes in conductance spectra of PZT were monitored by exciting the PZT at high frequencies using an impedance analyzer. The advantage of this new technique is that early-age characteristics of steel–concrete bond can be evaluated non-destructively. The following conclusions can be drawn from this study:

(1) From the EMI measurement, the early-age development of bonding between steel rebar and concrete could be monitored via the measured changes in the conductance spectra of the PZT sensor bonded to the steel rebar. It is postulated that the gradual changes in concrete controlled by the hydration process could be used as an indicator of bond development at the steel–concrete interface.

(2) Susceptance slope of the embedded PZT at different curing times is shown to decrease a little after the concrete placement but slowly increased and reached the peak value around the 12th hour and finally decreased close to the slope at the time before concrete placement. By monitoring the susceptance slope of the embedded PZT, the sensor is shown to survive the curing pressure. It can be said that the slope variation is likely due to the hydration heat from the reaction between cement and water.

(3) The results show that the early-age development of bonding between steel rebar and concrete are affected by various factors. The development of frequency shift of the PZT, used as an indicator of bond development during curing, shows a good agreement with varying w/c ratios. The results show that reinforced concrete with high w/c ratios would likely to gain lower bonding strength than low w/c ratio due to the loose microstructure at the steel–concrete interface. The lower rate of frequency shift may suggest that bond development is progressing slowly and one of the reasons could be due to low curing temperature. Finally, the lower amount of frequency shift by the poor compacted specimen compared to the fully compacted specimen demonstrated that poor compaction may result in lack of bonding across the interface between steel rebar and concrete.

Acknowledgments

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