Steel Bar corrosion monitoring based on encapsulated piezoelectric sensors

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Abstract. The durability of reinforced concrete has a great impact on the structural bearing capacity, while the corrosion of steel bars is the main reason for the degradation of structural durability. In this paper, a new type of encapsulated cement based piezoelectric sensor is developed and its working performance is verified. The consistency of the finite element simulation and the experimental results shows the feasibility of monitoring the corrosion of steel bars using encapsulated piezoelectric sensors. The research results show that the corrosion conditions of the steel bars can be determined by the relative amplitude of the measured signal through the encapsulated piezoelectric sensor.

1. Introduction
Steel bars play an important role in strength, durability, prevention of crack propagation and other aspects in a structure. Steel corrosion can cause cracks inside the concrete along the bars, greatly reducing the structural bearing capacity and service life. Therefore, effective monitoring methods are needed for reinforced concrete structures to assess the extent of steel corrosion. The following represent the more mature steel corrosion detection and monitoring methods at present: the half-cell half-potential method, the concrete resistivity method, chloride ion content testing, concrete corrosion cracks sizing and ultrasonic parameters assessment [1]. These methods are indirect measurements, and can only qualitatively describe the degree of corrosion; they cannot achieve quantitative on-line monitoring. For large structures it is even more difficult to achieve all-round monitoring.

The piezoelectric sensor has good linearity, fast response, ease of processing, low cost and other advantages, giving the piezoelectric sensor growing popularity in health monitoring. In order to monitor the early curing strength of concrete pouring, Yang Xiaoming, Li Zongjin et al. [2] developed a new cement-based sensor and researched the relationship between the cement-based piezoelectric sensor’s frequency independence and load amplitude with the voltage amplitude. They demonstrated the testability of the cement-based sensor on concrete structures. However, research in corrosion monitoring with piezoelectric sensors is still in the experimental stage, and there is also a lack of corresponding research in the aspect of uniform corrosion of steel bars.

2. Encapsulated piezoelectric performance research

2.1. Encapsulated piezoelectric sensor production process
In this paper, PZT5 piezoelectric ceramic tiles are used. When the piezoelectric sensor and the ceramics work together in concrete, the encapsulating material does not change the performance of the concrete
or the sensor. Based on this principle, AB glue was first used to encapsulate the PZT chip, then neat cement, then it was coated with conductive silver glue for an electromagnetic shielding effect. The performance parameters are in Table 1.

| Table 1. PZT5 bare chip parameters |
|-------------------------------------|
| Size (mm) | Piezoelectric coefficient d33 (pC/N) | Relative dielectric constant | Curie temperature (°C) | density (g/cm^3) |
| Φ10×1.0 | 670 | 5800 | 200 | 7.45 |

Production process:
(1) The wire is joined. Soldering is used to join the PZT5 bare chip and wire. For the receiving sensor, the aluminum of the shielded wire is twisted together, and then secured to the outside of the sensor, thereby shielding the noise.
(2) The PZT5 bare chip is encapsulated. After evenly mixing the AB glue in a 1: 1 ratio, the exposed PZT copper wire is completely encapsulated to prevent a short circuit of the sensor due to water entering, and after curing, conductive silver paste applied to the surface (see Figure 1-a).
(3) The cement base is produced. The encapsulated PZT pieces are put into a 20 × 20 × 20 mm square mold, the water-cement is added in a ratio of 0.5 of the cement paste, and cured for a period of time (see Figure 1-b).
(4) Shielding is carried out. Conductive silver paste is applied to the outer surface of the cured cement base, and the shielded wire is glued to the sensor surface, Figures 1-c show the receiving end of the piezoelectric sensor after shielding.

![Fabrication process of encapsulated piezoelectric sensor](image1)

**Figure 1.** Fabrication process of encapsulated piezoelectric sensor

2.2. Encapsulated piezoelectric sensor shielding performance
The encapsulated piezoelectric sensor and a piezoelectric sensor without shielding processing are directly connected to the oscilloscope, and a signal can be obtained as shown in Figure 2. It can be seen that after shielding the noise signal basically disappears. At the same time, after FFT conversion it can be seen that the noise signal interference frequency is about 50 Hz, and the peak is about 1.5 mV.

![Environmental noise signal](image2)

**Figure 2.** Environmental noise signal
2.3. Encapsulated piezoelectric sensor stability

The encapsulated piezoelectric sensor is used for continuous monitoring of the signal changes during the hydration process of the neat cement mortar, and the signal and waveform is read every 30 minutes. The monitoring process is shown in Figure 3.

The average values of two simultaneous test groups are taken, and the results are basically similar. Due to limited space, only the average is shown as an example. The results are shown in Figure 4.

![Figure 3. Gravel and cement hydration](image)

![Figure 4. Mortar amplitude time curve](image)

When the ultrasonic signal from the encapsulated piezoelectric sensor propagates in the neat cement mortar, it demonstrates stability after the first increase. At about two and a half hours there is a greater decline in signal amplitude, and the signal tends to stabilize after 10 hours. This is due to the fact that the strength has increased after cement hydration, resulting in limited deformation of the sensor, so that the sensitivity of the sensor to the signal falls [3]. These results indicate that the encapsulated piezoelectric sensor can maintain its stability in the cement mortar after standing for 10 hours.

3. Steel corrosion monitoring experiment

3.1. Reinforced cement mortar specimen production

A number of steel bar - cement mortar specimens were produced, their mixture ratios and size are shown in Table 2. Ordinary Portland cement of grade 32.5, sand and ribbed steel bars with a diameter of 10 mm and length of 140 mm were used. The three parallel identical specimens produced were monitored. The completed specimens are shown in Figure 5.

3.2. Steel rebar corrosion monitoring

The pre-made steel corrosion specimen was placed in a 5% concentration NaCl solution and soaked for 48 hours with the solution making full contact with the steel to enable corrosion to occur. Then the specimen was connected with the DC power source. The DC power source current was set to 0.1 A, and the data was measured at every 2% of the theoretical corrosion rate, i.e. the data was read once every 15.5 hours. The monitoring continued for 155 hours. For each working condition a sinusoidal excitation signal was used, the voltage amplitude was plus or minus 5 V. Each frequency screening was performed, preferably at a large amplitude band, due to the fact that the high frequency amplitude of these piezoelectric ceramics is rather large. Thus, this monitoring used the ultrasonic frequency band of 180-200 kHz for continuous testing which is commonly applied in non-destructive testing in the structural health monitoring field. Figure 6 shows the experimental setup for uniform corrosion monitoring of reinforced bar.

The tightness of the attachment of the sensor and steel rebar will affect the sensitivity of the sensor to the received signal. This can cause a system error in the measurement values of the experiment and make the subsequent horizontal comparison difficult. In order to eliminate this error, the relative amplitude (ξ) as defined herein is the ratio of the corresponding monitor signal amplitude of any corrosion rate (A_T) and the monitor signal amplitude of the corrosion rate at time 0 (A_0), namely:
\[
\xi = \frac{A_T}{A_0}
\]  

(1)

Table 2. Sample size

| Mix Ratio | Specimen size | Compressive strength (MPa) |
|-----------|---------------|---------------------------|
| Cement 2  | 180×40×40     | 26.97                     |
| Sand 2    |               |                           |
| Water 0.5 |               |                           |

Corrosion monitoring was performed for the three parallel identical specimens, and the signals collected underwent bandpass filtering noise reduction to extract the amplitude of each frequency monitoring signal. The curve of each self-monitoring signal amplitude over power-on time was obtained, the relative amplitude \( \xi \) defined using formula (1) was used, and finally the curve of relative amplitude over power-on time was obtained. After obtaining the respective relative amplitude - corrosion rate curves, the three specimens were averaged, and the final average relative amplitude – power-on time curves and average relative amplitude - corrosion rate curves were obtained. These are shown in figures 7 and 8.

Figures 7 and 8 are the relative magnitude - time curve and relative amplitude - corrosion rate curve, respectively. It can be seen from the figures that:
(1) When the power-on time is less than 20 hours and the actual corrosion rate is at 2% or less, the relative amplitude is between 0 and 1, and there is a decrease. When the steel begins to corrode, the steel surface exhibits localized pitting, and the signal amplitude is reduced when reaching the terminal due to defects in the surface causing signal emission passing through the steel bar [4,5]. Another possible reason is that before the specimen starts cracking, rust expansion increases the adhesive force.
between the steel and concrete, so that the adhesive force between steel and concrete does not drop and actually slightly increases [6].

(2) When the power-on time is between 20 and 80 hours, the actual corrosion rate is 2% to 7%, the relative amplitude is between 1-3, and the relative amplitude greatly increases as the corrosion rate increases. This is because the accumulation of rust in the corrosion process can cause the effective diameter of the steel rebar to decrease, and form a corrosion layer at the rebar and mortar interface, causing the adhesive force to gradually drop [5]. After the adhesive force between the rebar and mortar drops, debonding occurs in both, the original signal transmitted from the rebar surroundings to the mortar is gradually reduced due to the decline of the degree of adhesion in both, and the signal propagated from the steel is thereby increased3[7]. The relative signal amplitude reaches the maximum value, marking the point where the steel and mortar are completely debonded, and the formation of a complete layer of rust.

(3) When the actual corrosion rate is between 7-13%, the relative amplitude is between 2 and 3, and the relative amplitude tends to be stable and decreases slightly as the corrosion rate increases. It may due to that with the further corrosion of the steel, the mortar surrounding the steel rebar encounters greater expansion force and cracking, resulting in attenuation in the high-frequency monitoring signal due to the crack damage, and with the deepening and extension of the cracks the amplitude decreases. Therefore, the corrosion rate can be determined according to the relative magnitude and change trends at certain times.

4. Conclusions
(1) The encapsulated piezoelectric sensor performance meets the corrosion monitoring requirements. The shielded encapsulated sensor can shield the surrounding noise signals with a frequency of 50 Hz, and amplitude of about 1.5 mV. After cement-base coating it is able to reduce each frequency signal amplitude, and can attenuate signal amplitude in the water by about 94.8%, while as the size of the cement base increases, the amplitude attenuation also gradually increases.

(2) From the experimental results, it can be seen that the experimentally measured relative amplitude – corrosion rate curve and the simulated curve show a generally consistent tendency, but there is still a certain discrepancy. When the corrosion rate is less than 7%, the difference between both is rather small. When the corrosion rate is 0-2%, the relative amplitude decreases; when the corrosion rate is 2-7%, the relative amplitude increases along with the corrosion rate. When the corrosion rate is greater than 7%. This corrosion rate satisfies the requirements of structural safety monitoring in actual projects.

5. References
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