Numerical study of monitoring of early-age concrete strength development using PZT induced stress wave

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Abstract. The purpose of this paper is to verify the validity of concrete strength monitoring method based on piezoelectric wave dynamic technology by the numerical simulation ways. Since the elastic modulus of concrete increases linearly with its strength, the elastic modulus of concrete at different ages is set to simulate its strength growth. The stress wave is transmitted and received by the piezoelectric sensor embedded in concrete, and the stress wave energy value is taken as the strength identification parameter, and its variation trend with the strength is analyzed. The results show that with the increase of concrete strength, the energy value of monitoring signal has a monotonically decreasing trend. In the early stage of concrete, the monitoring signal energy decreases at a large rate and then tends to be flat. In the early stage, the strength growth rate of concrete is faster, and tends to be flat in the later stage. Furthermore, the curve of capability ratio and strength ratio was established, and the two presented good linear lines. The results of this paper show that the concrete strength monitoring method based on pressure wave dynamic technology can be used to monitor the concrete strength.

1. Introduction

Concrete is the most widely used building material in the field of construction. It has been widely applied to the construction of various buildings and structures.

The quality of concrete material is closely related to structural safety. However, in the process of construction, it has been observed that the ultimate strength of the concrete is lower than the expected design strength because of inadequate maintenance and improper construction method, thus leaving hidden danger to the safety of the structure. Therefore, the necessary monitoring of concrete strength is one of the important measures to control the quality of the project.

The methods of spring back value, ultrasonic and compressive strength are widely used in the detection of concrete strength at home and abroad [1, 2].

Although these methods are widely used and mature in technology, there are still some limitations in the practical application process. For example, the spring back value method is susceptible to the influence of concrete aggregate, hence the result is not accurate. The required equipment of ultrasonic method is expensive.

In the compressive strength test method, the test block and the structure cannot be maintained under the same conditions sometime. Therefore, a new method is urgently needed to remedy the deficiency of traditional methods.

In recent years, health monitoring technology based on piezoceramic, represented by lead zirconatetitanate (PZT), has attracted extensive attention in the field of concrete health monitoring,
especially in the identification of concrete cracks and damage, and has achieved rich results [3 - 8]. The high sensitivity of piezoceramic materials to concrete state makes it possible for them to be used for concrete strength monitoring [9 - 12].

In this paper, the validity of stress wave method for concrete strength monitoring is verified by numerical simulation. At the same time, the corresponding relationship between concrete strength index and monitoring signal identification parameters is established.

Compared with the traditional concrete detection method, the concrete strength monitoring method based on piezoelectric intelligent materials can realize the in-situ monitoring of concrete strength for the whole age, so as to achieve the purpose of quality control.

This is of great significance to ensure that the actual strength of concrete materials is determined for the state and safety of the structure.

2. Principle of concrete strength monitoring based on piezoelectric wave method

2.1. Piezoelectric smart aggregate

Piezoelectric smart material is one of the main types of smart materials and has piezoelectric effect. Because of the spontaneity and reversibility of piezoelectric effect, piezoelectric smart materials can be made into typical bidirectional sensor elements, and used as signal transmitting actuator and receiving sensor.

Based on this characteristic, piezoelectric sensors have been widely used in the fields of ultrasonic, communication, aerospace, radar and detonating, which are combined with laser and infrared technology, and turn into an important device for the development of new technology and high technology.

The application of piezoelectric ceramic materials in the health monitoring of concrete structures is a new research direction in the academic circle.

The piezoelectric ceramic sensor has many advantages, such as low energy consumption, high sensitivity, fast response, low cost and light weight, so it has a wide application prospect in the field of health monitoring of concrete structures.

However, the enormous structure and complex construction process of the concrete structure make the technology encounter many unavoidable problems. Especially, the material of the piezoceramic is more brittle.

For instance, when directly embedded in the main structure during the construction process, it is easy to damage the piezoelectric ceramic.

Moreover, the service period of concrete structures is longer, which often takes decades or even hundreds of years, and this requires the sensor to have better durability in order to continuous work in a long time.

In addition, piezoelectric ceramic sensors are very sensitive to environmental changes, and the changes in temperature and humidity may affect the measurement results of sensors.

In order to solve the above problems, Song et al. developed the concept of "Smart Aggregate" (SA). The SA is used as the main component of structural health monitoring and embedded in the structure. The steps of the PZT patch cast into the form of SA are shown in figure 1.

The PZT patch welded wire was put into steel mould. Then, epoxy resin was cast into the steel as packaging layer, which can improve the brittleness of PZT patch and isolate the influence of humidity, water and acid-base environment on the performance of PZT patch.

This will not affect the function of PZT, and to a certain extent instead, protect the piezoelectric ceramic sheet, and increase the life of the sensor. The steel mould makes SA with anti-noise properties.
2.2. The basic principle of detecting concrete strength by piezoelectric wave method

A couple of SAs buried in concrete specimen can form a monitoring group. One SA generates stress wave as a signal transmitter, while the other receives stress wave as a signal receiver. By analyzing the variation of the propagation parameters of the received stress wave such as wave shape, amplitude or frequency, the state change of the medium in the propagation path of the stress wave can be deduced.

The propagation parameters of the stress wave are closely related to the properties of the propagating medium. The generation of the stress waves is the result of the mutual movement between the particles, which is closely related to the elastic connection between the particles, that is, it is related to the elastic density and elastic modulus of the propagating medium. After the concrete is poured and formed, with the maintenance process proceeding, the initially mobile liquid mixture will become the final solid form through hydration reaction.

The most important change of concrete state characteristics is that the strength value has been increasing, and the mechanical parameters such as elastic modulus of concrete will also increase. Combined with the analysis of the stress wave changes and the mechanical properties of concrete, the monitoring signals collected by SAs should be constantly changing before the hydration reaction of concrete is not completed.

By determining and analyzing the changes in the parameters of these acoustic signals, the information about the state of concrete is mastered, so as to realize the monitoring and backstepping of the strength state of the concrete.

3. The establishment of finite element model of concrete beams embedded with PZT patches

3.1. The finite element model of concrete beam embedded with PZT patches

A concrete beam model which size is 150 mm×150 mm×600 mm is used in research word. The size of two built-in PZT patches is Φ20×1 mm. The distance between two PZT patches is 500 mm, which is located at the center line of 50 mm at both ends of concrete.

The model and the locations of PZT patches are shown in figure 2. The meshing of the three-dimensional finite element model of concrete beams with embedded PZT patches is shown in figure 3.
Three strength grades of concrete are studied. The relationship between age and modulus of elasticity of C30 and C40 can be described by equation (1):

$$E(t) = 37.5e^{-0.6/t}$$  \hspace{1cm} (1)

The relationship between age and modulus of elasticity of C50 can be described by equation (2)

$$E(t) = 38.2e^{-0.3/t}$$  \hspace{1cm} (2)

where $E(t)$ is elastic modulus function of $t$, and $t$ is the time with a unit of day. Considering medium damping, the concrete material is assumed to be a homogeneous elastic medium with Rayleigh damping to compensate for the effect of microstructures on stress waves.

**Figure 2.** Model size schematic.

3.2. Simulating method of concrete strength increase

The concrete model is simplified to homogeneous elastic material, and the influence of aggregate on the stress wave can be neglected. Some studies indicate that there is a linear relationship between concrete strength and its elastic modulus as shown in figure 4.

This means the growth of concrete strength is bound to increase with the elastic modulus. Based on the relationship between concrete strength and elastic modulus, this numerical simulation will establish a concrete strength growth model, by changing the elastic modulus of concrete. The relationship between age and elastic modulus under different strength grades is described as equation (1) and (2).

The concrete strength models of 3d, 7d, 14d and 28d are established in turn. Therefore, in order to simply simulate the change of concrete strength, only the elastic modulus, Poisson’s ratio and density of concrete are considered when setting parameters.

**Figure 3.** Mesh generation of model.

**Figure 4.** Relationship between compressive strength and modulus of elasticity of concrete.
3.3. Constitutive relationship setting of PZT
The property density of the piezoelectric material is 7600 kg/m\(^3\), and the elastic modulus and dielectric constant are orthogonal. The vibration direction of PZT pieces material is defined as vibration along the thickness direction, that is \(D_{33}\) direction. The PZT pieces embedded in concrete is in the second boundary condition, namely mechanical clamping and electrical short circuit.

The constitutive equation can be written in equation (3):

\[
\begin{align*}
T &= e^E S - e^E \\
D &= eS + \varepsilon^S E
\end{align*}
\]

where \(T\) and \(D\) are stress and potential tensor; \(S\) and \(E\) as strain and electric field intensity tensor; \(e^E\) and \(\varepsilon^S\) are elastic stiffness constants and node constant matrices; \(e\) and \(e^T\) are the transposed matrixes of piezoelectric stress constant matrix and piezoelectric stress constant matrix.

The intermediate stiffness matrix is \(e^E\), the piezoelectric stress constant matrix \(e\) and the dielectric constant matrix are \(\varepsilon^S\), as equations (4) - (6):

\[
[c] = \begin{bmatrix}
126 & 77.8 & 74.3 & 0 & 0 & 0 \\
77.8 & 126 & 74.3 & 0 & 0 & 0 \\
74.3 & 74.3 & 115 & 0 & 0 & 0 \\
0 & 0 & 24.1 & 0 & 0 & 0 \\
0 & 0 & 0 & 25.6 & 0 & 0 \\
0 & 0 & 0 & 0 & 25.6 & 0
\end{bmatrix} \times 10^9 \text{N/m}^2
\]

\[
[e] = \begin{bmatrix}
0 & 0 & -5.2 \\
0 & 0 & -5.2 \\
0 & 0 & 15.1 \\
0 & 0 & 0 \\
12.7 & 0 & 0 \\
0 & 12.7 & 0
\end{bmatrix} \text{C/m}^2
\]

\[
[e^T] = \begin{bmatrix}
6.46 & 0 & 0 \\
0 & 6.46 & 0 \\
0 & 0 & 5.62
\end{bmatrix} \times 10^{-9} \text{F/m}
\]

3.4. Application and acceptance of signals
In the model, one PZT (PZT1) patch is used for signal transmission. The other PZT (PZT2) patch is used to receive the signals. The pulse wave is used as monitoring signal since it is sensitive to crack damage of concrete.

Signal frequency is also an important factor to be considered, which will affect signal sensitivity and propagation distance. Generally, propagates length of the high frequency signal is short, while the propagates length of low frequency signal is long. Because the size of concrete members in buildings is usually large, it is appropriate to select low frequency.

The signal parameters are shown in detail in table 1.

| Signal type   | Amplitude | Frequency                  |
|---------------|-----------|----------------------------|
| Pulse wave    | 5v        | 500 Hz, 1 kHz, 3 kHz, 5 kHz, 10 kHz |

Table 1. Signal types and related parameters table.
4. Equations and mathematics. Numerical simulation and results analysis

4.1. Monitoring signal and working condition selection

The processes of PZT patches transmitting and receiving signals are simulated. It can be seen from the propagation law of displacement nephogram that: a waveform pulse is generated as soon as PZT1 is stimulated.

With the wave diffuses around, the waveform separates two wave packets. The wave that travels faster is the P-wave and the slower one is S-wave. The displacement nephogram of the wave at different time during its propagation is shown in figure 5. With the wave propagation, there will be reflection wave and other clutters.

![Propagation displacement cloud pattern of wave in the model.](image)

Therefore, it can be judged that the waves PZT2 received were complex which were the superposition of multiple morphological waves. But the head wave received by PZT2 must be the P-wave, because it propagates fastest. Moreover, the P-wave who arrives at PZT2 firstly does not contain clutter. Its change can reflect the state of concrete best. So, the head wave of receipt signals is used to deduce concrete strength. The signal waveform received by PZT2 is shown in figure 6. The head wave in the figure is a P-wave with faster propagation speed and no other waveform superposition.

With the increase of signal time, the superposition of shear wave and clutter appears in the waveform. At this time, the amplitude of the waveform increases obviously. This result is consistent with the output of displacement nephogram.

4.2. Characteristic parameters of concrete strength identification

The signals of different frequencies about different concrete age are obtained and their energy values are shown as in figure 7. It can be seen from the figure that the energy values of signals at each frequency decrease monotonically with the age of concrete. The trend curves of energy values can reflect the
change of concrete strength. It can be used as the identification characteristic parameter in concrete strength monitoring.

The corrected determinant coefficient (Adj. R-square) were used as an index for accuracy analysis of fitting curves.

Comparing the fitting curves of different frequency monitoring signals. The closer the coefficient is to 1, the better the accuracy of fitting curve is. Comparing the fitting curves of different frequency monitoring signals, the corrected determinant coefficient (Adj. R-square) statistics are obtained as shown in table 2.

When the signal frequency is 1 kHz, the correction decision coefficient is 0.993, which is the closest to 1. That means the fitting curve is the best when the frequency of the monitoring signal is 1 kHz, and 1 kHz is the optimal monitoring signal frequency.

![Figure 6. Original waveform received by the sensor.](image)

![Figure 7. Age-energy relationship curve.](image)

| Adj. R-square | 500 Hz | 1 kHz | 3 kHz | 5 kHz | 10 kHz |
|---------------|--------|-------|-------|-------|--------|
|               | 0.899  | 0.993 | 0.652 | 0.503 | 0.332  |

### 4.3. Result analysis

Further, Five-peak pulse with frequency of 1 kHz is used as monitoring signal. The variation of strength of C30, C40 and C50 concrete with age was studied respectively. Relationships between monitoring signal energy, concrete strength and age of those three strength grades concrete were studied by numerical simulation results. Normalizing the date, the relationship curves about energy ratio, strength ratio with age were gained and shown in figure 8.

![Figure 8. Relationship curves about energy ratio, strength ratio with age of C30, C40 and C50 concrete.](image)
Contrasting two curves in the same coordinate system, they all have monotonic consistency with age. The energy ratio-age curve is monotonically decreasing, and the strength ratio-age curve is monotonically increasing. The development trends of two curves are the same. Before 168 hours (7 days) of age, the two curves all develop sharply. Then they become gently. This proves that there is a corresponding relationship between strength ratio and energy ratio. It’s feasible to predict the concrete strength and its development trend by using monitoring signal energy.

The direct relationship between energy ratio and strength ratio can be constructed through the intermediate variable of age.

As shown in figure 9, whatever the strength grade of concrete, the relationship between energy ratio and strength ratio is approximately linear. And they are in inverse proportion, which means with the increase of concrete age, the strength of concrete increases, the strength ratio increases, while the energy ratio decreases.

![Figure 9. Strength ratio-energy ratio diagram of C30, C40 and C50 concrete.](image)

The three lines in figure 9 represent three different concrete strength grades. It can be judged that: the higher the strength grade of concrete, the upper the line is. And the lower the strength grade of concrete, the lower the line is.

Furthermore, with the increase of concrete strength grade, the slope of the line between energy ratio and strength ratio becomes smaller, the final attenuation rate of the monitoring signal also becomes smaller. In this paper, when the concrete age of 28 days is reached, the final attenuation rate of monitoring signal energy corresponding of C30 concrete is about 65%, which is about 55% of C40 concrete and about 45% of C50 concrete.

5. Conclusions
In this paper, the feasibility of using SA to monitor concrete strength is studied by numerical simulation. The concrete beam model with embedded PZT transducers had been established, and the PZT transducers were stimulated to transmit and receive signals. Wave analysis method is used to study the change of monitoring signal with the increase of concrete strength. The conclusions can be drawn as that:

- it is feasible to use PZT transducers and wave analysis method to monitor concrete strength. The energy of monitoring signal decreases monotonously with the increase of concrete strength. It can reflect the change of concrete strength very well and be suitable as characteristic parameters of concrete strength identification.
- The five-peak pulse signal can be used as the signal type of concrete strength monitoring. When
the signal frequency is 1 kHz, the corrected determinant coefficients of the fitting curve between the monitoring signal energy and the age of concrete are the best. So, 1 kHz can be used as the optimal frequency parameters of monitoring signal.

- The relationship between the energy ratio of monitoring signal and the strength ratio of concrete is established. They approximate satisfies the linear relationship. By comparing the energy ratio-strength ratio lines of three strength grades of concrete, it is found that the higher the strength grade of concrete, the upper the energy ratio-strength ratio relationship line is, the smaller the inclination of line is, the smaller the final energy decay rate is.

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