Abstract—Early-age strength monitoring, impact detection, and structural health monitoring are important issues for concrete structures, especially concrete infrastructures such as bridges. A Distributed Intelligent Multi-purpose Sensor Network (DIMSNN) using innovative piezoelectric-based smart aggregates is proposed in this paper to address these important issues. The smart aggregate is fabricated by embedding a water-proofed piezoelectric patch into a small concrete block. The smart aggregates are then placed at the desired locations in concrete structures before casting to form a distributed intelligent multi-purpose sensor network. In this paper, a two-story concrete frame is used as the object to test the multi-functionality of smart aggregates and the DIMSN. The early-age strength monitoring is performed by monitoring the harmonic response amplitude of smart aggregates. Experimental results show that the predicted concrete strength matches the experimental results obtained in the compressive test. Impact tests are by performed by impacting the concrete frame at different locations. Experimental results show that the impact response is captured by the distributed smart aggregates and the energy of the impact response is related to the distance between the smart aggregate and the impact location. After the concrete strength is fully developed, structural health monitoring is conducted on the concrete frame through a destructive push-over test. Experimental results show that the proposed damage index matrix reveals the time history of health status of different locations. The proposed smart aggregate-based health monitoring approach is more sensitive than the traditional approaches that use microscopes and LVDTs. The proposed distributed intelligent multi-purpose sensor network has the potential to be implemented to the comprehensive performance evaluation of concrete civil structures.

Index Terms—Sensor network, Smart aggregate, Piezoelectric material, Health monitoring, Impact detection, and Concrete early age strength monitoring

I. INTRODUCTION

Concrete structures are the most popular civil structures. Concrete infrastructures, such as bridges, play an important role not only in a nation’s transportation system but also in a nation’s economy. Throughout the life cycle of a concrete structure, many important issues have to be addressed properly to ensure the safe operation of these structures. At the early age of a concrete structure, strength monitoring is vital to determine its readiness for service. During its service, it is important to detect impact, such as those caused by vehicles, ships, or barges, to the structure and to continuously evaluate the structure health status. Presently, there is no single transducer can perform all these tasks at a low cost. With recent development in sensors and microprocessors, it is now possible to develop a single transducer to perform early-age strength monitoring, impact detection, and structural health monitoring for concrete structures, especially for concrete infrastructures, such as concrete bridges. This technology is the piezoceramic-based smart aggregate. The smart aggregate is a one-cubic inch precast concrete block with a wired embedded PZT (Lead Zirconate Titanate, a type of piezoceramic) patch. This smart aggregate with an associated microprocessor is intelligent since it can sense and actuate. This smart aggregate is multifunctional and can be used for early-age strength monitoring, impact detection, and structural health monitoring.

In this paper, piezoelectric based-smart aggregates are used to form a distributed intelligent multi-purpose sensor network to address the important issues associated with concrete structures. These include the early-age concrete strength monitoring, impact detection & evaluation, and the structural health monitoring. A two-story concrete frame instrumented with the proposed multi-purpose smart aggregates is used as the testing object. Experimental results show that the proposed intelligent multi-purpose sensor network can monitor the concrete strength in the early-age of concrete. After the concrete strength has been fully developed, the proposed sensor network can detect impacts on the structure and perform structural health monitoring of the structure by using the proposed damage index matrix.

II. SMART AGGREGATES

The concept of embedding sensors in a concrete structure is not new, however, in the literature, most of the embedded sensors are related to corrosion detection. Chloride acts as a catalyst in the corrosion of the reinforcing steel, or rebar in civil structures. To monitor the level of chloride ingress in concrete bridge decks, Watters et al. (2003) developed a wireless sensor called smart pebble to indicate chloride concentration levels. Carkhuff and Cain (2003) designed corrosion sensors called smart aggregates to be buried into the concrete to monitor subsurface highway conditions in determining corrosion actions. Current smart sensors can only
perform one function such as corrosion detection and cannot perform other important functions, such as early age strength monitoring, impact detection, and structural health monitoring.

In this paper, a multi-functional piezoelectric-based smart sensor device, called a smart aggregate (shown in Fig.1), is developed by embedding a water-proofed PZT (a commonly used piezoceramic material) patch with wire leads into a small concrete block as shown in Fig. 2. This configuration offers a protection to the fragile piezoceramic patch. The proposed smart aggregates can perform early-age concrete strength monitoring, impact detection & evaluation, and structural health monitoring of civil structures. The smart aggregate functions from the construction of the concrete structure through its lifecycle. To form a Distributed Intelligent Multi-purpose Sensor Network (DIMSN), the smart aggregates are embedded at the desired distributed locations before casting.

The proposed smart aggregate-based DIMSN has the advantages of low cost, fast response, solid-state actuation, and most importantly, active sensing, all of which are inherited from piezoelectrics. Active sensing in the case of smart aggregates means one smart aggregate is actively excited by a desired wave form so that other distributed smart aggregates detect the responses. By analyzing the sensor signals, many important properties of the structures can be monitored and evaluated.

### III. Multi-functionality of smart aggregates

The piezoelectric property of the embedded PZT patch enables the multi-functionality of the proposed smart aggregate and the smart aggregate-based DIMSN. Piezoelectricity indicates the ability of a certain material to generate electric voltage when subjected to mechanical strain and conversely generate mechanical strain when applied to an electric field. Due to this special piezoelectric property, the proposed piezoelectric-based smart aggregate can be used for early-age concrete strength monitoring, impact detection, and structural health monitoring of civil structure.

#### A. Early-age concrete strength monitoring

Early-age strength monitoring is a major concern for the construction of concrete structures. There are two major categories of non-destructive evaluation methods used for the early-age performance monitoring of concrete structures: hydration heat-based monitoring methods (Lin et al. 2004) and ultrasonic technology-based monitoring methods (Demirboga et al. 2004). In this paper, a pair of embedded smart aggregates is used for the early-age strength monitoring purpose by taking advantage of its active sensing property: one will be excited by a harmonic wave and the other will sense the response.

To explain the principle of using smart aggregates for early age strength monitoring, a one-dimensional concrete column is used. The propagation of stress waves in a concrete column can be viewed as one-dimensional longitudinal wave propagation. The wave equation (Achenbach, 1973) can be written as:

\[
\frac{\partial^2 u}{\partial t^2} = \frac{1}{c_0^2} \frac{\partial^2 u}{\partial x^2} \quad (c_0^2 = E/\rho)
\]

where \( u \) is the displacement of an element, \( E \) is the Young’s modulus, and \( \rho \) is the density of material.

The amplitude of the harmonic response can be expressed as

\[
A = \left( \frac{1}{\omega} \right) \left( \frac{4\rho^2}{E\rho} \right)^{1/2}
\]

where \( A \) is the harmonic amplitude, \( \omega \) is the angular frequency, \( \rho \) is the average of the power of the harmonic response over a period.

As shown in equation (2), the harmonic amplitude is affected by the Young’s modulus, \( E \), of the medium. During the early-age development of concrete, its Young’s modulus increases as the concrete stiffens and gains strength during the early age. Consequently, the harmonic amplitude will decrease with the increase of the Young’s modulus. Moreover, the Young’s modulus is a major factor in determining the concrete strength. Therefore, the harmonic amplitude is correlated with the concrete strength through the status of Young’s modulus. To evaluate the concrete strength at early ages, a fuzzy correlation system between the harmonic amplitude and the compressive strength is trained based on the experimental data by using the batch least squares algorithm.

#### B. Impact detection and evaluation

Impact on a civil infrastructure, such as a bridge pier, or a bridge girder, can cause permanent damage and may result in the failure of structure. Therefore, it is important to detect the impact and evaluate the impact level in time for the safety issue of the civil infrastructures.

In the proposed smart aggregate, the open-circuit voltage yielded by the PZT transducer inside the smart aggregate when it is compressed with a force \( F \) is given by

\[
V = g_{33}Ft/A
\]

where \( A \) is the area of the PZT patch, \( t \) is its thickness, and \( g_{33} \) is the piezoelectric voltage constant which is defined as the electric field generated in a material per unit mechanical stress applied to it. The first subscript refers to the direction of the electric field generated in the material or the applied electric displacement; the second refers to the direction of the applied
stress or the direction of the induced strain. From equation (3), the open-circuit voltage yield by the PZT transducer is proportional to the compressed force and can be utilized to evaluate the impact force.

C. Structural health monitoring

In recent years, piezoelectric materials have been successfully applied to the structural health monitoring of concrete structures due to their advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation. There are two major categories of piezoelectric-based health monitoring: 1) Impedance-based approach, in which the impedance of piezoelectric transducers can be applied to the health monitoring of concrete structures (Tseng and Wang 2004), and 2) Vibration-based health monitoring approach. The basic principle of this method is to use one piezoelectric transducer to emit different types of stress waves inside the structure. Cracks or other damage in the concrete provide stress relief. When the stress wave propagates across the crack, the amplitude and the transmission energy will be attenuated by the stress release (Song et al., 2005)

In this paper, wavelet packet analysis is used as a signal-processing tool to analyze the sensor signals detected by the smart aggregates. The sensor signal S is decomposed by an n-level wavelet packet decomposition into 2^n signal sets \( \{ X_1, X_2, \ldots, X_{2^n} \} \). \( E_{i,j} \) is the energy of the decomposed signal, where \( i \) is the time index and \( j \) is the frequency band (\( j=1\ldots2^n \)). \( X_c \) can be expressed as

\[
X_j = [x_{j,1}, x_{j,2}, \ldots, x_{j,m}],
\]

(4)

where \( m \) is the amount of sampling data. Additionally,

\[
E_{i,j} = \|X_j\|_2^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2.
\]

(5)

The energy vector at time index \( i \) can be given as

\[
E_i = [E_{i,1}, E_{i,2}, \ldots, E_{i,2^n}].
\]

(6)

Various kinds of damage indices have been developed for health monitoring of civil structures in recent years. Root-mean-square deviation (RMSD) is a commonly used damage index to compare the difference between the signatures of healthy and damaged state (Soh et al. (2000), Tseng and Naidu (2002)). In the proposed approach, the damage index is formed by calculating the RMSD between the energy vectors of the healthy state and the damaged state. The energy vector for healthy data is \( E_h = [E_{h,1}, E_{h,2}, \ldots, E_{h,2^n}] \). The energy vector \( E_i \) for damage state at time index \( i \) is defined as \( E_i = [E_{i,1}, E_{i,2}, \ldots, E_{i,2^n}] \). The damage index at time \( i \) is defined as

\[
I = \sqrt{\frac{\sum_{j=1}^{2^n} (E_{i,j} - E_{h,j})^2}{\sum_{j=1}^{2^n} E_{h,j}^2}}.
\]

(7)

The proposed damage index represents the transmission energy loss portion caused by damage. When the damage index is close to 0, it means that the concrete structure is in a healthy state. The greater the damage index, the more serious the damage is. When more than two smart aggregates are used, a Distributed Intelligent Multi-purpose Sensor Network (DIMSN) is formed. To represent the health status at different locations of a concrete structure, a damage index matrix \( M_{n\times n} \) is defined as:

\[
M_{n\times n} = [E_{i,j}]_{n\times m} \quad (i=1,\ldots,m \quad \text{and} \quad j=1,\ldots,n)
\]

(8)

where the matrix element at the \( i^{th} \) row and \( j^{th} \) column, \( E_{i,j} \), is the damage index of the \( i^{th} \) smart aggregate at the time of the \( j^{th} \) test (i.e. \( i \) is the sensor index, \( j \) is the time index); \( m \) is the total number of smart aggregates and \( n \) is the total number of tests.

IV. EXPERIMENTAL SETUP FOR COMPREHENSIVE TESTS

A. Concrete frame with smart aggregate based sensor network

A two-story concrete frame instrumented with piezoceramic-based smart aggregates, as shown in Figs. 3 and 4, is fabricated as the object for comprehensive tests, which includes early-age strength monitoring, impact detection, and structural health monitoring. Eighteen smart aggregates are embedded at the desired locations in the concrete frame as shown in Fig. 4 to form a smart aggregate-based DIMSN.

Fig. 3 Concrete frame for comprehensive performance evaluation test

B. Testing setup

Two hydraulic actuators are installed at the top-right corner of the concrete frame to apply loads to the frame structure to conduct the so called “push over” test. The load is increasingly applied to the structure until failure. LVDTs are also installed to detect the displacement at different locations of the concrete frame. A real-time control and digital data acquisition system is utilized to actuate the appropriate smart aggregate and to record the sensor signals from the distributed sensor network.
V. EXPERIMENTAL RESULTS OF THE DIMSN

The proposed smart aggregate-based DIMSN are applied to the early-age concrete strength monitoring, impact detection & evaluation, and structural health monitoring of the concrete frame. Experimental results demonstrate the effectiveness and the functionality of the proposed smart-aggregate-based DIMSN.

A. Early age concrete strength monitoring

The smart aggregate-based early-age strength monitoring approach introduced in section III-A is used to monitor the early-age concrete strength development of the concrete frame. As a reference, thirty-six concrete cylinders, each with 4 inches in diameter and 8 inches in height, are manufactured to help to experimentally obtain the early age concrete compressive strength. The concrete cylinder specimens are fabricated using the same concrete which is used to fabricate the 2-story concrete frame. Among the concrete cylinders, three of them are instrumented with the piezoelectric-based smart aggregates to monitor the early-age concrete strength. On each day of the first week, three concrete cylinders are crushed in a compressive test to obtain an average value for the compressive concrete strength for each day. The same loading test is also performed on the 14th, 21st, and 28th days to obtain the compressive concrete strength. Based on the experimental data of the compressive concrete strength, a compressive strength curve is plotted versus the age in days as the solid line shown in Fig. 6. The experimental data shows that the compressive concrete strength increases quickly through the first week and continues to increase at a decaying rate for the remaining days.

Smart aggregates based on active sensing are also used to monitor the early age strength monitoring. For comparison purposes, the harmonic response amplitudes are normalized to have the maximum value of 1. From the comparison of the average normalized harmonic amplitudes in the concrete frame with that in concrete cylinders, as shown in Fig. 5, it can be seen that the harmonic amplitude of smart aggregates in both the concrete frame and concrete cylinder share the similar development trend. The normalized harmonic amplitudes drop tremendously in the first week and decrease at a decaying rate, which also matches the development trend of concrete strength.

A fuzzy correlation system is trained based on the experimental data of the first-12 day harmonic amplitude-compressive strength data pair of concrete cylinder specimens by using the batch least square algorithm. Five linguistic variables (smaller, small, medium, large, larger) are defined to represent the input domain and output domain with their membership values between 0 and 1. Fuzzy inference rules are defined according to the experience that harmonic amplitude decreases as the concrete strength increases in the early ages. The center average defuzzification method is used in the proposed fuzzy correlation system. The center values of the output membership function are identified by the batch least squares algorithm based on the training data.

The estimated compressive concrete strength from the 12th day to 28th day estimated by the fuzzy correlation system is shown in Fig. 6. The harmonic amplitude of the smart aggregate sensor from both cylinder and frame are used to predict the concrete strength from the 12th day to 28th day. From the experimental results, it can be seen that the predicted 12th day to 28th day concrete strength by using the cylinder data matches the experimental data of concrete strength. By using the concrete frame experimental data as the input for the fuzzy correlation system, the predicted compressive strength also matches the experimental data well, although the fuzzy correlation system is trained by the experimental data from concrete cylinders. This means that the correlation system trained by the experimental cylinder data can be used for the
concrete strength monitoring of the concrete frame.

Based on the above experimental results, following conclusions can be drawn:

1) The smart aggregate-based DIMSN can be successfully applied to the early-age concrete strength monitoring of a concrete structure.

2) The harmonic amplitude development of concrete cylinders and the concrete frame at early-ages can share the similar trend curve, meaning that the general trend of the concrete strength development of both concrete cylinder and concrete frame are similar.

B. Impact detection and evaluation

During the impact detection test, the concrete frame is impacted by a hammer at impact spots I and II as shown in Fig. 4. The energy of the $i^{th}$ sensor signal $E_i$ is defined as

$$E_i = \int u_i^2 \, dt \quad (9)$$

From sensor energy of the time responses detected by smart aggregates as shown in Fig. 7, it can be seen that the impulse responses can be captured by the distributed smart aggregates at different locations when the concrete frame is impacted. The sensor energy plot also shows that when the concrete frame is impacted on spot I, the sensor signal of PZT2 has largest amplitude and largest sensor energy compared with other sensors. This is because PZT2 is the closest to impact spot I compared with other sensors. When the concrete frame is impacted on spot II, the sensor signal of PZT5 has largest amplitude and largest sensor energy compared with other sensors. This is because PZT 5 is closer to the impact spot II than other smart aggregates. From the experimental results, following conclusions can be drawn:

1. When the concrete frame is impacted, the proposed smart aggregate-based DIMSN can detect the impulse response at different locations.

2. The amplitude of sensor signal, sensor signal energy and energy distribution is related with the location of impact spot. The closer the smart aggregate is to the impact spot, the higher the sensor signal amplitude and the sensor energy will be.

C. Structural health monitoring

During the structural health monitoring test, a push over test is conducted. Before the showing of a major crack, the test is in force control mode. After the appearance of a major crack, the test is set in the displacement control mode. During the force control mode, the load (force) is increased gradually at a fixed rate to fail the concrete frame. During the displacement control mode, the concrete frame is pushed by the hydraulic actuators to certain position at a specified rate and then these positions will be held for a certain time for data acquisition.

1. Experimental results of microscope-based approach and LVDT-based approach

After the loading test in force control mode, the concrete frame yields and visible cracks are beginning to appear on the surface at different locations of the concrete frame. The crack width for the first crack is observed by using a microscope and it is plotted versus the load, as shown in Fig. 8, which clearly reveals that the relationship between the crack width and the load value is linear before the load value increases to 5 tons. After the load value reaches 5 tons, the crack width increases dramatically and the relationship between crack width and load is highly nonlinear. This means the concrete frame yields at the load value of 5 tons. The experimental results of LVDT measurements also verify that the concrete frame yields at the load value of 5 tons.

2. Experimental results of smart aggregate-based DIMSN

During both load control and displacement control, the smart aggregates are utilized for the real-time structural health monitoring of the concrete frame. In the structural health monitoring algorithm, wavelet packet analysis is utilized as a signal-processing tool to analyze the sensor signals. The wavelet packet-based damage index matrix proposed in section III is utilized in the structural health monitoring of concrete frame.

Fig. 7. Energy level of different sensors for impact test

<table>
<thead>
<tr>
<th>Test No</th>
<th>Description</th>
<th>Test No</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No load is applied</td>
<td>9</td>
<td>Displacement=1.9 in</td>
</tr>
<tr>
<td>2</td>
<td>Increased to 4 tons, and unload</td>
<td>10</td>
<td>Displacement=2.5 in</td>
</tr>
<tr>
<td>3</td>
<td>Load= 2 tons</td>
<td>11</td>
<td>Displacement=3 in</td>
</tr>
<tr>
<td>4</td>
<td>Load= 3 tons</td>
<td>12</td>
<td>Displacement=3 in</td>
</tr>
<tr>
<td>5</td>
<td>Load= 4 tons</td>
<td>13</td>
<td>Displacement=3.5 in</td>
</tr>
<tr>
<td>6</td>
<td>Load=5 tons</td>
<td>14</td>
<td>Displacement=4 in</td>
</tr>
<tr>
<td>7</td>
<td>Displacement control starts Displacement=1.6 inches</td>
<td>15</td>
<td>Unload</td>
</tr>
</tbody>
</table>

The average damage index matrix is calculated as the average damage index value of each sensor with different smart aggregates as actuator. The average damage index matrix represents the health status of the whole concrete frame. Structural heath monitoring is conducted concurrently during the loading process. The details of each tests during the loading process is shown in Table I. From the average damage index matrix shown in Fig. 9, the damage index values have suddenly increased to a critical value from test 4 with the load value at 3 tons to test 5 with the load value at 4 tons. It can be said that the health status reached a critical status at the load value of 4 tons. The critical value observed by the proposed smart aggregate based DIMSN is ahead of the
critical value of 5 tons as observed by traditional health monitoring tools-microscope and LVDTs. Therefore the proposed smart aggregate-based structural health monitoring approach is more sensitive than the traditional microscope-based approach and the LVDT-based approach.

From the average damage index matrix, it can also be seen that PZT2, PZT6 and PZT14 have greater damage index values than those of other sensors. This means the damage status near PZT2, PZT6 and PZT14 is more severe than the damage status at the locations around other distributed sensors as verified by the visual inspection. This shows the effectiveness of the proposed damage index matrix to evaluate the severity of the damage at different locations.

From the experimental results, following conclusions can be drawn:
1. The damage index matrix show the damage status with location information and time information. The critical point captured by the proposed smart aggregate-based approach is ahead of the critical point captured by the traditional approaches based microscopes and LVDTs.
2. The average damage index matrix shows the overall health status of the concrete frame. The health status at different locations can be represented by the average damage index matrix.

VI. CONCLUSIONS

In this paper, a smart aggregate-based distributed intelligent multipurpose sensor network has been developed to address several important issues regarding concrete structures, including the early-age concrete strength monitoring, the impact detection & evaluation, and the structural health monitoring. A 2-story concrete frame instrumented with distributed smart aggregates is used as a testing object. From the experimental results, the proposed smart aggregate-based DIMSN can monitor and predict the concrete strength at early ages by using the trained fuzzy correlation system. After the concrete strength has been fully developed, impact test and structural health monitoring test are conducted on the concrete frame using the same smart-aggregate DIMSN. The experimental results of impact test show that the impact on the concrete frame can be detected by the distributed smart aggregates and the impact level can be evaluated. The experimental results of structural health monitoring show that the health status at different locations of the concrete frame can be evaluated by the proposed wavelet packet-based damage index matrix. Also, the proposed smart aggregate-based health monitoring approach is more sensitive than the traditional health monitoring approaches. In conclusion, the proposed smart aggregate-based DIMSN is multi-purpose and can perform early age strength monitoring, impact detection and health monitoring. The proposed smart aggregate-based DIMSN has the potential to be implemented to real concrete civil structures to enhance safety.

REFERENCES