Construction and Building Materials 131 (2017) 57–65

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An investigation on the aggregate-shape embedded piezoelectric sensor for civil infrastructure health monitoring

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HIGHLIGHTS

- A new piezoelectric sensor for infrastructure health monitoring is designed.
- 3D printing technique is used for sensor packaging.
- Sensor is designed in aggregate shape.

ARTICLE INFO

Article history:
Received 17 August 2016
Received in revised form 3 October 2016
Accepted 12 November 2016

Keywords:
Piezoelectric sensor
Aggregate-shape
Embedded
Infrastructure
Health monitoring

ABSTRACT

In this paper, a new type of aggregate-shape embedded piezoelectric sensor for health monitoring of civil infrastructures was developed. The sensor was designed by using piezoelectric ceramic chip as the functional phase, and a new composite material as packaging phase. 3D printing technology was also used for packaging system design and sensor fabrication. The frequency independence, linearity, sensitivity, response rate, and service performance of the sensor were tested by frequency scanning and amplitude scanning. Experimental results show that within the vibration frequency range of common civil engineering structures, the new aggregate-shape embedded piezoelectric sensor has good mechanical and workability properties. Test results also show that the new embedded sensors have very good mechanical-electrical coupling performance, which builds a solid foundation for further application in the civil engineering infrastructures.

1. Introduction

In recent years, with the fast development of national economy and construction technology, many large-scale civil engineering infrastructures such as highways and bridges have been built in China. These infrastructures will endure erosion, aging, fatigue and other hostile environmental conditions during the long term service, which may cause a catastrophic accident in extreme cases [1]. Generally, before the destruction of civil engineering infrastructures, fracture, fatigue cracking and other diseases will gradually appear in the structures. It is therefore necessary to conduct long-term health monitoring on these structures by using sensor network. The sensors can be embedded into the structure during the construction process so as to monitor the service status of infrastructures from the beginning of the construction, and further to ensure the safety of the civil engineering infrastructure [2,3].

Normally, the traditional monitoring sensors include accelerometers, displacement sensor, force sensor, resistance strain gauge [4,5]. There are also new sensor materials such as optical fiber, memory alloy and piezoelectric materials [6–8]. However, the commonly used sensors in civil engineering infrastructures have some shortcomings. For example, the service life of the sensor is much less than the life of the infrastructure [9]; sensors in the structure are easy to fail; sensor material and the concrete structure have poor compatibility; embedded sensors may change the stress distribution of the structure; sensor equipment is expensive [10,11]. In 2001, Li proposed a new type of piezoelectric composite material, which is very suitable for the health monitoring of concrete structure [12,13]. However, the piezoelectric material cannot be directly used as the sensors embedded in the structures [14]. A proper design of packaging the material using composite materials is needed to improve the structure compatibility and the mechanical performance [15]. Meanwhile, although

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http://dx.doi.org/10.1016/j.conbuildmat.2016.11.050

there have been many researches in the civil infrastructure material characterizations [16,17], there still needs research on the field of smart health monitoring of civil infrastructures and develop a smart material with both perceptive function and drive functions. It should also have a good compatibility with the traditional infrastructure materials. The piezoelectric sensor has these advantages. In addition, it has fast response rate and good durability compared to the traditional sensors. The most prominent advantage of 3D printing technology is that the product with any shape can be directly generated using the computer graphics data. This doesn't depend on the mechanical processing mold any longer. To implement the sensor into the civil infrastructure, it should be compatible with the infrastructure characteristics. In this way, an aggregate-shape sensor could satisfy such requirement, where there have been several researches in this field [18]. Therefore, it can shorten the producing time of production, reduce the cost and increase the precision. 3D printing technology can also help us to quickly realize the structure design of sensors with different size, different structures and different shapes.

Based on the previous research in infrastructure health monitoring [19,20], in this paper, a new aggregate-shape embedded piezoelectric sensor was designed. Within the vibrations frequency range of civil engineering structure, the workability and service performance of the sensors were tested. First, through the experiment, the optimum mixing ratio of composite materials for packaging was obtained. Its material properties and mechanical performance were also tested; second, combined with the 3D printing technology, the packaging for piezoelectric materials using composite materials to manufacture the aggregate-shape sensors were designed. Different piezoelectric sensors are prepared and the efficiencies were tested; finally, the frequency independence, the linearity, the response rate and the service performance of the different sensors were tested. The experimental results verify the feasibility of the aggregate-shape embedded piezoelectric sensors for the application in monitoring civil engineering infrastructure.

2. Design and performance test

2.1. Mix design

The packaging material has two functions: one is to protect the piezoelectric elements from external environment (including rainfall and frost) erosion so as to improve the sensor's durability; another is to ensure the electrically and insulation performance of piezoelectric sensor. The packaging material of this research mainly consists of cement, epoxy resin, curing agent, diluent and anti-foam agent. By adjusting the ratio of filler, polymer and other agents, a composite material with good mechanical properties, excellent waterproof performance, and good corrosion resistance can be obtained. The design of mix proportion is shown in Table 1.

Materials used in this test mainly includes cement, epoxy resin, curing agent, diluent and anti-foam agent. All of them are nontoxic and environmentally friendly products. The detailed information is shown in Table 2 and Table 3.

2.2. Mechanical properties test

The compressive strength and flexural strength of the packaging composite materials of different mix ratio at different ages are tested, as shown in Table 4. The tested samples are prisms, and its size is 40 mm × 40 mm × 160 mm. The compressive strength and bending strength were tested according to the specification "IS0 679-2009 cement – test methods – determination of strength".

It is can be seen that with the cement increasing, the compressive strength of the composite materials at the same age presents an increasing first and then a decreasing trend later. The compressive strengths at 3d, 7d and 28d are highest when epoxy resin: cement = 3:2. This is due to that with the increasing in cement packing, the polymer material for cement particles decreases, the defects of epoxy composite structure begin to accumulate and the compacting property and compressive strength decrease. A higher content of rigid fillers results in greater flexural strength. When the cement content increases about four times, the flexural bending strength increases about twice. This trend applied to the curing time from 3 days to 28 days. With the curing time increasing, the flexural bending strength also increased. But the increase amplitude was not obvious from 3 days to 7 days. By contrast, the increase of flexural bending strength from 7 days to 28 days was significant.

2.3. Micro topography analysis

The cement and epoxy resin composite material is a combination of inorganic material and organic material. The cement was used as the supporting filler, the epoxy resin and the additive were used as the bonding material. Polymerization reaction occurred and gradually a complete membrane structure formed. Fig. 1 shows the Scanning Electron Microscopy (SEM) images of the micro structure of the composites with different mix ratios (epoxy resin: cement).

It is can be observed that, when the polymer-cement ratio is 3:1, there are many micro pores and cavities on the surface. When the polymer-cement ratio is 3:2, the solidification products of cement and epoxy resin are more dense, and there are much less pores and cavities, indicating a better performance; when the polymer-cement ratio are 3:3 and 3:4, with the increase of cement, epoxy resin content reduced, which results in the weakening of the interfacial bonding property of colloid material and filler [21,22]. It is can be concluded that the composite material has a good microstructure when the ratio of polymer to cement ratio is 3:2. This is due to that the polymer gradually forms into a continuous film, bonding with the cement, to build a network structure. The performance of the composite structure is improved, including the compressive strength, flexural strength, durability, flexibility.

2.4. Water absorption test

In order to further validate the micro-morphology analysis, the water absorption test is carried out. Table 5 shows the water absorption testing results of the designed composite materials.

Table 1
Design of mix proportion of packaging composite materials.

Mix ratio number	Cement	Epoxy resin	Curing agent	Diluent (%)	Anti-foam agent (%)
01	1	3	1.1	10	1
02	2	3	1.1	10	1
03	3	3	1.1	10	1
04	4	3	1.1	10	1

Note: the data in the table are the mass ratio.