Early-age performance monitoring of cement-based materials by using optical FBG sensors

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ABSTRACT: With more and more widely used of the cement-based materials such as neat cement paste, cement mortar and concrete in structures, people want to see what their performances like. As is known, the working performances of cement-based materials are affected very much by their hardening process in the early-age. But the common measuring techniques on the early curing of the cement-based materials are limited for some of their disadvantages, such as: difficulties in embedding sensors inside the concrete, limited measuring points, poor durability and interference of electromagnetic wave. So in this paper, according to the sensing properties of the Fiber Bragg Gratings sensors and self-characters of the cement-based materials, we have successfully finished measuring and monitoring the early-age inner-strain and temperature changes of the neat cement paste, concrete with and without restrictions, mass concrete and negative concrete systematically. We developed three types of FBG sensors suitable for being embedded and monitoring in cement-based materials, while the embedding technology and the embedding requirements of FBG sensors in cement-based materials are also discussed. The results show that FBG sensors are well proper for measuring and monitoring the temperature and strain changes including self-shrinkage, dry shrinkage, plastic shrinkage, temperature expansion, frost heaving and etc inside different cement-based materials during their early-age. This technique provides us a new useful measuring method on early curing monitoring of cement-based materials and greater understanding of details of their hardening process.

KEYWORDS: FBG (Fiber Bragg Gratings); cement-based materials; hardening monitoring; FRP

1 INSTRUCTION

Cement-based materials such as neat cement paste, cement mortar and concrete are the materials the most used in civil engineering. Therefore, a good knowledge about their mechanical properties and behaviors is essential. After the mixing of cement, aggregates and water, the cement hydration process is activated and the life of cement-based materials begin. As is known, the working performance of cement-based materials is affected very much by the hardening process of the early-age. During the hydration process the fluid multiphase structure transforms into a hardened structure and its mechanical properties change (elastic modulus, thermal expansion coefficient, Poisson ratio, strength, etc.)[1].

Though there are many methods to measure the early-age temperature, shrinkage and expansion deformation changes of the cement-based materials, which includes: drying shrinkage measuring method, self-shrinkage measuring method and plate type specimen method [2,3], the common measuring techniques on the early curing of the cement-based materials are still limited for some of the disadvantages, such as: difficulties in embedding sensors inside the materials、limited measuring points、poor durability and interference of electromagnetic wave. And also traditional methods are some-degree limited in measuring accuracy, so it is very difficult giving us the proper strain and temperature changes of cement-based materials in the early-age hardening process[4~6].

According to the special targets, in this paper, we used tow kinds of temperature sensors and three kinds of strain sensors monitoring different kinds of cement-based materials: naked FBG for neat cement paste and concrete specimens, metal tube packaged FBG strain sensors for mass concrete specimens, while FRP packaged FBG strain sensors for mass concrete structures. Except that FRP packaged FBG temperature sensors are for mass concrete structures temperature measuring, metal tube packaged FBG temperature sensors are for the others.

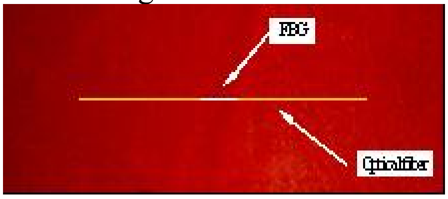
2 TYPES OF THE FBG SENSORS AND THE EMBEDDING TECHNIQUES IN CEMENT-BASED MATERIALS

Cement-based materials are completed materials because that they can be regarded as isotropic materials in general view but in microscopic view they appear much more different structures.

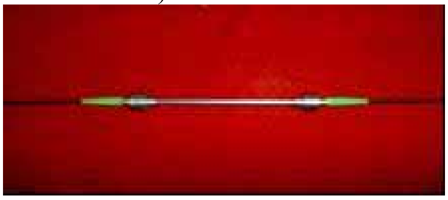
Considering the coarse and fine aggregates contained in concrete, we commonly use the length three times of the aggregate diameter to define the strain changes for concrete structures, so as is mentioned, we developed tow kinds of temperature sensors and three kinds of strain sensors to monitor different kinds of cement-based materials. And different kinds of sensors need different embedding techniques.

2.1 *Types of the FBG sensors*

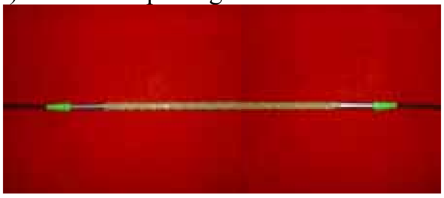
The strain measuring sensors are shown in Figure1.



a) Naked FBG



b) Metal tube packaged FBG strain sensor

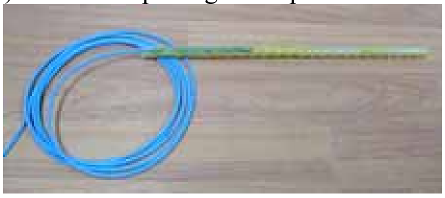


c) FRP packaged FBG strain sensor

Figure1. Sketch of FBG strain sensors

The temperature sensors are shown in Figure 2.

a) Metal tube packaged temperature sensor



b) FRP packaged FBG temperature sensor

Figure 2. Sketch of FBG temperature sensors

2.2 *Operating and temperature compensation principle of FBG sensors*

FBG can measure both stress and temperature, so in this paper, we use two FBG sensors sensing temperature and strain simultaneously. That means single FBG sensor was freely packaged in a capillary tube as a temperature sensor sensing the temperature changes, while the other FBG sensor was embedded inside the materials sensing temperature and strain simultaneously. These two FBG sensors are so near that it can be considered they are in the same temperature field. So their sensing properties can be described as follow:

$$\Delta\lambda_1 / \lambda_1 = K_{\varepsilon 1}\varepsilon + K_{T1}\Delta T \qquad (1)$$

$$\Delta\lambda_2 / \lambda_2 = K_{T2}\Delta T \qquad (2)$$

Where: λ_1, λ_2 are the wavelengths of the two FBG sensors; $K_{\varepsilon 1}$ is the strain sensitivity coefficient; K_{T1} , K_{T2} are the temperature sensitivity coefficients of the two Fiber Bragg Gratings.

The strain sensitivity coefficient and the temperature sensitivity coefficient of FBG are separately 1.2 pm/με and 10 pm/℃. For the distinguish ability of our interrogator is 1 pm, we can make our accuracy 1με and 0.1℃. According to the FBG wavelength we gained, the inner strain and temperature changes of cement-based materials in the early-age can be easily obtained.

2.3 *Embedding technology of the sensors in cement-based materials*

Naked FBG is small, fragile, and easily broken. So it is very important for us to put it inside the cement-based materials safely and make it work well. So the embedding method for naked FBG in this paper is "tube-drawing", while the other kinds of sensors are embedded directly.

"Tube-drawing" is like this: Firstly, put the naked FBG into a small tube with the diameter 3mm. At the same time, a small hole is needed in one side of the mould. Before pouring pastes, put the small tube with naked FBG into the mould through the hole, and then pouring and mixing the cement pastes. After that, draw the small tube out of the mould from the small hole. The FBG would be located in the midst of the specimen. After a while, with the help of self-healing of cement pastes, the naked FBG would be successfully embedded inside the specimen.

3 EARLY-AGE PERFORMANCE MONITORING OF CEMENT-BASED MATERIALS

In this paper, we have done some early-age monitoring work on cement-based materials including neat cement paste, concrete with and without restrictions, mass concrete specimens and mass concrete structures, negative concrete.

3.1 *The early-age monitoring on neat cement paste*

At least one strain sensor and one temperature sensor were embedded inside the specimens. The strain sensors were to measure the strain changes, while the temperature sensors were to measure the temperature changes and to do temperature compensation work. The sketch of Fiber Bragg Gratings embedded in cement-based materials specimen is as shown in Figure3. The monitoring results is as described in Figure4 and Figure5.

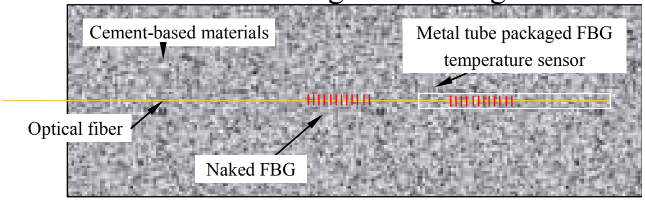


Figure 3. Sketch of FBGs embedded in specimens of neat cement paste and concrete without restrictions

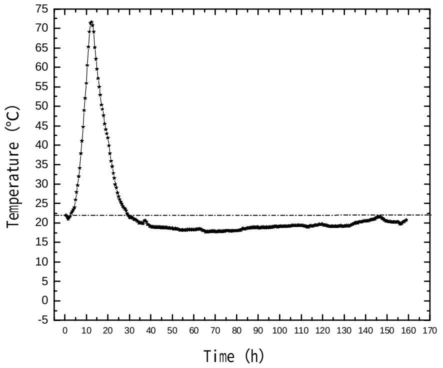


Figure 4. Inner temperature-time relationship for curing cement paste （7days）

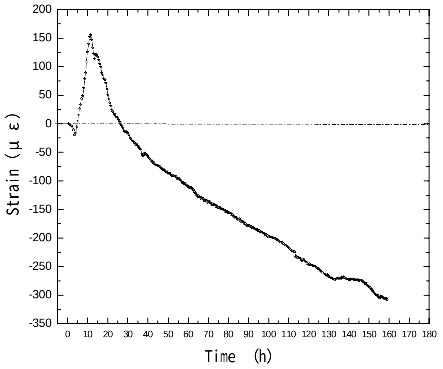


Figure 5. Inner strain-time relationship for curing cement paste （7days）

Here the inner strain and temperature changes of neat cement paste is well obtained, the inner temperature ascends about 50 ℃, while in the 3 days , the expensive strain is about 150 μ ε and the shrinkage strain at 7 days is about 300 μ ε, which are well consistent with the common situation.

3.2 *The early-age monitoring on concrete without restriction*

The Portland cement we used in this part is P·O42.5R produced by Mudanjiang cement group of China, the volume of the specimen for measuring strain and temperature is 100mm×100mm×400mm. The mix proportion and properties of concrete is as Table 1. The sketch of situation of FBG sensors is also as shown in Figure1.

We have continuously monitored the there specimens for 3 days, and the data of the strain and temperature changes we obtained is as shown in Figure6 and Figure7.

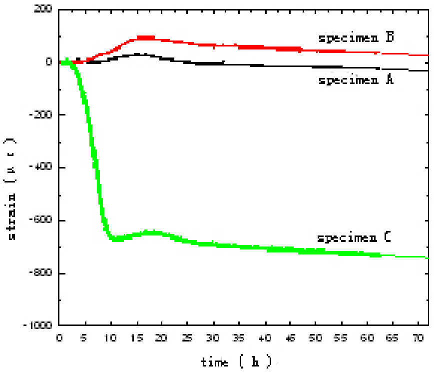


Figure 6. Strain course for concrete specimen

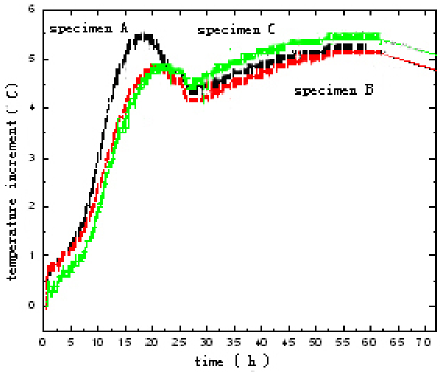


Figure 7. Temperature changes in concrete specimen

We can see from Figure6 that the strain sensor in specimen C worked well, while the other tow not. This may be because the bonding power between the naked FBG and the concrete is too poor, or where the sensor is, there is just a big coarse aggregate. Here, about 700 μ ε shrinkage strain is obtained. In Figure7, the information obtained by the three temperature sensors reflects a real situation.

3.3 *The early-age monitoring on concrete with restriction**

The volume of the specimen in this experiment is 600mm×600mm×63mm. The mix proportion and properties of concrete is also as Table 1.Fourteen φ10mm×100mm bolts are set in every edge of the mould, as Figure8 shows.

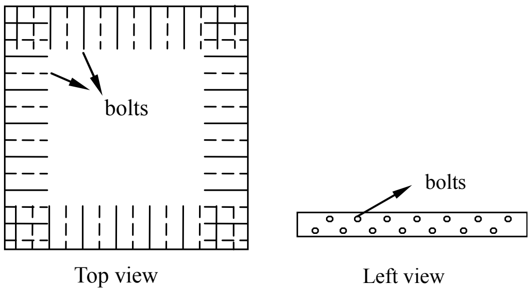


Figure 8. Sketch of the mould with bolts

When doing experiments in this mould, concrete inside is under tow kinds of restrictions. One is from the bolts, and the other is from the neighbor concrete. This is coincidence with the real structures well. The concrete curing temperature is a constant (22℃). And the positions of Fiber Bragg Gratings embedded in the concrete specimen are as Figure9 shows. Saving data after the concrete finished pouring.

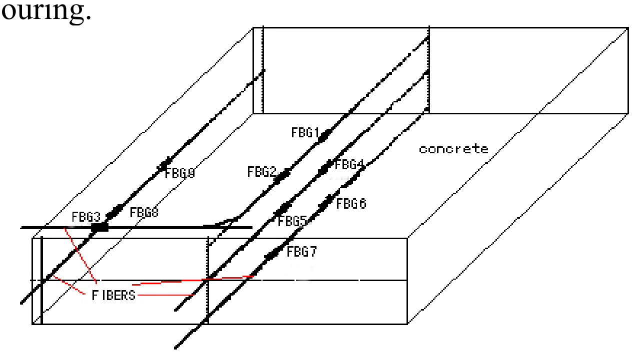


Figure 9. Sketch of FBGs embedded in concrete specimen

We have continuously monitored the specimen for 7 days, and the strain changes we obtained are as Figure10 to Figure13 show.

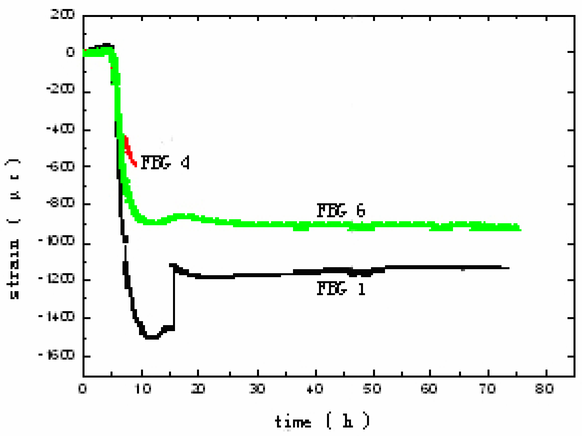


Figure 10. Strain course for FBG1、4、6 in specimen

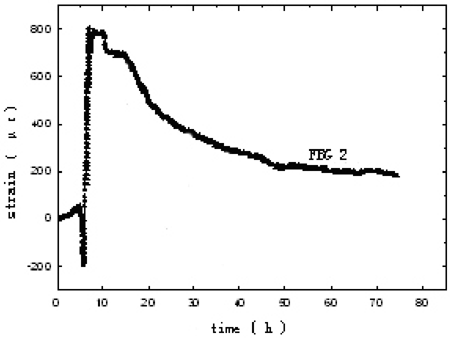


Figure 11. Strain course for FBG2 in specimen

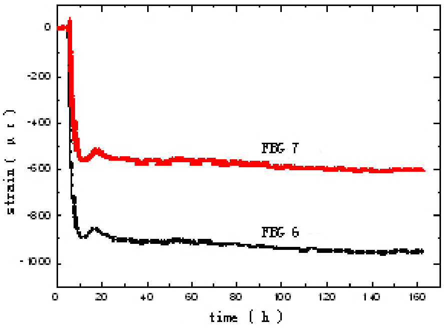


Figure 12. Strain course for FBG6、7 in specimen

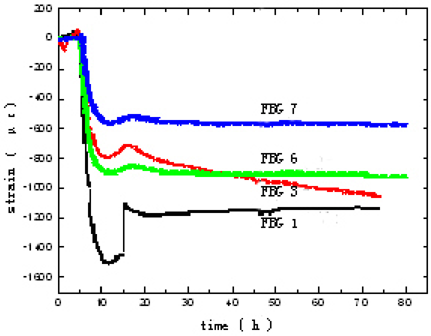


Figure 13. Strain course for FBG1、3、6、7 in specimen

Figure10 to Figure13 clearly shows the 1d to 7d inner strain changes of the concrete with restrictions: in the early 5 hours, the concrete began expanding. This is mainly because the temperature increasing and the swelling stress occurred inside the concrete. After that, the shrinkage strain occurred and rising quickly. From the Figs below we can analyze the shrinkages and cracks in different areas of the concrete specimen. The inflection points on the curves in the graphs mean that in that moment, maybe some small cracks appeared.

Table 1　Mix proportion and properties of concrete

Mix proportion　(kg/m3)					Slump Constant (cm)	Time of setting (h: min)		Compression strength of 28d (MPa)
Cement	Macadam	Sand	Water	Super water reducing agent		Initial setting	Final setting	
520	1131	693	156	4.42	18.5	6:6	8:18	78

3.4 *The early-age monitoring on mass concrete specimen and mass concrete structures*

Four kinds of FBG sensors are used in this part: Metal tube packaged FBG strain and temperature sensors, FRP packaged FBG strain and temperature sensors.

3.4.1 *The early-age monitoring on mass concrete specimen in laboratory*

The volume of the specimen in this experiment is 600mm×600mm×63mm. The mix proportion and properties of concrete is still as Table 1. And the specimen is kept heat by six pieces of benzene plates to simulate the real situation of mass concrete structures. As shown in Figure14.

Figure 14. Mass concrete specimen

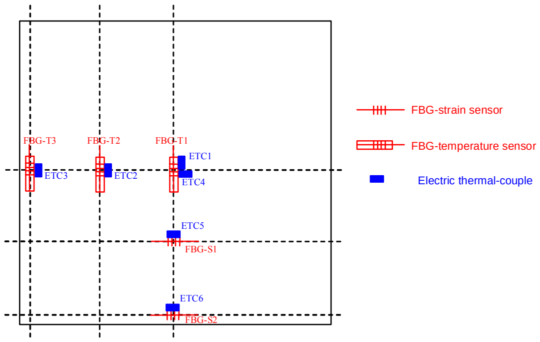


Figure 15. Abridged general view of positions of every kinds of sensors

Because of the small volume of the specimen, the temperature and strain changes are almost the same even though in different positions. The monitoring results are as shown in Figure16 and Figure17.

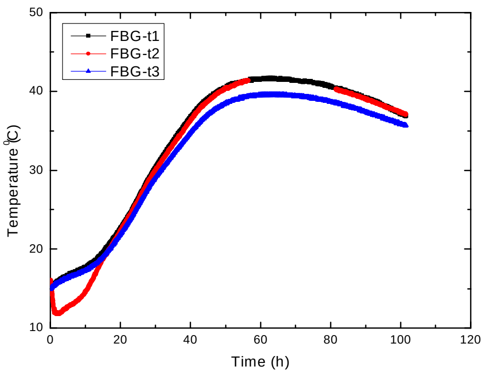


Figure 16. Temperature changes monitored by FBGs

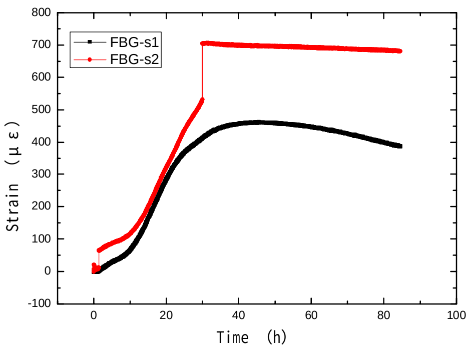


Figure 17. Strain changes monitored by FBGs

The temperature and strain changes are also well obtained by our sensors. In different positions of the specimen, the temperature changes are the same because the benzene plates, while the strain changes are some level different, even at some points, cracks appears.

3.4.2 *The temperature and strain monitoring on mass concrete structures of Nanjing the 3rd Yangtze bridge*

The main pier, transition pier and assistant pier of the Nanjing 3rd Yangtze Bridge are all made of mass concrete. Totally, 225 temperature sensors and 12 strain sensors were installed in main pier caps, main tower seat, transition pier cap and assistant pier cap. These sensors worked well and here, we take assistant pier cap, cap in upriver direction of main pier as examples to explain the temperature and strain monitoring behaviors of the sensors.

Figure18 and Figure19 are the monitoring results, which are very helpful to us to do the work for construction control.

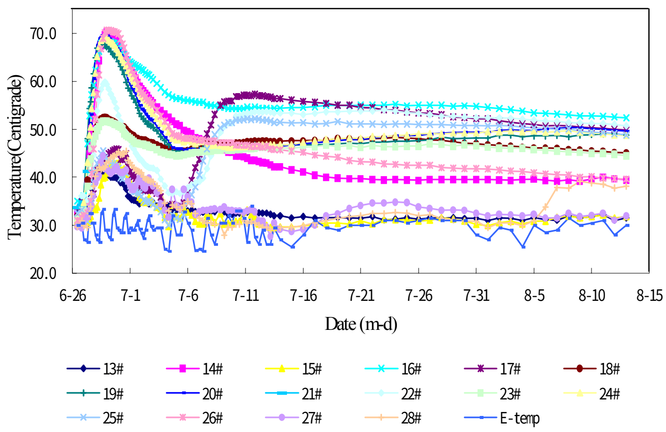


Figure 18. Temperature monitoring results of upriver main pier cap

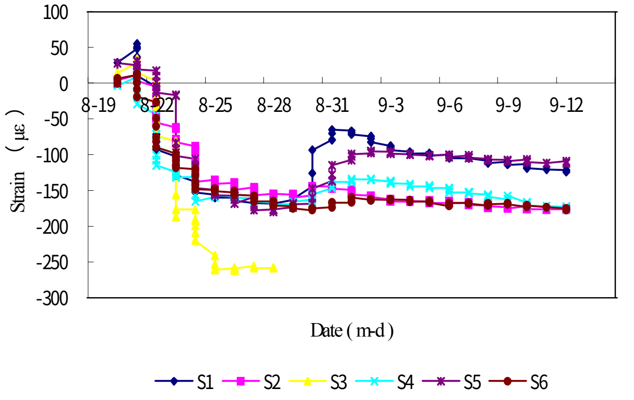


Figure 19. The strain monitoring results of assistant pier cap

Figure19 shows directly the inner deformation of the concrete at the early age. And we can also draw that even some expansion deformation appear with the temperature ascend, after pass the temperature peak, the shrinkage deformation of the concrete become much higher, which mainly contains plastic shrinkage and self-shrinkage. Construction control decision was given according to the monitored temperature field and calculated stress information.

3.5 *The early-age monitoring on Early-freezing of Negative Concrete*

The above monitoring works are all in positive temperature situations, in this part we did some research work on early-freezing of negative concrete monitoring to see how the FBG sensors work and whether the changing rule of early-freezing of negative concrete is well obtained. We chose 3 temperature levels: -5℃, -10℃and-15℃ as testing temperature. And the mix proportion and properties of the concrete in this experiment is as shown in table 2. The embedding situation of FBG in the specimen is also as shown in Figure3.

Table 2. Mix proportion and properties of concrete

Water (kg/m3)	Cement (kg/m3)	Fly ash (kg/m3)	Fine aggregate (kg/m3)	Coarse aggregate (kg/m3)	Pumping agent (%)
173	460	50	648	1058	1.5

The results show that FBG sensors have finished a good job. Here we select the monitoring results at -15℃ as an example to show how the FBG sensors work. After mixing, the specimens were located at 22℃ for about 4 hours, and then they were put into the refrigerator at -15℃ for 7 days, after that we picked out the specimen and put them in the laboratory room at about 22℃. The Strain changes with age of Early-freezing of Negative Concrete at -15℃ obtained by FBG sensors are shown in Figure20.

Figure20 shows clearly that FBG strain sensors can be used in negative concrete for monitoring the strain changes on whole curing process in different temperatures.

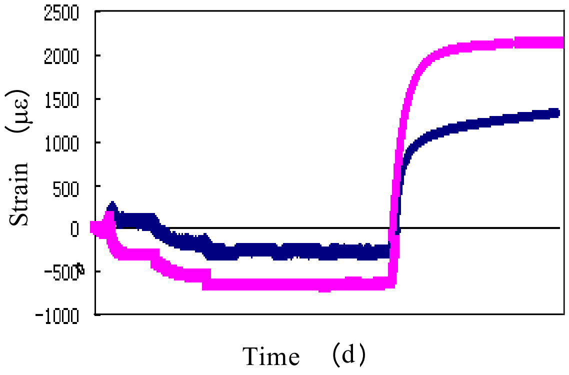


Figure 20. Strain changes with age of Early-freezing of Negative Concrete at -15℃monitored by FBG

4 CONCLUSIONS AND DISCUSSIONS

According to the sensing properties of FBG sensors and self-characters of the cement-based materials in the early-age, we have successfully finished monitoring the early-age inner strain and temperature changes of different kinds of cement-based materials including neat cement paste, concrete with and without restrictions, mass concrete specimens and mass concrete structures, negative concrete with FBG sensors systematically. We discussed the embedding technology and the embedding requirements of the Fiber Bragg Gratings. And some good results are obtained, the followings are drawn:

(1) FBG is a good kind of useful sensor in concrete hardening process monitoring.

(2) Tube-drawing is a effective method for us to embed naked FBG inside the cement-based materials.

(3) We can use FBG monitoring not only the inner strain but also the temperature changing regularities of the cement-based materials in the early-age.

(4) We can use FBG sensors monitoring not only positive cement-based materials but also negative cement-based materials.

The development of cement-based materials can not depart from the study in their early-age, FBG would play an important role in this field.

ACKNOWLEDGEMENTS

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* Small part of the paper about the early-age monitoring on concrete with restriction was introduced in authors' reference 7.

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