Experiment on the Monitoring of Backfilling of Cavities around an Old Railway Tunnel Using Plastic Optical Fibers

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It has become an issue to confirm the performance of backfill grouting of cavities behind the tunnel linings. A simple optical fiber sensor with a tip-shaped end is proposed to monitor the arrival of grout material by detecting the change of returning light based on the light reflection and refraction. It utilizes two same plastic optical fibers as the medium of light transmission. Two optical fibers, each with a 45 bevel angle, are bonded parallel with the adhesive agent at one end, forming a right triangle prism structure. With the same input light source from one fiber, it is quite different of the returning light from the other fiber depending on whether the optical fiber sensor is in the water (grout material) or not. In this report, a preliminary test and a field experiment in the old tunnel repair work were carried out respectively to verify the feasibility of detecting the arrival of grout material. It is found that it is possible to judge the arrival of grout material at the monitoring point with the optical fiber sensor. Finally, the future work is discussed briefly.

Key Words: *tunnel cavity, backfill grouting, monitoring, optical fiber sensor*

1. INTRODUCTION

The issue of deterioration of infrastructure has gained much attention since the collapse of the ceiling board in Sasago Tunnel in 2012[1]. It is urgent to repair and strengthen the old tunnels in service which have serious defects in structure, such as the progressive lining cracks, large deformations, etc. Especially, in some tunnels which were constructed by the traditional timbering support method, the cavities are often found behind the tunnel lining. It is useful to fill the cavities with grout materials in order to unify the ground and tunnel structure, so that the stabilization of the ground and the tunnel can be achieved.

Great progress has been made in the grout materials and equipment. However, the accuracy of the measurement of the distribution and size of the cavities behind the tunnel linings is not sufficient. The backfill grout of the cavity is mainly managed by both the grouting pressure and the leakage of grout material from the check hole in practice. But, to check the actual situation of backfill effectively remains an issue. Therefore, it is needed to monitor the grouting situation where the grout material is difficult to reach between the injection hole and the nearby check hole. Moreover, the method for monitoring should be simple and low-cost.

A monitoring scheme called On-Site Visualization (OSV) is proposed to capture the deformation of structure and make the measured results visible by different colors of light. Thus, the workers at the construction site are able to judge the risks by themselves as early as possible and take action to prevent accidents from happening. Based on this concept, a kind of plastic optical fiber sensor is introduced to monitor the arrival of grout material behind the tunnel lining. A preliminary test and a field experiment were carried out to verify the feasibility of this method. The future work is also discussed briefly.

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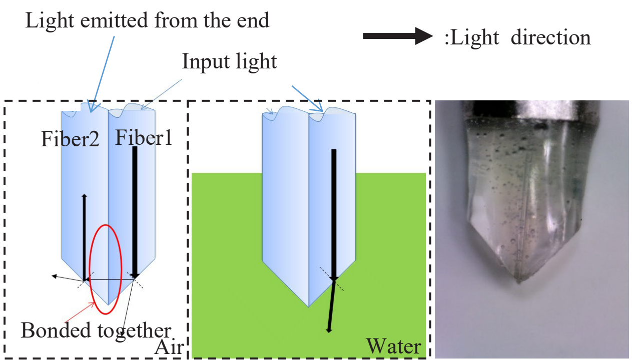
2. MECHANISM

A simple plastic optical fiber (shortened as POF) sensor is proposed, which is able to detect the existence of liquid (water) by the reflection of light from the prism end of the optical fiber[2]. It utilizes two POFs (1 mm in diameter) as the media of light transmission. The right triangle prism is formed directly at one end where two bare optical fibers are bonded as shown in **Fig.1**. In the air, when the light from the first fiber hits the sloped



(a) In the air (b) In the water (c) Real sensor

Fig.1 Structure of sensor and light refraction.

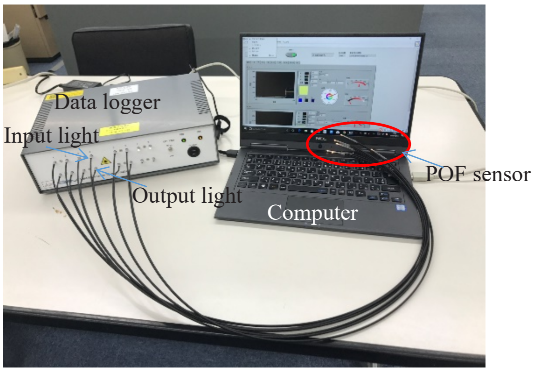


Photo.1 Light State Sensing System (LS^3)

interface, the internal reflection of light would happen rather than dispersion. Some of the light would be reflected into the second fiber, passing through the boundary of the two fibers. Then the light would be reflected again at the sloped surface of the second fiber, which could be seen directly at the end of the second fiber. When the prism end of POF sensor is placed in the water, the light would be dispersed rather than reflected at the two sloped surfaces. So the light from the end of second fiber becomes weak. A light state sensing system (LS^3) was developed to measure the emitted light intensity, which had the light source, a data logger and a computer (see **Photo.1**) [3].

The POF sensor was tested in the water and the fresh concrete, as shown in **Fig.2**. First, the sensor was inserted vertically into the water and then pulled out into the air, repeatedly. Thus, the measured light intensity became very small, less than 1000 (arbitrary unit) in the water. The light intensity returned to its initial value when the sensor was in the air. Next, the sensor was inserted into the fresh concrete. The light intensity became around 3700, higher than in the water. There was some change of the light intensity when the sensor was pulled out into the air. Finally, the sensor was washed in the water and the light intensity returned to the initial value once again in the air.

As became clear above, the POF sensor can tell the difference of air, water and the cement-based material (such as fresh concrete) clearly by the change of the returning light intensity, because different material has different refractive index of light. Based on this mechanism, the POF sensors were tested to monitor the existence of grout material used in the tunnel repair work.

3. PRELIMINARY EXPERIMENT

A preliminary experiment was conducted in order to find the response of the POF sensor in the case of grouting. Three POF sensors were set up along the inner side of a bucket at different heights as shown in **Fig.3** and **Photo.2**. In order to investigate the effect of direction of the POF sensor, two sensors were fixed up in the downward direction and the other was in the opposite direction. Although the shape of the cavity behind the tunnel lining is very complex, in the grouting process it is considered that the grouting level goes up gradually in a cavity. The grout material was poured slowly into the bucket from the bottom so that the simple grouting process could be simulated. As shown in **Table 1**, the 2-liquid type grout material was chosen consisting of cement and plasticizer. It had good workability under the pressure and long-term stability in the water.

The results of the grouting test in a bucket are shown in **Fig.4**. It is found that all the sensors had the real-time reactions to the arrival of grout material. The light intensity of ch1, which was at the lowest position in the bucket, dropped firstly as soon as the grout material met the POF sensor ch1. And next was ch2. Finally, the light intensity of ch3 decreased, which agreed well with the time difference of the arrival of grout material in the bucket.

About 30 seconds after the 1st grouting, the bucket was shaken lightly by hand so that the light intensity of the sensors fluctuated accordingly. After about 60 seconds, some grout material was added into the bucket. The light intensity of ch1 and ch3 changed a bit, while ch2 had no reaction. It seems that there was no obvious effect of the direction of sensor when the POF sensor was in the grout material. The reason that the

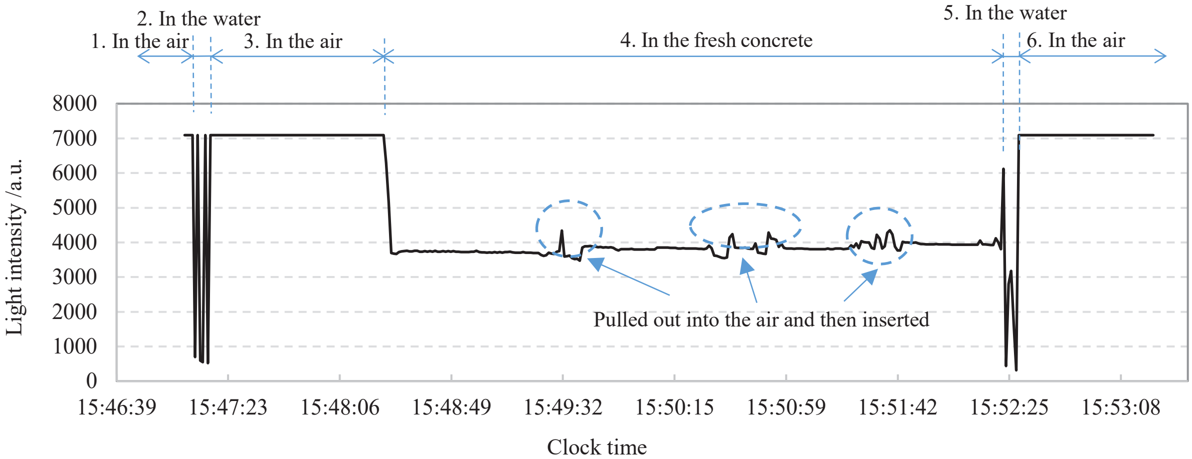


Fig.2 Test in the water and fresh concrete with the POF sensor

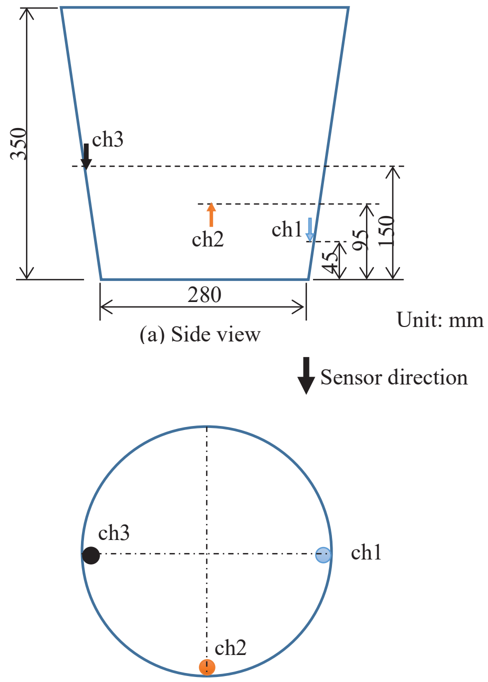


Fig.3 Layout of POF sensors in a bucket

(a) Setup of sensors (b) Grout material

Photo.2 Grouting test in a bucket

measured light intensity would either increase or decrease was because a little difference of the grout material around the sensor could be detected in real time as the grout material was shaken. The change of measured light intensity while the material was shaken was small, compared with the intensity at the arrival of grout material. Therefore, the POF sensors can be set up as needed to monitor the arrival of grout material, regardless of their directions.

4. FIELD EXPERIMENT

4.1 Project overview

The field experiment was carried out in a repair work of Tateno Tunnel, which is a railway tunnel between Tateno Station and Akamizu Station along JR Kyushu Hohi Main Line in Kumamoto. It was built by the traditional timbering support method and has been in-service for more than 100 years. The tunnel was damaged by the Kumamoto Earthquake in 2016. Many cracks could be found in the lining of the tunnel. What's worse, there were many cavities and voids behind the lining of the tunnel according to the radar investigation. As a result, in order to protect the structure of the tunnel, this old tunnel had to be repaired and reinforced carefully.

4.2 Monitoring plan

The cavities behind the tunnel were filled with the grout material, same as that used in the preliminary experiment. The grout holes were drilled directly with an interval of 2.5 m along

Table 1 Main ingredients of grout mixture (One batch).

Ingredient 1	Base material (1007liters)		
	Cement	Water	Water-reducing agent
Content	659kg	791kg	1.65kg
Ingredient 2	Plasticizer (217liters)		
	Plasticizer -A	Plasticizer -B	Water
Content	2kg	25kg	200kg

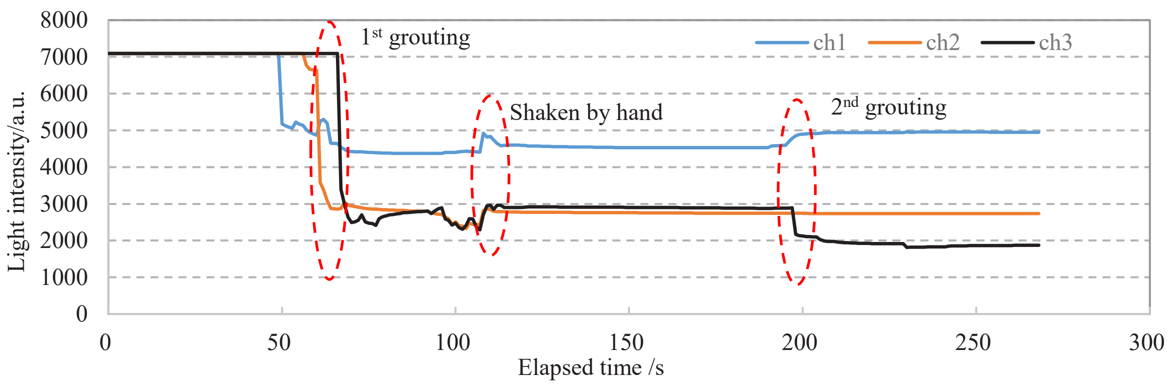


Fig.4 Light intensity change with time during grouting in a bucket.

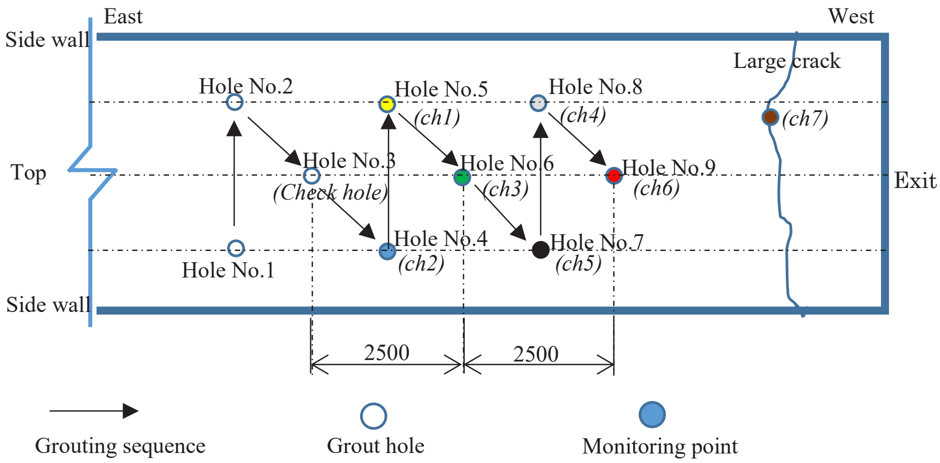
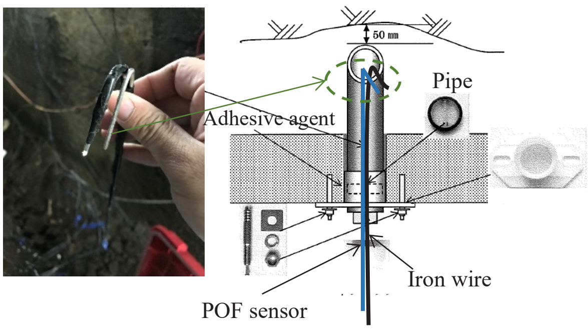


Fig.5 Layout of the grout holes and the monitoring points at the crown along the tunnel

Photo.3 Monitoring points at the crown along the tunnel



(a) Actual fiber sensor (b) Installation image

Fig.6 Details of setup of the sensor in field experiment

the crown of the tunnel in three lines as shown in **Fig.5** and **Photo.3**. When the grout material was injected from the grout hole, the holes nearby were used as the check points to find whether the grout material had arrived as expected.

Because it was considered that the cavities and voids at the crown of the tunnel were difficult to fill with the grout material completely, the monitoring points were decided at the crown of tunnel to check the actual grouting situation.

Table 2 Reactions of sensors during every injection.

Grout hole	-	ch1	ch2	ch3	ch4	ch5	ch6	ch7
No.1	L		×					
	R		×					
No.2	L	○						
	R	○						
No.3	L	×	×					
	R	×	×					
No.4 (ch2)	L			×		×		
	R			×		×		
No.5 (ch1)	L			×	○			
	R			×	○			
No.6 (ch3)	L				×	×		
	R				×	○		
No.7 (ch5)	L						×	
	R						×	
No.8 (ch4)	L						×	×
	R						×	×
No.9 (ch6)	L							×
	R							×

Notes:
1. No.4 (ch2) means the grouting was conducted at the grout hole No.4, where the sensor ch2 was set up.
2. L is a shortening for leakage of grout material from the check hole.
3. R is a shortening for reaction of the sensor.
4. ○ means yes, it happened, while × means no, it didn't.
5. Shadow area means the most possible grout hole to be affected by the grouting.

For convenience, the POF sensors with the hook shape were installed directly inside the check hole as shown in **Figs.5** and **6**. The end of the sensor was outside the pipe, directly below the top end of the pipe in the cavity (about 20 mm below the inclined pipe end). The stiff steel wire was utilized to give support to the POF sensor. As a result, the reaction of POF sensor could be checked and compared directly if there was the leakage of grout material from the same grout hole. There were 6 sensors (ch1~ch6) set up directly in 6 grout holes respectively. The sensor ch7 was set up in a wide and continuous crack near the exit of the tunnel. After the sensor was removed, the following grouting would be conducted from the hole where the sensor was set up. The experiment started on the morning of May 9th, 2019. And the whole grouting work was finished at 4:00 in the afternoon.

4.3 Results and analysis

The results of the reactions of sensors during the grouting process are shown in **Table 2**. It is seen that the POF sensors could have the reaction when there were leakages of grout material from the same holes. To take ch4 for example, the grout material was injected from the grout hole No.5 where the sensor ch1 was located from 12:20. At about 13:08, the leakage was found from the hole where the ch4 was located.

It is seen from **Fig.7** that the light intensity dropped sharply at the same time (marked as the red circle), showing clearly the arrival of grout material. In **Fig.8**, when the grouting was conducted from the 3rd grout hole, there was no leakage from the check hole (ch3). And the POF sensor ch3 had no reaction until the end of grouting. Because the following 6th grouting would be conducted from the hole where the sensor ch3 was located, the cavity around the hole No.6 would be filled with grout material.

When the grouting was conducted from the grout hole No.6 (ch3), the POF sensor ch5 had reaction even though there was no leakage from the grout hole No.7 (ch5), as shown in **Fig.9**. It indicates that the grout material passed through the location of ch3 while the level of grout material remained below the upper end of the pipe.

The sensor ch7 was inserted directly into the crack of the lining. It was thought that the leakage of grout material could happen when the grouting was conducted from the hole nearby. The result in **Fig.10** shows that there was no reaction of the sensor during the grouting process. In fact, there was no leakage from that crack either. It can be considered that it would be hard to predict the flow of grouting in the cavities behind the tunnel lining. The tunnel lining from the hole No.9 to the exit would be reconstructed in this repair work. Thus the cavity behind the lining crack could be treated properly.

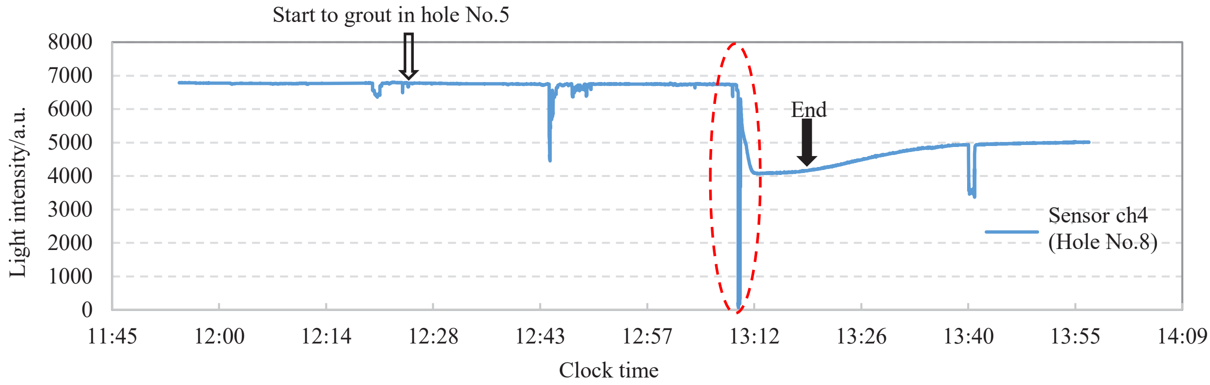


Fig.7 Change of the reflected light of sensor ch4 with time during the grouting process in grout hole No.5

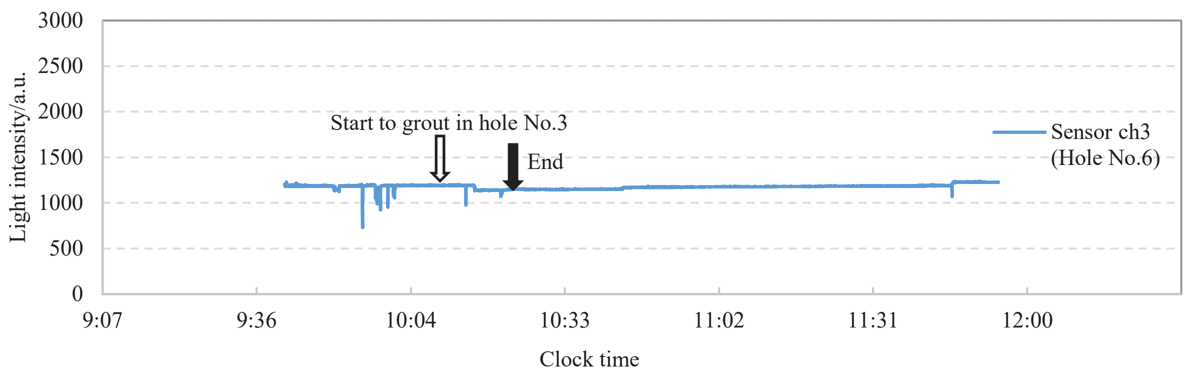


Fig.8 Change of the reflected light of sensor ch3 with time during the grouting process in grout hole No.3

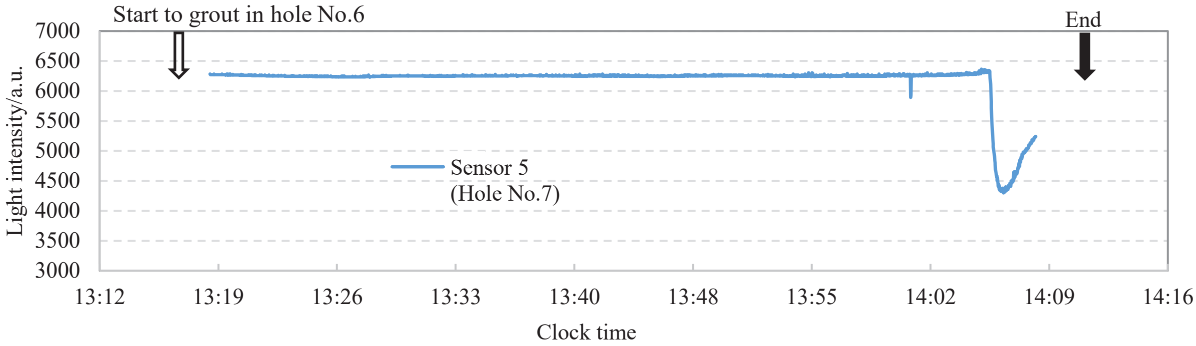


Fig.9 Change of the reflected light of sensor ch5 with time during the grouting process in grout hole No.6

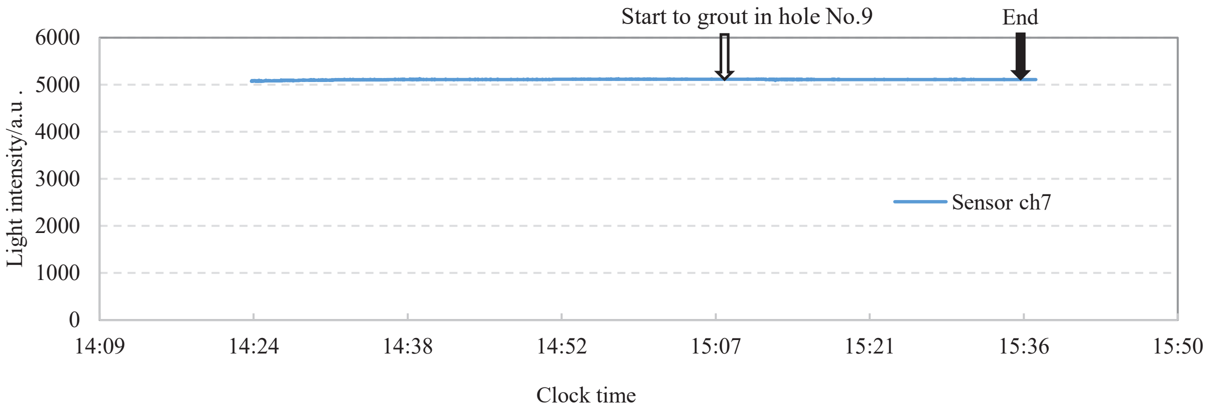


Fig.10 Change of the reflected light of sensor ch7 with time during the grouting process in grout hole No.9

5. DISCUSSIONS

Since the proposed POF sensor is the one-point monitoring of the backfill grouting, it is very important to determine where to be observed according to a proper principle in practice. Because the diameter of the POF sensor is very small (less than 10mm), it is easy to set up in the lining of tunnel as needed, with less influence on the structure. In addition, because the optical fiber is soft and flexible, it is very convenient to arrange the layout of the fibers in the tunnel. To some extent, it turns out to be multi-point monitoring system if many POF sensors are used in a confined zone.

During the field experiment, the equipment LS^3, which was developed mostly for laboratory tests, was utilized to measure and record the intensity of light that returned from the optical fiber. On the construction site, the waterproofness and movability of the measuring equipment are important. A compact monitoring system should be developed to be applicable in the severe environment of the tunnel, helping improve the quality of backfill grouting.

6. SUMMARIES

A plastic optical fiber sensor is proposed to monitor the backfill grouting of cavities behind the tunnel linings. It makes use of the light reflection and refraction to tell the difference of the material where the sensor is placed. A preliminary test was conducted to find the response of the sensor, subject to different height or direction of sensor setup. It is found that the effect on detecting the arrival of grout material from the direction of POF sensor is not obvious. Further, the field experiment was carried out to verify the feasibility of monitoring of grouting. It shows that the sensors had good reactions to the arrival of grout material in the cavity. Although the situation of grouting behind the tunnel lining is complex, the monitoring with the sensor can make the flow of grouting clear, which enables the technicians to adjust the grouting correctly.

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光ファイバーを用いたトンネル覆工背面空洞充填のモニタリング実験

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本報告はトンネル覆工背面空洞の充填材の有無を判別するために，プラスチック光ファイバーセンサーを用いた方法を提案した．光ファイバーセンサーは2本の光ファイバーからなる直角プリズム構造で材料の屈折率の違いによって，反射された光強度が変化する．つまり，空気中では，最初の1本目の光ファイバーからの光が斜め面に当たると，光は内部反射によって分散される．一部の光は，光ファイバーの境界を通過し2本目の光ファイバーの斜面で再び反射され，2本目の光ファイバーの端部で直接見ることができる．また，光ファイバーセンサーのプリズム端を水中（充填材）に置くと，光はセンサー先端の2つの斜面で反射されるのではなく，ほとんど水に入る．したがって，2本目の光ファイバー端からの光は弱くなり，光強度の変化によって空気，水と充填材を判定できる．

本報告は光ファイバーセンサーを用いたトンネルの空洞充填確認方法の適用性について予備実験と現場実験を行い，検証したものである．

キーワード：トンネル空洞，裏込み注入，モニタリング，光ファイバーセンサー