In the New Austrian Tunneling Method (NATM) of tunnel design and construction, it is important to know the actual compressive strength of lining concrete at early ages, which determines the time of demolding and its future durability. The degree of hydration reaction of in-place concrete is regarded as a useful reference to estimate the development of the strength of concrete. Based on the concept of On-Site Visualization, this paper presents a new approach to monitoring the hardening progress of fresh concrete/mortar using plastic optical fiber (POF) sensors. The principle of sensing is illustrated conceptually. The fundamental experiments were carried out to investigate the change in the visible light intensity reflected from the sensing plane of POF sensor during the hydration of concrete/mortar at early ages. The typical influence factors were also studied. The hydration process of concrete/mortar at early ages was well observed by the POF sensors. The direction of POF sensor installation had a significant effect on the pattern of light intensity change. When the sensor was installed pointing downwards, the light intensity dropped at first but increased rapidly in a few hours, which indicated the phase evolution when the free water disappeared in the hardening concrete/mortar. While the sensor was set up pointing upwards, the light intensity dropped in the first stage and then grew up slowly with time. Furthermore, the hydration process of concrete was characterized by introducing the nominal refractive index (NRI), which could be calculated from the measured light intensity. Thus, the hydration of concrete could be divided into three stages approximately according to the curve of NRI of concrete (when the sensor was installed pointing upwards), which coincided with the common knowledge of the concrete hydration process. Finally, the future work is discussed briefly.

**Key Words:** hydration process, monitoring, plastic optical fiber sensor, reflected light change, nominal refractive index
1. INTRODUCTION

The secondary concrete lining in the NATM tunnel is constructed in order to provide a safe environment for the designed function during the service period\(^1\). Much attention has been paid to improve the quality of the lining concrete for better durability and serviceability of the tunnel. The hydration reaction of concrete has a large influence on the concrete quality, such as the final concrete strength and the durability, corresponding to the curing conditions, environmental temperature, etc\(^2,3\). In addition, it is important to determine when to remove the framework after the lining concrete placement, which is also related to the hydration reaction process of early-age concrete. Therefore, it is useful to monitor the hydration process on the field to estimate the development of the compressive strength of concrete and the framework stripping time.

The hydration of concrete involves physical and chemical reactions, which should be evaluated based on the testing environment. There are several approaches to monitor the hydration reaction process on the field by measuring the physical properties of concrete, such as ultrasonic pulse velocity (UPV), acoustic emission (AE), electrical conductivity, permittivity, and so on\(^4-14\). The UPV technique, a non-destructive testing method, is applied on the basic principle that the elastic wave depends on the traveling medium. The UPV change indicates the evolution of the microstructure during the hydration of fresh concrete, which could be observed after a few hours of the dormant stage. AE, a passive ultrasonic technique, is generally used for crack detection in solid materials. Some studies have shown that it is possible to apply AE to characterize the hardening process of concrete at early ages, since the transient elastic waves are generated by a rapid release of energy during the hydration reaction. The electrical conductivity technique is adopted to measure the electric resistivity between two electrodes with an electrical field during the hardening of cement-based concrete. It has been proved that the electrical conductivity of the cement mortar during the hydration process changes with the elution of ions in the electrolyte solution of the fresh concrete. The measurement is greatly affected by the geometry of the concrete sample. Temperature maturity is an indirect method to estimate the in-place compressive strength of concrete at early ages\(^15-18\). It is governed on the assumption that the strength of concrete at early ages is a function of its age and the temperature history. This method needs a relatively long time span to determine the activation energy during hydration. Since the measurement is very operational, it is adopted widely in the quality control of the lining concrete in tunnel engineering and other constructions.

It is found that these methods are usually used to characterize the hydration reaction and estimate the strength of concrete at early ages. But only some of them test the definite parameters of the materials, e.g., the electrical conductivity and the permittivity. Some of them need special expensive equipment, which makes its wide application difficult in practice. Hence, a cost-effective and simple method is required to monitor the hydration process of concrete at early ages on the field.

The concept of On-Site Visualization (OSV) has been proposed in Japan since 2006, which encourages the monitoring of the deformation of structures during construction and visualizes the measured data by different colors of LED light on the field in real-time\(^19-21\). Among the various techniques for monitoring and data visualization offered in the framework of the OSV, the use of new sensors made of POF has been found effective and promising in reading out important data from arbitrary points within engineering materials such as fresh cement mortar and concrete. This paper proposes a new approach to monitoring the complete process of the hardening process of concrete or mortar at early ages using POF sensors. First, the principle of sensing was illustrated; then, the fundamental experiments were conducted to investigate the change in light intensity during the hydration of concrete or mortar. The results were interpreted by introducing a parameter (nominal refractive index, or NRI) for the characterization of the hydration of the cement-based material. Finally, the future work is discussed briefly.

2. PRINCIPLE OF POF SENSOR

(1) Reflection and refractive of light

In geometric optics as shown in Fig.1, the reflection and refraction of light happen at the interface between two different isotropic media such as air and water. The formulas for the angles of incidence, reflection, and refraction are given by Snell's law:

\[
\frac{n_1}{n_2} = \frac{\sin \theta_1}{\sin \theta_2} = \frac{\sin \theta_2}{\sin \theta_1}
\]

where \(n_1\) and \(n_2\) are the refractive indices of the two media, and \(\theta_1\) and \(\theta_2\) are the angles of incidence and refraction, respectively.

The light intensity change during the hydration of concrete or mortar is monitored using a POF sensor. The sensor is placed at the interface between the concrete and the electrolyte solution. The light intensity is measured at different hydration stages, and the change is related to the hydration process. The measured data can be visualized in real-time using colors of LED light.

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Fig.1 Reflection and refraction of light at the interface.
as air and water. Snell’s law is used to trace the ray of refracted light. The intensity of reflected or refracted light is generally controlled by the refractive indices ($n_1$ and $n_2$) of the two media at any incident angle of light, which would be discussed in section 4. Conceptually, the intensity of reflected light depends largely on the difference ($\Delta n = |n_1 - n_2|$) of the two refractive indices. A larger $\Delta n$ can result in a larger intensity of reflected light. In addition, when light travels from one medium with a larger refractive index to the medium with a smaller refractive index, the total internal reflection occurs as long as the incident angle is larger than the critical angle. The POF was invented based on the principle of total internal reflection.

(2) **RR Sensor**

POF is cheaper and more flexible than glass optical fiber, making it easy to handle in practice. A simple POF sensor with the prism-end is proposed as shown in Fig. 2, which is able to detect the existence of liquid like water, by the reflection of light from the optical fiber (1 mm in diameter). The right triangle prism is formed directly at one end where two bare optical fibers are bonded by the transparent adhesive. In the sensor, when the light, indicated as L1, from the fiber 1 hits the sloped interface called the sensing plane, the light would be reflected and refracted at the interface. Some of the light L3’ would be reflected into the fiber 2, passing through the boundary of the two fibers. Then the light L3’ would be reflected and refracted again at another sensing plane and the reflected light L5 could be seen directly at the end of the second fiber. It is called RR sensor, since the light in the sensor is reflected and refracted at the sensing planes. For example, as the refractive index of POF is 1.49, the intensity of light L5 when the RR sensor is placed in the air would be larger than that in the water ($\Delta n = 1.49 - 1.33$).

(3) **Light state sensing system**

A light state sensing system (LS') was developed to measure the intensity of the light brought back by POF sensors. This optical data logger has the LED light source, optical data logging units, and is operated by the software installed on a personal computer (see Fig. 3). Since the 12-bit digital color sensor is adopted to detect three primary colors (red, green, and blue) of visible light in LS', the digital signal of light intensity is serially output as 12-bit digital data. The maximum value of each of the three primary colors is 4095 ($2^{12} - 1$), since the first value starts from 0.
In this study, the light intensity is defined by Expression (1) as the square root of the value of three primary colors:

\[ L = \sqrt{red^2 + green^2 + blue^2} \]  

whose max value is 7093.

The value of red is calculated as:

\[ red = \int_{T_1}^{T_2} V_{red} \times dt \]  

where \( dt \) is the integral time, \( T_2 - T_1 \) is the interval of integral time, and \( V_{red} \) is the value of light at the clock time \( T \). The value of the other two colors can be calculated in the same way.

Figure 4 shows the result of a simple test in which the water level in the beaker was lowered slowly. Two RR sensors were set at different heights, such that all sensing planes of the sensors were completely in water, initially. Then, the water in the beaker was heated at its bottom side so that the water level declined gradually due to evaporation. Both sensors experienced a sudden change in light intensity when the sensing planes of these sensors were exposed to the air from the water.

Therefore, the RR sensor is able to tell whether its sensing planes are in contact with water or air (two kinds of materials with different refractive indices) immediately. In other words, the phase of material (fluid or gaseous phase) could be detected by the RR sensor.

3. FUNDAMENTAL EXPERIMENT

(1) Fresh concrete experiment
a) Material and method

The Ordinary Portland Cement (OPC)-based concrete was investigated first by using the RR sensors. The concrete mix proportion is shown in Table 1. A concrete beam (water–cement ratio \( W/C = 49.5\% \)) was designed with dimensions of 1600(\( l \)) × 200(\( h \)) × 100(\( w \))mm as shown in Fig.5.

The hardening process of the concrete beam was monitored by RR sensors in eight sections. Each section had three RR sensors installed in three different directions (pointing upwards, downwards, and horizontally), respectively. The monitoring points were at the depth of about 50mm from the surface of the beam. Thus, the effect of the direction of RR sensor on the measured light intensity could be investigated. Moreover, the repeatable performance of the monitoring could be examined.

The temperature at the position of about 50mm from the upper surface was measured by two thermocouples (T1 and T2) at two points, respectively (see Table 1 Concrete mix proportion.

| W/C (%) | Unit weight (kg/m³) | Air Entrainment |
|---------|--------------------|-----------------|
| 49.5    | 180                | 364             |
| 778     | 971                | 3.89            |

T1, T2: thermometer, T3: room temp. T3 Unit: mm

Fig.5 Laboratory experiment of concrete hardening with RR sensors.
Fig. 5 (a)). At the same time, the room temperature $T_3$ was measured.

b) Experiment procedure

The concrete beam was cast in the mold after the RR sensors were set up. It was cured where the room temperature varied around 12 degrees. The demolding was not conducted during the experiment. The initial intensities of light measured by the RR sensors were adjusted to be close to each other by changing the integral time according to Expression (2). The record of all the data started before the placing of concrete when the RR sensors were in the air.

c) Results and analysis

First, the light intensity change would be analyzed. The results of reflected light intensity during the hydration of concrete at early ages within seven days are plotted as shown in Figs.6-8. In Fig.6, the left vertical axis is marked as the value of light intensity directly. While in Figs.7 and 8, the left ones are marked as the ratio of light intensity in the concrete to that in the air by Expression (3):

$$\frac{\text{Light intensity ratio}}{L_i^T_i} = \frac{\text{Light intensity in concrete}}{\text{Light intensity in air}}$$

which could be regarded as the reflection coefficient of light intensity during the hydration. Thus, the variation in the light intensity measured by different RR sensors could be reduced, because it was difficult to make all the initial values of light intensities measured by RR sensors the same. The right vertical axis in Figs.7 and 8 is the temperature during the experiment. The horizontal axis is the time starting from the placement of concrete. The red dashed line denotes the time corresponding to the temperature starting to increase and the max temperature during the hydration, respectively. The green dashed line represents the time when the light intensity increased dramatically.

Then, the influence factors would be discussed, including the direction of the sensor, the structure of the sensor, and the temperature. Figure 6 shows the light intensities measured for ch1–8, whose sensors were installed in the downward direction. The light intensities increased sharply in about 6.0–8.5 hours after the placement of concrete. There was no change in the light intensities as those absolute values were larger than 7093, resulting in the line of the light intensity ratio being kept horizontal with time. It was similar to the situation when the RR sensor emerged from the water to the air as shown in Fig.4. On the other hand, the trends in light intensity of ch9–24 whose directions were upward or horizontal in Figs.7–8 were completely different from the cases whose directions were downward in Fig.4.

The hardened mortar specimens with the RR sensors in two different directions (see Figs.9 (a) and (b)) were scanned by X-ray. As shown in Figs.9 (c) and (d), there was a void beneath the sensor in the downward direction. On the other hand, there was no void in front of the sensing planes of the RR sensor installed in the upward direction.

The process could be explained as shown in Fig.10. The sensing planes of the RR sensor were in full contact with the fresh mortar in the initial stage. Then, the void was formed due to the gravity of mortar, which was larger than that of RR sensor. In this stage, the void would be filled with the water mixture (free water mainly). On the sensing planes of the RR sensor, there was some mortar left, forming a thin film. Up to this point, there was not a large change but a little decrease in the light intensity. With the development of hydration reaction and bleeding in the mortar, the free water in the void became less and less, and finally, there was nothing but the air in the void. As a result, the light intensity increased significantly as soon as the sensor was exposed to the air. It should be noted that there was a thin mortar film on the sensing planes. This thin film seemed to have little effect on the increase of light intensity when the environment of RR sensor was switched from the free water to the air. Generally, the hardening of concrete or mortar develops from the initial mixture (fluid) phase, to the gel phase, and to the solid stage. It is a continuous process, without a clear boundary between the neighboring physical states. Herein, it could be thought that the time when the light intensity increased sharply indicated the end of the fluid phase of concrete or mortar during the hydration. In other words, the time when the free water disappeared could be detected by the RR sensor in the upward direction.

Figure 7 shows the changes in the light intensities of the RR sensors installed in the upward direction during the hydration. The changes in the light intensities were classified into two patterns. The temperature in the fresh concrete began to increase in about four hours after the placement and reached the maximum in about 11 hours according to T1 or T2. The peak temperature remained still for about three hours. Then, the temperature decreased gradually. It could be thought that the temperature in the concrete represented the hydration heat development. As shown in Fig.7 (a), the light intensity (ch9, ch13–15) decreased slowly in the first four hours when the hydration was not active. Then, it decreased with the gradient larger than before until the corresponding time of peak temperature (at 11 hours from the beginning of the experiment). We found that the light intensity continued decreasing but with a gradual gradient as the temperature went down. The minimum light intensity (ch13–15) was measured in 35–50 hours after the
placement of concrete. The corresponding time of the minimum light intensity of ch9 was about 20 hours, earlier than the others, which indicated faster hydration at the monitoring point of ch9. After passing the minimum value point, the light intensity kept increasing with a smaller gradient, compared with the initial stage of falling of light intensity. It is thought that the RR sensors (ch9, ch13–15) installed in the upward direction were in full contact with the concrete.

On the other hand, as shown in Fig.7 (b), the light intensity decreased in the trend, similar to Fig.7 (a), before the corresponding time of maximum temperature. Then the light intensity of ch10 and ch11 decreased with a small gradient continuously. On the other hand, the light intensity of ch12 and ch16 increased with a large gradient, whose value was bigger than the initial.

Figure 8 shows the light intensities of sensors installed in the horizontal direction during the hydration of concrete. As shown in Fig.8 (a), the light intensity increased dramatically before the corresponding time of maximum temperature. The time was close to that recorded by the RR sensors installed in the downward direction (Fig.6). The ratio of light intensity in the rising stage varied from 0.11–0.51,
which was larger than that of Fig. 7 (a) but smaller than that of Fig. 6 (light intensity ratio = 1).

Therefore, the effect of the direction of the sensor could be explained as shown in Fig. 11. Generally, the void occurred easily beneath the sensing planes of RR sensor, which was installed in the downward direction. The sensing planes of the RR sensor could be in full contact with the concrete or mortar when it was installed in the upward direction. When the RR sensor was installed in the horizontal direction, the possibility of the void appearing near the sensing planes would be between that expected for RR sensors installed in the downward direction and in the upward direction. Thus, in the following experiment, the sensors were set up in the upward direction to avoid the void formation in front of the sensing planes.

As the second influence factor, the structure of RR sensor is discussed here. Figure 12 shows three types of the cross-section of an RR sensor. Since the optical fiber had a circular cross-section, there would be a gap between the two fibers. The gap should be filled with the transparent adhesive. Otherwise, the gap would be filled with the water mixture in the fresh concrete or mortar. The light reflected by the first sensing plane of fiber would pass through the water mixture into the second fiber in the initial stage of hydration. With the development of hydration, fresh-water became less and less. The space would be filled with air (void), making it difficult for the light to travel through the interface (between fiber and air). As a result, the reflected light would become weaker and weaker after the corresponding time of maximum temperature as shown in Fig. 7 (ch10 and ch11). Therefore, the RR sensors without gap (2) in Fig. 12 (a) were suggested to be applied to reduce the variation in measured data of light intensities.

Since the temperature in fresh concrete would rise due to the hydration heat, it was necessary to investigate the effect of temperature on RR sensor during
the experiment. A laboratory experiment was carried out by putting a hardened mortar block (180 days old) into the heating water, as shown in Fig.13. Two RR sensors were at the location of 10mm from the bottom of the mortar block. The water was heated to about 42 degrees and kept still for 10 hours. Finally, the water temperature decreased gradually to the value of normal room temperature (15 degrees) as the heater stopped working. The temperature and the light intensities were recorded during the experiment. Since the RR sensor was very close to the water, the temperature around the sensor could be thought to be the same as the temperature of the water. The initial light intensity measured by the RR sensor in the mortar block before heating was regarded as the reference value. The ratio of light intensity in the vertical axis in Fig.14 was calculated by the current light intensity/initial light intensity, differently from that in Fig.7 (b). The reflected light intensity decreased as the temperature rose, which indicated a reverse correlation between the temperature and the light intensity. It is found that the temperature-induced ratio of light intensity was about 0.0039/degree. Because the temperature due to hydration reaction in fresh concrete in this study grew up from 19 degrees to 23.2 degrees (see Fig.7), the effect of temperature on the light intensity was only about 1.6%, which could be ignored in the result analysis. It should be noted that the effect of the moisture in the hardened mortar block was not considered in this experiment.

(2) Fresh mortar experiment
a) Material and method
Based on the analysis of the results of the concrete hardening experiment, the mortar hardening
experiment was conducted to verify which trend of light intensity was repeatable in Fig. 7. The mortar with the ratio of water to cement of 50% was designed, whose proportion is shown in Table 2. Four specimens were prepared, each of which had two RR sensors installed in the upward direction as shown in Fig. 15.

b) Experiment procedure

The experiment was carried out in the laboratory with air conditioners. First, the RR sensors were installed in the cylindrical mold at the designed position. Second, the fresh mortar was poured into the mold. At the same time, the data on the temperature and the light intensity were recorded during the experiment.

c) Results and analysis

As shown in Fig. 16, the temperature in the fresh mortar increased from 17.2 degrees gradually after the placement of mortar, and reached the maximum value of 22.1 degrees in about 14 hours. Although the temperature of the air conditioner was set up at 20 degrees, the room temperature varied during the daytime.

The light intensities recorded by most sensors changed in the trend similar to that in Fig. 7 (ch13–15). The initial light intensity ratio was in the range of 0.023–0.033. There was a small decrease after the placement of mortar. Then the light intensity went down with a larger increment until the corresponding time of maximum temperature \( t_c \) when the light intensity ratio was around 0.014–0.02. It continued decreasing with a smaller increment after passing \( t_c \). The light intensity of most sensors (except ch2 and ch8) reached the minimum value in about 60 hours \( t_{\text{min}} \) after the placement of mortar. Finally, the light intensity increased slightly, except for ch2 and ch8. The reason that ch2 and ch8 kept decreasing after passing \( t_{\text{min}} \) could be due to some gap still at the tip of the sensor. The final light intensity ratio was in the range of 0.007–0.013.

4. FURTHER INTERPRETATION

Generally, in optical mineralogy, the technique called transmitted light microscopy (TLM) is used to identify the composition of geological materials. A fundamental principle of TLM lies in that most materials, not only the dark-colored materials, but others that appear opaque, can transmit light if they are thin enough\(^{29)-38}\). Similarly, it is reasonable that the reflection and refraction of visible light happen at the interface between the sensing planes of RR sensor and the concrete or mortar in this study. Since the light intensity measured by RR sensor is affected greatly by the reflection and refraction during the hydration process, it could be regarded that the change in the light intensity indicated the physical property of hardening concrete or mortar. The complex refractive index (CRI) \( m \) is usually used to describe the physical property of absorbing materials, such as concrete or mortar, during the hydration reaction as shown in Expression (4):

\[
m = n + ik
\]

where the real part \( n \) is the refractive index, and the imaginary part \( k \) is the extinction coefficient, which represents the amount of attenuation when the visible light travels through the absorbing material. Table 3 summarizes the standard refractive indices of common materials at the wavelength of 589nm. Hence, the nominal refractive index \( n' \) (NRI, real part of \( m \)) of hardening concrete or mortar can be introduced corresponding to the light intensity measured by RR sensor in this study.

For simplicity, the \( n' \) of hardening concrete or

| Materials          | \( n \)  | Comment                                      |
|--------------------|--------|----------------------------------------------|
| Air                | 1.0003 | 0°C                                          |
| Water              | 1.333  | 20°C                                         |
| POF(PMMA)          | 1.49   | Observed mean value,                         |
|                    |        | At room temp.                                |
| Cement paste       | 1.25\(^{39}\) | Corresponding wavelength unknown           |
|                    |        |                                              |
| Hardened concrete  | Approxi- | Observed mean value                          |
|                    | mately 1.5- |                                               |
|                    | 1.6\(^{40}\) | of the main components                        |

Table 3 Representative refractive index \( n \) of conventional materials at a wavelength of 589nm.

Fig.16 Light intensity change in the mortar.

![Fig.16](image-url)
mortar can be calculated from the measured light intensity, in terms of two main factors. One is the reflection coefficient; the other is the incident angle of light. As it is well known that the refractive index determines the amount of light reflected at the interface and the simplified relationship between the refractive index, the reflection coefficient increases dramatically when the incident angle $\theta_1$ is in the range of $50^\circ$ to $63.2^\circ$.

From the above description in section 3, it is found that the RR sensor installed in the upward direction was able to detect the phase change during the hydration reaction continuously at early ages, because the sensor had better contact with the surrounding materials. Take the result of ch15 in concrete hardening experiment. The refractive index of concrete hardening experiment.

$$R_0' = \left( \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \right)^2$$ (6)

where $R_0'$ is the reflection coefficient, $n_1$ and $n_2$ are the refractive indices of two media, respectively. $\theta_1$ is the incident angle, and $\theta_2$ is the angle of refraction. When $\theta_1 = 0$, $\theta_2 = 0$, Expression (6) would be equal to Expression (5).

Figure 17 shows the ideal relationship between the incident angle $\theta_1$ and reflection coefficient $R_0$ in the case that $n_1 = 1.49$ and $n_2 = 1.33$. Here, it should be noted that the total internal reflection takes place as long as $\theta_1$ is larger than the critical incident angle $\theta_c = 63.2^\circ$ when $n_2 < n_1$ ($n_1 = 1.49$). The reflection coefficient increases dramatically when the incident angle $\theta_1$ is in the range of $50^\circ$ to $63.2^\circ$.

As shown in Figure 19, the light intensity decreased after the placement of concrete, which indicated an increase in the NRI of concrete. After passing point D of the minimum value, the $n'$ of concrete
continued increasing gradually. In general, the estimated \( n' \) of hardening concrete at early ages varied in the range from 1.25 to 1.55. Therefore, according to the curve of \( n' \) in Fig.19, the hydration process could be divided roughly into three stages. In the initial stage from A to B, it was the dormant period that lasted for about four hours. From B to C, it was the accelerating stage when the hydration produced a lot of heat and \( n' \) increased greatly. Then the hydration slowed down in the deceleration stage from C. In the meantime, \( n' \) of hardening concrete increased slowly. It had good agreement with the common knowledge from the previous research results of the concrete hydration process\(^{41)-44}\).

5. CONCLUSIONS AND FUTURE WORKS

A new approach was proposed to monitor the hardening process of concrete or mortar using RR sensors. The works in this study had proved this approach to be effective in monitoring the process of the hydration of concrete or mortar at early ages. The following conclusions could be found from the fundamental experiments:

- The hydration reaction of concrete or mortar at early ages has a direct correlation with the internal temperature. The variances in light intensity measured by RR sensors agree with the trend of the internal temperature, reflecting the development of the hydration of hardening concrete or mortar.
- The nominal refractive index (NRI) \( n' \) of hardening concrete or mortar was introduced as an indicator of the hydration process of concrete or mortar at early ages. The estimated \( n' \) increased in range from 1.25 to 1.55 during the hardening of concrete or mortar. The hydration process of concrete or mortar could be divided roughly into three stages according to the change in \( n' \) of the hardening concrete or mortar provided that RR sensors were installed in the upward direction.
- The direction of RR sensor embedded in the fresh concrete or mortar has a large effect on the change in the light intensity during the hydration. In the case that the sensor was installed in the upward direction, it is found that the light intensity measured by RR sensor changed with time continuously. While the RR sensor was pointing downwards, it was possible to form small voids beneath the tip of RR sensor. The void was first filled with water. Therefore, when the free water in the concrete disappeared a few hours after the placement of cement mortar or concrete, the light intensity increased sharply. It is a definite parameter to represent the phase changes (from fluid to gaseous phase) in the hydration reaction. In other words, the whole hydration process of fresh concrete or mortar can be observed by the RR sensor in the upward direction. The phase change during the hardening of fresh concrete or mortar can be monitored by RR sensor in the downward direction.
- Some other influence factors were investigated in this study. The manufacturing of RR sensor had an important effect on the change in the light intensity during the hydration reaction. The gap between the two fibers at the tip of the sensor should be filled with adhesive completely. In addition, the RR sensor reacted to the temperature of the surrounding materials. Nevertheless, the effect of temperature was so small that it could be ignored in the analysis of the results.

A representative curve of change in the light intensity could be achieved to indicate the hydration process by the RR sensor embedded in the upward direction in fresh concrete or mortar. In future work, the effect of different mix proportions of concrete or mortar, especially the ratio of water and cement (\( W/C \)), would be investigated on the measured light intensity during the hardening process. In order to reduce the variation in the results of measured light intensity, the RR sensors with good quality would be applied in the experiment. The setup of embedded sensors should be improved to ensure close contact between the sensing planes and surrounding materials. Finally, the estimated \( n' \) (NRI) ought to be calibrated carefully with the development of the compressive strength of concrete or mortar on the field so that the proper time to demold could be determined in the quality management of concrete.

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