Monitoring the Curing Process of Concrete Composites Using Plastic Optic Fiber Sensors

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ABSTRACT

Concrete is a kind of porous, particulate composite material. The curing temperature and environmental humidity as well as the internal moisture content will affect the hydration rate of this cementitious material. This study developed humidity sensors using inexpensive plastic optic fiber (POF) to record the internal relative humidity change of a concrete specimen during curing period. The POF humidity sensors were implanted into the concrete slab to monitor its strength development. Several take-core compression tests at scheduled dates were performed to evaluate the relation among the maturity function of concrete, the humidity profile, and the size of the specimens. The humidity distribution of a concrete slab was also compared with the theoretical calculation from the diffusion equations.

1. Introduction

Nowadays the fiber optic humidity sensors are getting more attention due to their immunity to electromagnetic interference (EMI), small size, noncorrosiveness, ability to perform long-term sensing over great distances. In this presentation a plastic optic fiber (POF) is adopted as the transmitting material. A cobalt chloride ($CoCl_2$) and gelatin coating were put on the U-shape bend of the POF as the sensing agent. The spectral absorption of this sensing part will change under different relative humidity, thus varies the light intensity of the POF humidity sensor in the receiving side.

Lots of cobalt chloride based POF humidity sensors have been developed [1-4]. Otsuki et al. [3] found that as radius of the sensing bend of a POF getting small, the sensitivity of the POF humidity sensor increase. Tay et al. developed an inexpensive POF humidity sensor using the $CoCl_2$ mixed with gelatin coating. Details of making this kind of solution and coating it to a POF bend can be found in [4]. In this study a Mitsubishi ESKA CK-40 bare optic fiber with fiber diameter of 4 mm, 6 mm and 8 mm, respectively, were used. The fiber has a refraction index of 1.49 and an attenuation of less than 200 dB per kilometer. Design parameters including the diameter of the POF, the coating methods, and the diameter of the U-shape region, are investigated to obtain an optimal humidity sensor.

The existing POF humidity sensor has been successfully applied in the environmental humidity measurements. Yet there is no evidence of using this kind of POF transducer embedded in the concrete structures to monitor the humidity profile of a concrete specimen and the strength development of the concrete. The PH value of fresh concrete might change the sensitivity of the coating layer of the POF humidity sensor. Therefore this presentation will focus on developing an appropriate packaging method for the POF humidity sensor inside the concrete specimen.

Several researches indicated that the early strength development of a concrete structure depends on the curing temperature, humidity, and age of concrete. This is the concept of maturity function [5,6,7]. The conventional maturity functions only consider the effect of curing temperature and time, and assuming that all the concrete structures were cured under enough moisture supply condition. While in general, the concrete structures were posed to variant weather condition after casting. The maturity functions yielded from the laboratory calibrated circumstance might over estimate the strength gain of the in-field concrete structures. The authors [8] have proposed a method to include the influence of environmental humidity on the strength growth of concrete cylinders. Experimental results showed that this modified maturity model can predict the strength gain of concrete cylinders under arbitrary humidity/temperature history. The authors tried to use the same maturity function to predict the strength growth of concrete slab under variant humidity/temperature condition, the prediction errors between the proposed model and the experimental data were high [9]. Since all the calibration and experimental specimens were concrete cylinders which have larger surface to volume ratio than that of a slab specimen. The cylinder type specimens have more surfaces to diffuse the humidity to reach a balanced humidity state. The humidity profile of a concrete cylinder is different from that of a concrete slab. The average relative humidity of a slab is higher than that of a concrete cylinder. Therefore a theoretical calculation of humidity diffusion of concrete slabs and cylinders are performed to find out the average humidity ratio of these two kinds of geometries. A modification according to this average humidity ratio is proposed to adjust the prediction model.

2. The POF Humidity Sensor

The POF was heated and bent into a U-shape sensing tip as shown in Fig. 1. The bending diameter were 2 mm, 3 mm and 4 mm, respectively. The bend part was dipped into the cobalt/gelatin solution. The solution composes cobalt hexahydrate 3% (by weight), gelatin 5% (by weight) and distilled water [4]. Different percent of gelatin was also used to compare their sensitivity with the existing formula. The POF sensor was put into a temperature/humidity controlled chamber to calibrate its sensitivity. A 650 nm LED was used as the light source, and a photometer (Industrial Fiber Optic) was employed as the detector to record the power loss due to humidity changes. Fig. 2 shows the output voltages of a 1 mm diameter POF humidity sensor measured at different temperature and humidity. The output voltage increases as the relative humidity increases. If the power loss was used as the y-coordinate, then a linear portion up to 80% RH can be seen (Fig. 2.). This trend shown is similar to the

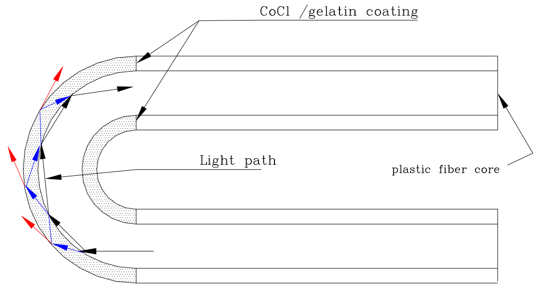

Fig. 1. The coating detail of a POF humidity

results in [4], however some deviations in the experimental data might due to the open/close of the temperature/humidity controlled chamber. It is noted that the U tip of the POF sensor cannot contact with the water directly, thus will experience a voltage drop.

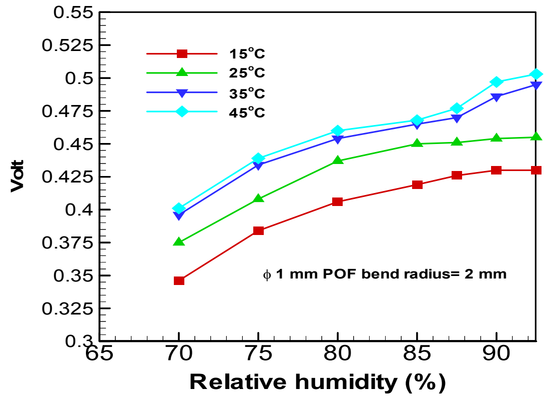

Fig. 2. The POF humidity response at different temperature and humidity

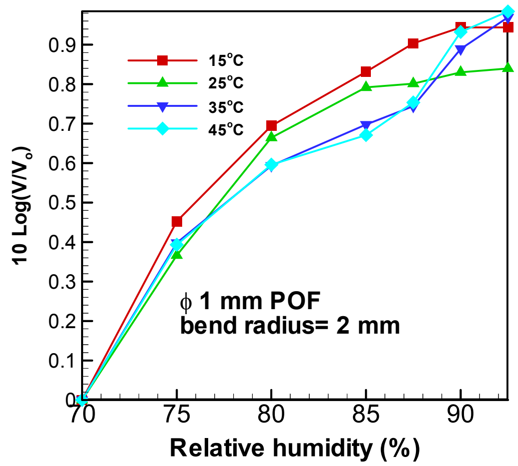

Fig. 3. The power loss of POF sensor at different temperature

3. Application to Strength Growth of a Concrete Slab

The strength development of a concrete slab was performed as a verification of the temperature and POF humidity monitoring of the proposed sensor. The slab has a dimension of 225 cm × 200 cm × 35 cm. The concrete has a designed strength of 35MPa. Table 1 shows the mix proportioning of this slab.

Table 1. Mix proportions of concrete

specimen f_c' (MPa)	w/c (%)	Unit weight (kg/m^3)				Air content (%)
		Water	Cement	Sand	Gravel	
35	0.63	240	375	853	734	2

The experimental procedure is illustrated in Fig. 4. Several take-core tests were performed to find the in-field compressive strengths of these two slabs. Since during the first three days, it is hard to drill from an unhardened slab, a pullout test was used to obtain the compressive strength of a slab indirectly. The take-core, pullout and thermal couple positions were shown in Fig. 5. The humidity sensor was used to record the environmental humidity. The POF humidity sensor will be applied in the near future to monitor the in inner and outside humidity of this slab. Fig. 6 is the experimental set-up for this strength growth monitoring program.

The authors have proposed a maturity function for the strength gain prediction of concrete cylinders under variant temperature and humidity. The details of this humidity adjusted rate constant model can be found in [8]. Fig. 7 shows the temperature/humidity of an outdoor an outdoor burlapped and water sprayed concrete slab. The average environmental humidity of this curing type is 95%. Fig. 8 is the temperature and humidity record of an outdoor air dried concrete slab. The humidity changes are different from the water sprayed cured one.

From the curing temperature and humidity history, we can obtain the strength prediction of this concrete slab, which is shown as the red line in Fig. 9. The difference between the prediction and measured strength is large, since the maturity model using all the test data from concrete cylinders which has larger surface to volume ratio than that of a concrete slab. Therefore a modification according to the water diffusion and size effect analysis of concrete specimen is performed to correct this error.

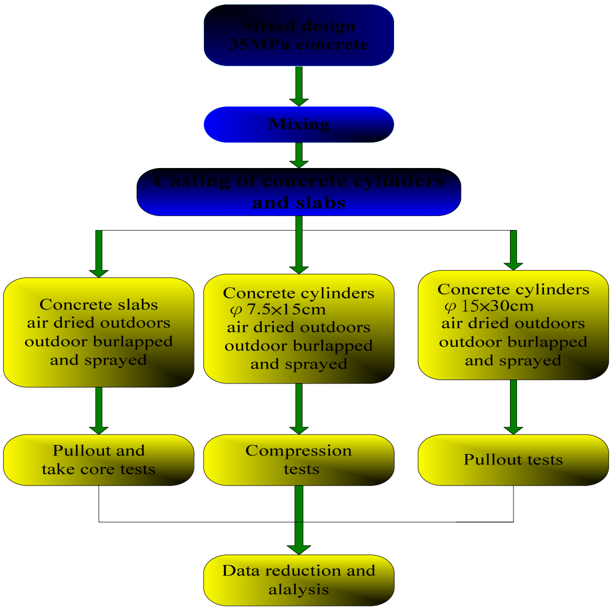

Fig. 4. Concrete slab strength growth test

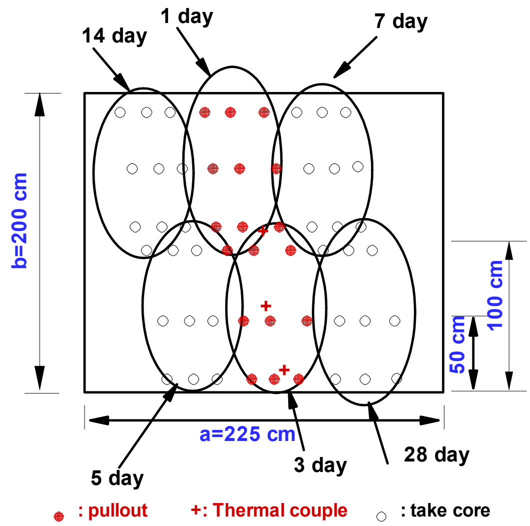

Fig. 5. Take-core, pullout and thermal couple positions of a concrete slab

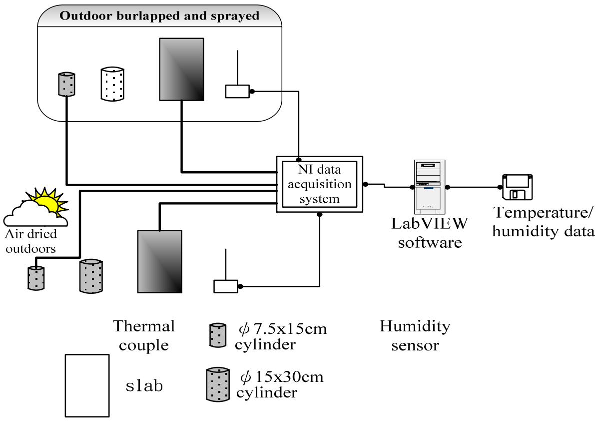

Fig. 6. Experimental set-up for strength growth monitoring of a concrete slab.

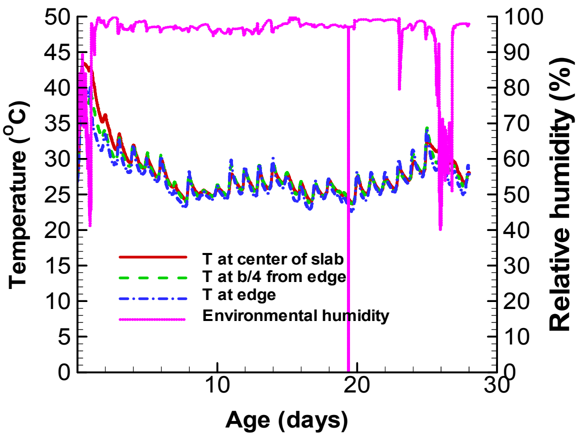

Fig. 7. The temperature and humidity of an outdoor burlapped and water sprayed concrete slab

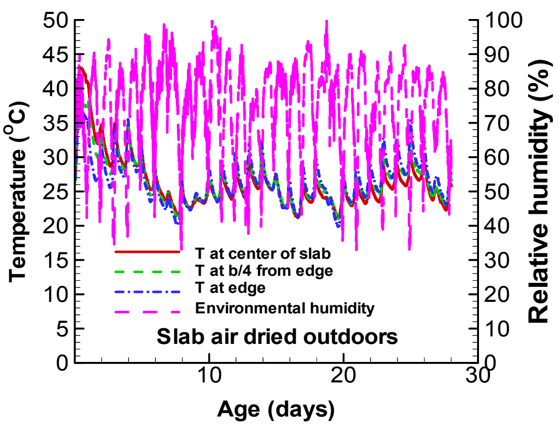

Fig. 8. The temperature and humidity of an outdoor air dried concrete slab

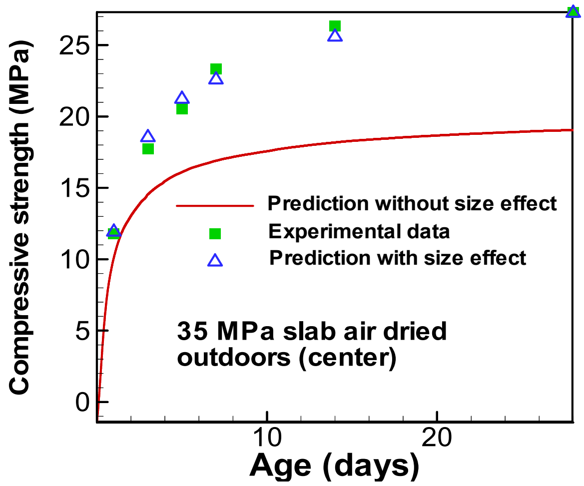

Fig. 9. Strength growth prediction of a concrete slab

4. The Concrete Diffusion Analysis

The maturity model obtained from the calibration tests of concrete cylinders considers the effect of curing temperature and the environmental humidity of concrete. This model can predict the early age strength growth of concrete cylinders at variant temperature/humidity history. However it cannot predict the strength gain of a concrete slab. Since the volume to surface ratio of a concrete slab is less than that of a concrete cylinder (the common testing piece with a diameter to height ratio of 1:2). Therefore the inner pore humidity of a slab will need more time to reach a balanced state with the environmental humidity. Bazant and Najjar have proposed a nonlinear water diffusion analysis for the moisture transport in concrete structures [10].

Assume that C is the diffusion coefficient of concrete (C=0.25 cm^2/day in this study), H(x, t) is the spatial and time humidity profile of a concrete slab. For a concrete slab, we have [10]

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(C\frac{\partial H}{\partial x}\right) \quad for \quad 0 < x \le L, \quad t > t_0 \qquad (1)$$

With initial conditions:

$$H = 1 \quad for \quad t = t_0, \quad 0 \le x \le L \qquad (2)$$

And boundary conditions:

$$H = H_{en} \quad for \quad x = L, \quad t > t_0 \qquad (3)$$

$$\partial H / \partial x = 0 \quad for \quad x = 0, \quad t \ge t_0 \qquad (4)$$

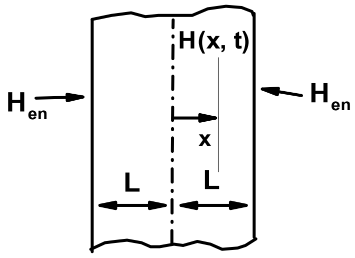

Fig. 10. Diffusion of a concrete slab

in which x is the distance from the center of the slab, H_{en} is the environmental humidity at top and bottom surfaces of the slab, L is the half depth of the slab (see Fig. 10), t is the age and t_o is the time when drying starts of the slab.

For a concrete cylinder, the following diffusion equation holds [10]:

$$\frac{\partial H}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(Cr\frac{\partial H}{\partial r}) \quad for\ 0 < r \le R, \quad t > t_0 \tag{5}$$

with initial conditions:

$$H = 1 \ \ for \quad t = t_0, \quad 0 \le r \le R \tag{6}$$

and boundary conditions:

$$H = H_{en} \ \ for\ r = R, \quad t > t_0 \tag{7}$$

$$\partial H / \partial r = 0 \quad for \quad r = 0, \ \ t \ge t_0 \tag{8}$$

in which r is the radial distance measured from the center of a concrete cylinder, and R is the radius of a concrete cylinder. If we further assume that C will not change with spatial distance, then the solution of a concrete slab is

$$H(x,t) = H_{en} + \sum_{n=1}^{\infty} e^{-k_n{}^2 C(t-t_0)} A_n \cdot \cos k_n x \tag{9}$$

where $k_n = \frac{2n-1}{2L}\pi$, and

$$A_n = 2 \cdot \frac{1-H_{en}}{k_n} \cdot \frac{\sin((n-0.5)\cdot\pi)}{L}$$

The humidity profile of a concrete cylinder is

$$H(r,t) = H_{en} + \sum_{n=1}^{\infty} \frac{2(1-H_{en})J_0(k_n r)}{Rk_n J_1(k_n R)} \cdot e^{-Ck_n^2(t-t_0)} \tag{10}$$

where J is the Bessel function, and k_n is the roots of $J_0(k_n R)$=0.

Figs. 11 and 12 show the humidity profiles at different age of concrete slabs cured outdoors with burlap/spray and air-dried conditions, respectively. For outdoor sprayed slab, the average humidity varies from 0.997 at the first day to 0.985 at the 28th day. For air dried slab, the average humidity over the depth ranges from 0.926 to 0.980. For concrete cylinders, the average humidity over the radius varies from 0.952 to 0.993, which is close to the concrete slab with the same curing condition. Fig. 14 is the humidity profile of a concrete cylinder with outdoor air dried cure condition. The average humidity changes from 0.995 at the first day to 0.760 at the 28^{th} day. This means the concrete cylinder is easier to reach a balanced humidity state with the outer surface than the concrete slab due to the size effect. Taking into account of this ratio of average humidity of a slab to a cylinder, we can derive a size effect modification factor as

$$\beta = 1.3121 \frac{\overline{H}_{slab}(x,t)}{\overline{H}_{cylinder}(r,t)} - 0.1884 \tag{11}$$

The modified predictive results are shown in Fig. 9, a good agreement can be seen.

5. Conclusions

A POF humidity sensor was developed to record the environmental humidity and curing process of concrete specimens. Inexpensive measurement system with LED light source and photodetector can calibrate this humidity sensor. Two concrete slabs cured outdoors with air dried and burlap sprayed conditions, were cast to monitor their strength growth through recorded temperature and humidity data. Experimental results showed that the strength gain of a concrete slab can be yielded with a humidity and size effect adjusted model, provided the humidity profile of the concrete specimen can be evaluated.

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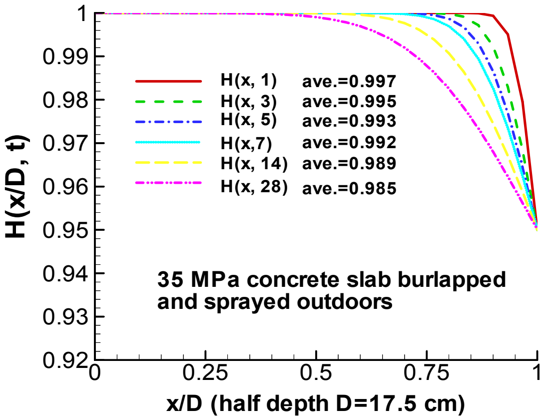

Fig. 11. The humidity profile of a concrete slab with outdoor burlapped and sprayed.

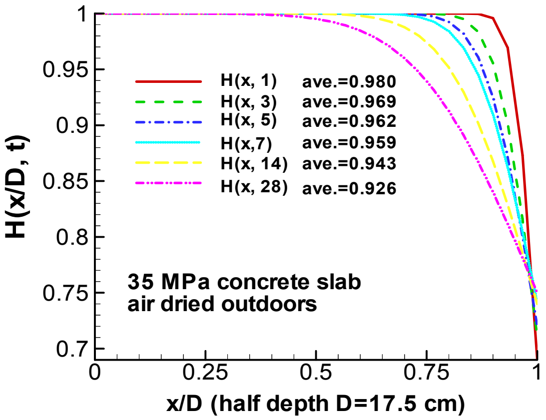

Fig. 12. The humidity profile of a concrete slab air dried outdoors

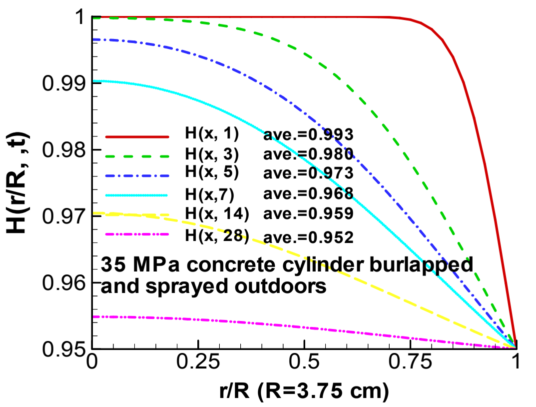

Fig. 13. The humidity profile of a concrete cylinder with outdoor burlapped and sprayed

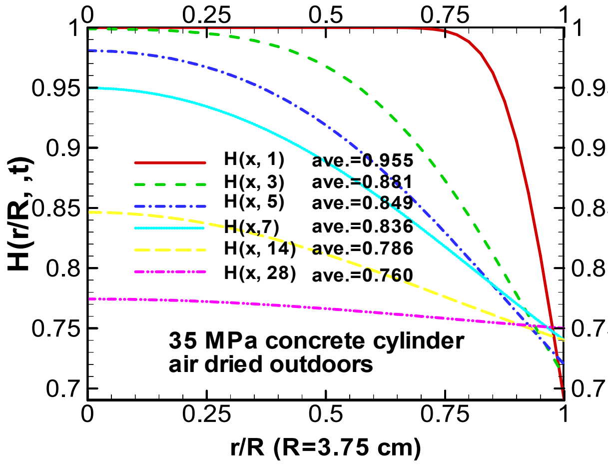

Fig. 14. The humidity profile of a concrete cylinder air dried outdoors

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