Abstract
The Fabry-Perot sensor is one type of fiber-optic sensing technology based on interferometry principles. It is designed to measure localised strains with high precision. As one of its multiple applications, the sensor can be cast in concrete to become embedded fiber-optic strain gauge. This paper presents the use of Fabry-Perot sensors in a long-term concrete shrinkage experiment conducted in The University of Hong Kong. In this study, shrinkage test specimens are cast from 5 concrete mixes covering conventional concrete (with and without shrinkage reducing agents), high strength concrete and self-consolidating concrete. The specimens are all prismatic with dimensions 75 mm by 75 mm by 250 mm. Each of them is instrumented with a fiber-optic sensor. Shrinkage strain measurements are taken up to one-year period. The Fabry-Perot sensors have been testified to possess good robustness and stability. Experimental results revealed the one-year shrinkage strains (as well as the estimated ultimate shrinkage strains) of the specimens are within the range of 400 to 700 microstrains. The shrinkage strain measurements provide important information for evaluation of shrinkage half-time, which is found to be around two weeks for mixes without addition of shrinkage reducing agent.

1. INTRODUCTION
Shrinkage of concrete could lead to substantial shortening movement of the concrete structure and, if the movement is restrained, serious cracking of the structure. To improve the understanding of the shrinkage phenomenon of concrete, numerous experimental investigations had been carried out since 1960’s until very recently. In those experiments, the concrete shrinkage had been measured by dial gauges [1-3] or embedded strain gauges [4]. However, the use of such gauges was not without problem. When concrete is fresh, water in capillary pores is consumed by the hydration of cement. The loss of water leads to volumetric change which is referred to as autogenous shrinkage. The low stiffness of very early age concrete makes the measurement of autogenous shrinkage very difficult [5]. Secondly, the shrinkage movements of laboratory specimens involve only small displacements. The resolution of dial gauges may not be adequate for measuring the shrinkage strains. Thirdly,
shrinkage measurements are carried out for a long period of time, under which electronic gauges may exhibit drifts in the measurements. Theoretically, the shrinkage tests should last as long as practicable because the drying shrinkage of concrete could continue for very long time after casting. A desirable measurement device would be such that it gives accurate measurements, possesses high stability up to at least several years, and is operable when the concrete is freshly cast. In this regard, the fiber-optic sensor seems to be an optimal candidate, as described in the following.

Fiber optics had been conceived of as, in their earliest application, a medium for the transmission of light in medical endoscopy. The applications of fiber optics on the telecommunication industry started in the mid-60’s of the last century, and ever since has been undergoing tremendous advancement. The advantages associated with fiber-optic sensors include small size, light weight, high precision, low attenuation when travels through distance and, last but not least, there is no electric current passing through the sensor. Since the fiber-optic sensors are not conducting electricity, they are immune to electromagnetic interference, and do not possess the problem of drift during prolonged sensing. The use of fiber-optic sensors for embedment in concrete and concrete structures was first suggested by Mendez et al. in 1989 [6] and was also put forward by Mendez himself [7]. Recently, fiber-optic sensors had been utilized in non-destructive evaluation of concrete structures for detection of voidage in concrete [8], acquisition of stress and strain states under external loading [9], measurement of weights of vehicles traveling on pavements [10], long-term bridge monitoring [11], and identification of cracks [12]. Literature review revealed no specific works on concrete shrinkage tests instrumented with fiber-optic sensors, notwithstanding that the characteristics of fiber-optic make it very suitable to be embedded in concrete for measuring the drying shrinkage. In order to acquire accurate and reliable shrinkage data of concrete produced in Hong Kong, the authors started an experimental study on concrete shrinkage measurement using fiber-optic sensors.

2. FIBER-OPTIC SENSOR

The fiber-optic sensor employed in this study is an embedded type of strain gauge, which is based on Fabry-Perot optical technology [13]. Three major components are present: the optical fiber, the embedded strain gauge, and the readout unit. The components are shown in Figure 1 and are described in the following.

2.1 Optical fiber

The structure of the optical fiber is illustrated in Figure 2(a). The fiber consists of a silica glass core surrounded by a glass cladding material, which has a smaller refractive index than the core in order to produce total internal reflection in the core region. The outer diameter of the cladding measures 125 µm. The core and cladding are protected by polymer sheathing. The concrete surrounding the optical fiber provides an alkaline environment (the pH value can be greater than 13 in concrete [14]). The polymer sheathing isolates the glass core and cladding from the alkaline environment, otherwise the glass would react with the hydroxide ions by way of the alkali-silica reaction.
2.2 Embedded strain gauge

The embedded strain gauge is illustrated in Figure 2(b). It is embedded inside a concrete specimen by mounting it into the mould of the specimen before concreting. The strain gauge has a length of 70 mm. It consists of a 3.2 mm diameter stainless steel body provided with two end flanges for better locking against the surrounding concrete. The stainless steel body encapsulates the Fabry-Perot sensor and protects the latter from mechanical disturbances due to vibration and trowelling of fresh concrete. Figure 2(c) illustrates the working principle of the Fabry-Perot sensor. The sensor consists of two optical fibers facing each other and fused in a glass capillary of 200 μm diameter. The gap between the two fibers is known as the Fabry-Perot cavity [15]. A mirror made of semi-reflective material is coated upon each fiber’s tip, with the reflecting surface normal to the axis of the optical fiber. When the concrete surrounding the embedded strain gauge experiences a strain, the Fabry-Perot cavity changes in length which can be detected by the readout unit as described in the next paragraph. The measurement range, resolution and accuracy of the Fabry-Perot sensor are 2000 με, 0.2 με and 0.5 με, respectively.

2.3 Readout unit

The readout unit contains a Fizeau interferometer, which is able to correlate the length of the Fabry-Perot cavity to the measurand, i.e. the concrete strain [15]. The readout unit emits white light which travels through the optical fiber to reach the embedded strain gauge and is reflected by the mirror coating across the Fabry-Perot cavity, with formation of interference pattern in the cavity. The path difference of the interference pattern is registered by the Fizeau interferometer for determination of the concrete strain. Since the phase shift of the light signal is very sensitive to the length changes of the Fabry-Perot cavity, the interferometer is able to produce high-resolution measurements.
3. TEST METHOD

3.1 Shrinkage test specimens
The concrete shrinkage test specimens are all prismatic and of size 75 mm by 75 mm by 250 mm, as shown in Figure 3(a). Steel moulds are used for casting the specimens. Immediately after casting, the trowelled surfaces of the specimens are covered with plastic sheets so that all surfaces of the specimens are protected from drying. The specimens are
demoulded at 24 hours after casting and then cured under saturated condition until the age of 7 days. After the curing period, each concrete specimen is rotated sideways by 90°. The specimen is then coated at the two end surfaces and the two side surfaces with an impermeable polymer latex impregnated cementitious membrane, so that only the top and the bottom surfaces would be subjected to drying. The coating of surfaces is illustrated in Figure 3(b). With only the top and bottom surfaces subjected to drying, it is aimed to simulate the effects of one-dimensional moisture diffusion. The effective thickness for drying of each specimen is same as the height of the specimen, i.e., 75 mm.

(a) Dimensions of specimen and location of embedded strain gauge

(b) Coating of surfaces

Figure 3: Shrinkage test specimens
3.2 Testing conditions

At 7 days of age, the specimens are placed inside the condition chamber which is maintained at the required temperature and humidity for the drying shrinkage tests. Figure 4 shows the condition chamber with specimens placed inside. The condition chamber is made of perspex. It is designed and fabricated in The University of Hong Kong. The chamber comprises of an internal box placed inside an external box and has internal dimensions of 900 mm by 900 mm by 900 mm. Such a double-layer design provides good insulation of the specimens from the external environmental fluctuations and allows the temperature of the chamber to be controlled by adjusting the temperature of the air circulating around the space between the internal and the external boxes. The relative humidity (RH) inside the chamber is controlled by putting dry silica gel beads when the RH is too high or wet cloths when the RH is too low. The chamber is controlled at a temperature of 27±1°C and a RH of 75±5%. During the first eight weeks after placing the specimens in the chamber, the shrinkage strains of the specimens are measured every day and thereafter as the shrinkage of the specimens slows down, the shrinkage strains of the specimens are measured at a gradually reducing frequency.

Fan for air circulation

Figure 4: Specimens placed inside condition chamber
3.3 Experimental program

The shrinkage behaviour of 5 concrete mixes is reported in this paper. The mix proportion is provided in Table 1. All the concrete mix ingredients are materials readily available in Hong Kong. Among the 5 mixes, Mixes 1 to 3 are conventional concrete mixes. A naphthalene-based superplasticizer is used for the three mixes. Mixes 2 and 3 contain respectively two different brands of shrinkage reducing agents (SRA), viz. Eclipse (supplied by Grace) and Tetraguard AS21 (supplied by Degussa). They are for the purpose of evaluating the effectiveness of incorporating SRA on the drying shrinkage of concrete. Mix 4 is a high-strength concrete (HSC) mix. Both pulverized fuel ash (PFA) and condensed silica fume (CSF) are incorporated in order to achieve high strength. The PFA and CSF are complying with BS 3892 and ASTM C-1240-03, respectively. Mix 5 is a self-consolidating concrete (SCC) mix, which employs a polycarboxylate-based superplasticizer. The water/cementitious materials ratios for Mixes 1, 2, 3, 4 and 5 are 0.48, 0.45, 0.45, 0.36 and 0.34, respectively.

Table 1: Mix proportions of concrete shrinkage test specimens

<table>
<thead>
<tr>
<th>Mix. no.</th>
<th>Water content (kg/m³)</th>
<th>OPC content (kg/m³)</th>
<th>PFA content (kg/m³)</th>
<th>CSF content (kg/m³)</th>
<th>Fine aggregate (kg/m³)</th>
<th>10 mm aggregate (kg/m³)</th>
<th>20 mm aggregate (kg/m³)</th>
<th>Superplasticizer dosage</th>
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<tr>
<td>1</td>
<td>209</td>
<td>436</td>
<td>0</td>
<td>0</td>
<td>655</td>
<td>356</td>
<td>712</td>
<td>4.6 ℓ/m³</td>
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<tr>
<td>2</td>
<td>204</td>
<td>453</td>
<td>0</td>
<td>0</td>
<td>655</td>
<td>356</td>
<td>712</td>
<td>4.6 ℓ/m³</td>
</tr>
<tr>
<td>3</td>
<td>204</td>
<td>453</td>
<td>0</td>
<td>0</td>
<td>655</td>
<td>356</td>
<td>712</td>
<td>5.1 ℓ/m³</td>
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<tr>
<td>4</td>
<td>174</td>
<td>339</td>
<td>121</td>
<td>24</td>
<td>665</td>
<td>356</td>
<td>712</td>
<td>3.4 kg/m³</td>
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<tr>
<td>5</td>
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<td>409</td>
<td>102</td>
<td>0</td>
<td>766</td>
<td>568</td>
<td>369</td>
<td>8.9 ℓ/m³</td>
</tr>
</tbody>
</table>

Notes:
1. OPC, PFA, CSF stand for ordinary Portland cement, pulverized fuel ash, and condensed silica fume, respectively.
2. Superplasticizer used in Mixes 1, 2 and 3 is Daracem 100 (supplied by Grace), whereas superplasticizers used in Mixes 4 and 5 are respectively FDN-HF (supplied by Vast Hill) and Glenium SP8S (supplied by Degussa).
3. Shrinkage reducing agent used in Mixes 2 and 3 are Eclipse (supplied by Grace) and Tetraguard AS21 (supplied by Degussa), respectively. Both are of 6.8 kg/m³ dosage.

Slump test and 28-day cube crushing test are carried out for the 5 concrete mixes. The fresh concrete slump values (measured to the nearest 5 mm) and the mean 28-day concrete cube strengths for all 5 mixes are tabulated in Table 2. In addition, the flow value (taken as the average of two mutually perpendicular spread values of the slumped mix, each measured to the nearest 5 mm) for Mix 5 (SCC mix) is recorded and reported in Table 2. The mean 28-day cube strength of Mix 4 (HSC mix) is 79.4 MPa, which satisfies the requirement of high strength. The slump and flow values of Mix 5 (SCC mix) are respectively 255 mm and 745 mm, which satisfy the requirements of being self-consolidating.

For each concrete mix, shrinkage test specimens are produced in duplicates with two identical specimens cast from the same batch of concrete mix and tested at the same time and
under the same conditions. This enables the verification of test results by cross-checking the shrinkage measurements from the two identical specimens.

Table 2: Workability, strength and shrinkage test results

<table>
<thead>
<tr>
<th>Mix. no.</th>
<th>Mean 28-day cube strength (MPa)</th>
<th>Slump (mm)</th>
<th>Flow (mm)</th>
<th>7-day autogenous shrinkage (µε)</th>
<th>One-year drying shrinkage (µε)</th>
<th>Estimated ultimate shrinkage (µε)</th>
<th>Shrinkage half-time (days)</th>
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<tr>
<td>1</td>
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<td>745</td>
<td>96</td>
<td>419</td>
<td>442</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Notes:
1. Only the flow value of Mix 5 (SCC mix) is measured.

4. SHRINKAGE TEST RESULTS

The shrinkage-time curves of the concrete specimens up to one-year period are presented in Figure 5. The time of drying is measured from the time the specimens being placed into the condition chamber. To save readers’ effort from reading-off the shrinkage-time curves, the averaged shrinkage strain for each concrete mix (i.e. mean value of shrinkage strain measurements of the respective duplicated specimens) at one year after drying is presented in Table 2. Among the 5 mixes, Mix 1 (conventional concrete mix without SRA) gives the largest shrinkage strain of 662 µε. The shrinkage strains of Mixes 1 to 3 provide basis for evaluation of the effectiveness of SRA. It can be worked out that the shrinkage of Mix 2 (which contains Eclipse) is reduced by 30.5% compared with Mix 1, whereas the shrinkage of Mix 3 (which contains Tetraguard AS21) is reduced by 11.2% compared with Mix 1. Besides, the dimensional stabilities of HSC and SCC mixes in regard to drying shrinkage can also be evaluated. In comparison with Mix 1, the one-year shrinkage strains of Mixes 4 and 5 are 10.0% and 36.7% less, respectively.

As the authors have mentioned in the preceding section, the specimens are cured under saturated condition for 7 days prior to placement into the condition chamber. The shrinkage measurements occurred during the curing period are recorded. As drying is practically not taking place during wet curing, the measured shrinkage can be taken as the autogenous shrinkage of specimens. The averaged autogenous shrinkage strain for each concrete mix at end of the 7-day curing period is presented in Table 2. It can be seen that the autogenous shrinkage shows significant variations from 6 µε for Mix 2 to 98 µε for Mix 4.
(a) Mix 1-Convention concrete without shrinkage reducing admixture

(b) Mix 2-Convention concrete with shrinkage reducing agent (Eclipse)
(c) Mix 3-Conventional concrete with shrinkage reducing agent (Tetraguard AS21)

(d) Mix 4-High strength concrete
The shrinkage-time curves suggest that the shrinkage at one year after drying is much slowed down compared with the shrinkage at start of drying, and that the one-year shrinkage strains are plausibly approaching to the ultimate values. According to Bazant et al. [2], it is possible to estimate, by performing regression analyses, the ultimate shrinkage strains from long-term shrinkage test data. Following the procedures laid down in Reference [2] and using the mathematical model developed by Bazant and Panula [16], the estimated ultimate shrinkage strain for each concrete specimen is evaluated. The averaged ultimate shrinkage strains for the concrete mixes are tabulated in Table 2. They are found to be 2% to 11% higher than their respective one-year shrinkage strains.

Another important quantity that could be reflected from the shrinkage test results is the shrinkage half-time. It is defined as the time at which half of the ultimate shrinkage strain would occur. The shrinkage half-time is determined for each specimen based on the estimated ultimate shrinkage strain. The averaged shrinkage half-time for each concrete mix is reported in Table 2. It can be seen that without the addition of SRA, the shrinkage half-time of concrete produced in Hong Kong is actually very short (varies from 14 to 18 days). Addition of SRA significantly lengthens the shrinkage half-time to as long as 25 to 45 days, depending on which type of SRA is used.

(e) Mix 5-Self-consolidating concrete

Figure 5: Shrinkage-time curves
5. CONCLUSIONS

The embedded type fiber-optic sensors are successfully employed in the long-term shrinkage test of concrete specimens. The fiber-optic sensors are capable to give precise and stable readings as demonstrated by the test results. The autogenous shrinkage at end of 7-day curing period and the one-year drying shrinkage are obtained from the test results, from which the ultimate shrinkage strains and the shrinkage half-time can be deduced. It may be concluded from the test results that under a temperature of 27±1°C and a relative humidity of 75±5%, the one-year shrinkage strains (as well as the estimated ultimate shrinkage strains) of concrete mixes produced in Hong Kong fall within the range of 400 µε to 700 µε. Besides, the two types of SRA investigated are found to be effective in reducing shrinkage, the percentage reduction of so is of the order 10% or even higher, dependent on which type of SRA is used. Lastly, the HSC and SCC mixes in this study demonstrate higher dimensional stabilities than the conventional concrete mix. This may be explained by the lower water/cementitious materials ratios in the HSC and SCC mixes, where a smaller amount of evaporable water is present.

REFERENCES