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Monitoring of concrete at very early age using stiff SOFO sensor

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Abstract

The SOFO system is based on low-coherence interferometry in single-mode fibres and allows the measurement of deformations in civil structures built with classical civil engineering materials (concrete, steel and wood). It has been successfully tested in different types of structures such as bridges, dams, tunnels and piles. In order to monitor behaviour of concrete at the very early age a stiff SOFO sensor has been developed. Using standard SOFO sensor it is possible to measure deformation of concrete at the very early age (thermal swelling and shrinkage). However, by coupling it with a stiff sensor, it is possible to determine the hardening time of concrete and to measure initial stress in the rebars. The stiff sensor and the results obtained using its first prototype are presented in this paper.

Keywords: Fibre optic sensors; Very early age of concrete; Hardening time of concrete

1. Introduction

Concrete is the material the most used in civil engineering. Therefore, a good knowledge about its mechanical properties and behaviour is essential.

After the mixing of cement, granulate and water, the cement hydration process is activated and the life of a cement composite begins. 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.). As a result of the chemical reactions, the concrete deforms: it swells because of heat released during the hydration and shrinks due to cooling, evaporation and chemical reactions (endogenous shrinkage).

The period in the concrete's life which begins with pouring and finishes with hardening is considered here as *the very early age of concrete*. Deformation during this period is *the very early age deformation*. The period which begins with pouring and finishes when the thermal processes in concrete terminate is considered here as *the early age of concrete*. Consequently, the corresponding deformation is *the early age deformation of concrete*. Hence, very early age deformation is included in the early age deformation.

Deformation of concrete at the very early age can give rich information about the concrete, particularly the evolution of its mechanical properties. In the literature, we did not find any reference to tests developed in order to monitor the evolution of the concrete properties from the pouring and into the very early age. The very early age deformation is indeed not easy to measure because of the viscosity and the low stiffness of mixture. Classical set-ups are not appropriate for measurements on non-hardened structures.

The SOFO [1] deformation measurement system, recently developed at IMAC [2]-EPFL, [3] is based on low-coherence interferometry in fibre optic sensors and is capable of measuring the deformations of concrete at the very early age [1]. In order to measure a hardening time of concrete at the early age, an appropriated sensor, named *stiff sensor*, is being developed at IMAC-EPFL. The first prototypes of the stiff sensor have been

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tested and the results are very satisfying. These results and the stiff SOFO sensor are presented in this paper.

2. SOFO measurement system

The SOFO measurement system is composed of a portable reading unit, different types of fibre optic sensors as well as a software package allowing the storage and the computer aided analysis of a large number of measurements. The system is based on low-coherence interferometry [2], and its functional principle is represented in Fig. 1.

Each sensor consists of two monomode optical fibres: the measurement fibre and the reference fibre. The measurement fibre is in mechanical contact with the host structure and follows its deformation, while the reference fibre, placed close to the measurement fibre, is loose and independent of the behaviour of the structure. Any deformation of the structure will result in a change of the length difference between the two fibres.

Infrared light is emitted by the LED, sent by the monomode optical fibre to the sensor, split by the coupler and introduced in two arms of the sensor. The light reflects off the mirrors silvered on the ends of both fibres and returns through the coupler to the reading unit, i.e., to the Michelson interferometer. The light is interfered in the coupler and contains the information of the length difference between the measurement and the reference fibre. This difference is detected by the mobile mirror and transmitted to the external PC. By successively repeating the measurement, it is possible to determine the evolution of the deformation of the monitored structure.

The SOFO system is well adapted to in situ applications. The reading unit is portable, battery powered and waterproof, making it ideal for dusty and humid environments as usually found in most building sites.

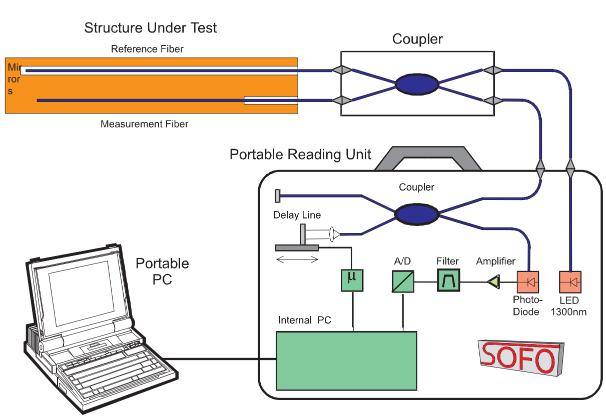

Fig. 1. Set-up of the SOFO system.

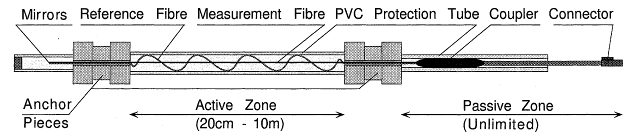

Fig. 2. Schema of SOFO standard sensor.

3. Standard sensor

The standard SOFO sensor [3] is composed of two zones: the active zone where the deformations are measured, and the passive zone that serves as an information guide. The sensor is schematically represented in Fig. 2.

The active zone is limited by two anchor pieces and consists of two optical fibres placed in a protection tube. The anchor pieces have a double role: to attach the sensor to the structure, and to transmit the deformation from the structure to the active zone. The deformation of the structure provokes the change of the distance between the anchor pieces, and this change is registered by the measurement fibre. The measurement fibre is prestressed between the anchor pieces in order to measure the shortening of the structure as well as its elongation. The reference fibre is independent of both the measurement fibre and the deformation of the structure, and its purpose is to cancel the temperature influences. Both fibres exit from the active zone and continue to the passive zone. The length of the active zone of standard sensor is between 20 cm and 10 m.

The passive zone transmits the information from the active zone to the reading unit. It is composed of one monomode optical fibre, connector and coupler, all protected by a plastic tube. The coupler is placed in the passive zone of the sensor, close to the anchor piece in order to increase the precision and to facilitate the manipulation during the measurement. The length of the passive zone can be practically unlimited and depends only on the distance between the sensor emplacement position and the reading unit. If this distance is very long (several tenths of a metre) the passive zone could be extended by a simple fibre optic cable. The sensor is linked with the reading unit by means of E2000 connectors.

The sensors are protected by PVC tube that allows for easy manipulation, fast installation, and good resistance during the pouring and vibrating of the concrete.

4. Concrete hardening

As previously mentioned the fresh concrete is a multiphase mixture of cement, water and aggregate. It

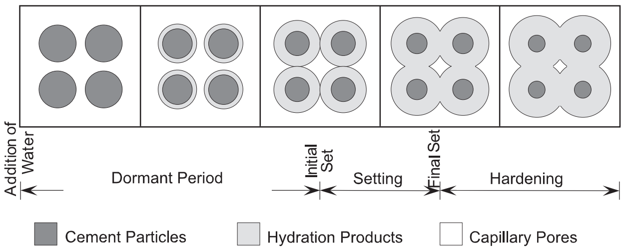

Fig. 3. Hardening of cement paste.

transforms from a liquid to a hardened structure due to chemical reactions of the hydration process. The liquid phase of fresh concrete is the cement paste and consequently, the concrete hardening depends on the cement paste hardening. The hardening of cement paste is schematically represented in Fig. 3 [4].

In Fig. 3 three stages of the cement paste are represented. The dormant period begins after the addition of water to the cement. During the dormant period the concrete is liquid. Setting starts when the hydrated cement particles begin to be in mutual contact and ends when the cement paste became solid. The end of setting is defined by the Vicat test. The setting period is a transition period during which the cement paste is transforming from a liquid to a hardened structure. After the setting, cement paste continues to harden, and its mechanical strength increases.

The hardening time of concrete is not strictly defined in the literature. We consider that the hardening time of concrete corresponds to the cement paste representation as shown in Fig. 3, square four. At this stage the setting of the cement paste is done, the concrete is hardened and certain strength is developed.

5. Test idea

The standard SOFO sensor is not very stiff. Therefore, it is sensitive to a very small force, and follows the behaviour of the host structure without perturbing seriously its strain field. Placed in the fresh concrete it is able to measure deformations at the very early age, before the setting.

During the hydration of concrete, swelling occurs due to the thermal process. The swelling begins after the dormant period and follows the hydration process of the concrete. Since the fresh concrete is a mixture of a fluid phase (cement paste) and a solid phase (gravel and sand), it has a certain initial stiffness. This stiffness is sufficient to transmit the deformation of swelling to the standard sensor, but it is insufficient to support any load. During the hydration, the structure of concrete transforms, the concrete hardens and the stiffness increases. There is a time after which the cement is set, the concrete is hardened and its stiffness is significant. This time we refer to as the hardening time of concrete.

In order to determine the hardening time of concrete, a stiff sensor has been developed. The stiff sensor is placed next to the standard one in order to compare their deformations during the swelling. In the beginning, after the pouring of the concrete, the standard sensor measures the swelling of concrete, while the stiff sensor remains inactive. The deformation of concrete is not entirely transmitted to it. The difference between the deformations of two sensors increases. After the concrete hardening, both sensors are activated and measure the same deformation. Thus, the deformation of concrete is entirely transmitted to the stiff sensor and the difference in the deformations of two sensors stays constant. The moment of the concrete hardening is registered as the moment after which the measured deformation difference between two sensors becomes constant (Fig. 7).

6. Stiff sensor

The concept of the stiff sensor is the same as the standard sensor one. The only difference is, that the rigidity of protection tube is several orders higher and the thermal dilatation ratio is lower than the rigidity and the thermal dilatation ratio of concrete at the very early age. The stiffness of the tube guarantees insensitivity of sensor to the very early age concrete swelling, while the thermal dilatation ratio of the tube ensures incompatibility between thermal sensor deformation and the concrete thermal swelling.

The stiff sensors are prepared and tested in SOFO laboratory at IMAC-EPFL. The schema of the prototype of stiff sensor is represented in Fig. 4.

The steel protection tube is used. There are two reasons for using a steel tube. The first is the very high stiffness of steel, and the second is that the coefficient of thermal expansion that is lower than that of the concrete at the very early age [5]. The endogenous shrinkage of concrete was not considered when choosing the material of the tube. Being made of steel, the stiff sensor has the same behaviour in the concrete as the non-anchored rebar.

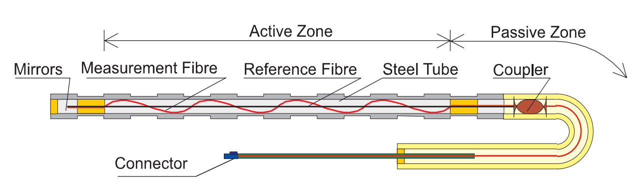

Fig. 4. Schema of SOFO stiff sensor.

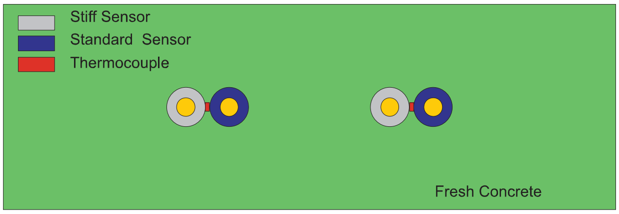

Fig. 5. Emplacement of sensors in concrete slab (cross section).

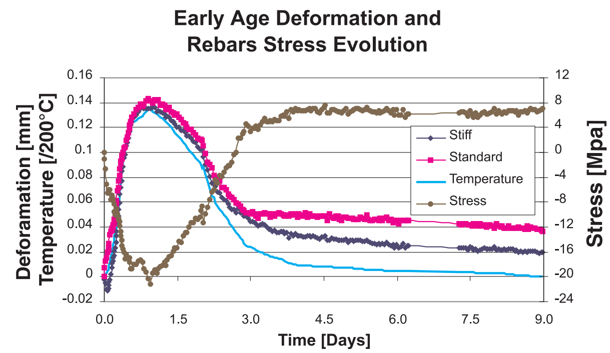

Fig. 6. Concrete early age deformation.

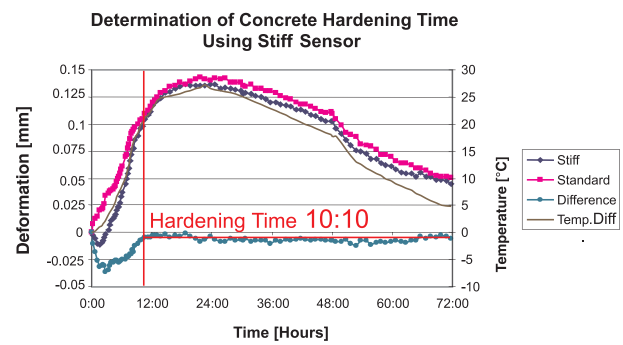

Fig. 7. Measurement of concrete hardening time.

7. Test description

Two packages consisting of the standard sensor, the stiff sensor and a thermocouple are placed in a formwork as represented in Fig. 5.

The active zone of each sensor is 60 cm long. The concrete is prepared using cement "Normo 4" according to Swiss norms, with a c/w ratio of 0.50. The dimension of the concrete slab is $38 \times 110 \times 200$ cm^3. In order to decrease the influence of shrinkage due to evaporation and to increase the thermal swelling at the very early age, the concrete was covered by isolation mats during the first 48 h. Deformation and temperature measurements were made during nine days. The ambient temperature was kept constant at 18°C.

8. Results and discussions

All sensors used in this experience are fabricated at the IMAC laboratory using a set-up that is less expensive than the set-up normally used in in situ monitoring (without the internal coupler, see Figs. 1, 2 and 4), but which resulted in some problems during the measurements. First, one stiff sensor was damaged during the concrete pouring, therefore the results of the measurements of only one couple of stiff and standard sensor are presented. Second, the accidental disconnection and reconnection of the standard sensor, three days after the pouring, provoked a measurement reading error. Disconnection of the sensor when using the external coupler (Fig. 1) causes perturbation of the sensor's passive zone hence, a reading error. This type of sensor is less expensive but can be used only for monitoring in the laboratory. Disconnection problem is avoided if internal coupler (Figs. 2 and 4) is used as is customary in in situ measurements. However, taking into consideration the appeared errors the results from this test are still valid.

The results are presented in Figs. 6 and 7. Fig. 6 presents a diagram of deformation evolution during nine days, measured by the standard and the stiff sensor. In Fig. 7 only the first 72 h from Fig. 6 are presented.

8.1. Concrete very early age and early age deformation measurement

Since the concrete was isolated we consider that the deformation due to evaporation is low and can be disregarded during the curing. The deformation due to auto-stressing provoked by stiffness of formwork we also consider as negligible. Therefore, the early age deformation is composed of the following four types of deformation: thermal deformation (swelling and shrinkage), endogenous shrinkage, carbonation shrinkage and the evaporation shrinkage after the curing [6]. The sum of these four types of deformations was measured using the standard sensor during the first three days and the stiff sensor thereafter, due to the error mentioned above.

The deformation measurements as well as measurements of the temperature offset from 18°C are represented in Fig. 6.

8.2. Rebars pre-stressing measurements

The stiff sensor behaves as a rebar embedded in the concrete because it is made of steel. Therefore, the stiff sensor has measured, in fact, the evolution of a rebar deformation during the early age of concrete and this measurement is represented in Fig. 6.

Before the test, the thermal expansion ratio of stiff sensor was measured. Consequently, it is possible to calculate the evolution of average stress in the stiff sensor from the deformation measurements. The average stress at time τ is calculated using Eq. (1) and its evolution is represented in Fig. 6.

$$\sigma_{s,a}(\tau) = E[\varepsilon_m(\tau) - \alpha_t \Delta t(\tau)], \quad (1)$$

where $\sigma_{s,a}$ is the average stress in the stiff sensor, E the modulus of elasticity of steel, ε_m the measured deformation of stiff sensor, α_t the coefficient of thermal exp. of steel, Δt the temperature difference.

During the swelling period (Fig. 6), the stiff sensor (rebar) was compressed. This means that either the concrete thermal expansion ratio is lower than that of steel, which is less probable [5], or alternatively, that the endogenous shrinkage decreases the thermal swelling, which is more probable. Finally, after the cooling, the stiff sensor is tensioned, but this tension is low.

8.3. Concrete hardening time measurement

The first 72 h of measurements made by the stiff and the standard sensor, as well as their difference and the temperature variation of the concrete are represented in Fig. 7.

As supposed, after a certain time both sensors began to measure the same type of deformation, and the difference of their measurements became constant. This time corresponds to a certain hardening of concrete, but also depends on the rigidity of the stiff sensor too. Before this time, the concrete was soft and thus unable to transmit its deformation to the stiff sensor. The stiff sensor was squeezing into it. After this time the concrete was hardened and it has imposed the deformation to the stiff sensor. Therefore this time is considered as hardening time of concrete. It is clearly observed and indicated in Fig. 7.

9. Conclusions and future results

By using a sensor couple of one stiff and one standard SOFO sensor it is possible to follow the evolution of deformation at the early age of concrete and also to determine the hardening time of concrete and pre-stressing of rebars during the very early age of concrete. No special laboratory conditions are needed, therefore all these measurement can be effected in situ, in building site conditions, but using the sensors with internal coupler.

Our research continues in order to improve the sensor, to examine the differences in the behaviour of sensors with different stiffness, and to accept the sensor's final configuration. In addition, a theory background of hardening time must be developed in order to explain and quantify the phenomenon.

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References

[1] Vurpillot S, Inaudi D, Ducret J-M. Bridge monitoring by fibre optics deformation sensors: design, emplacement and results. In: Smart Structures and Materials, SPIE vol. 2719, San Diego, California, USA, 28 & 29 February 1996.

[2] Inaudi D. Fibre optic sensor network for the monitoring of civil engineering structure. Thesis No. 1612. Swiss Federal Institute of Technology, Lausanne, 1997.

[3] Inaudi D, Vurpillot S, Casanova N, Osa-Wyser A. Development and field test of deformation sensors for concrete embedding. In: Smart Structures and Materials, SPIE vol. 2721, San Diego, California, USA, 1996.

[4] Soroka I. Concrete in hot environments. E & FN SPON. London: Chapman & Hall, 1993.

[5] Laplante P, Boulay C. Evolution du coefficient de dilatation thermique du béton en fonction de sa maturité aux tout premiers âges. Materials and Structures 1994;27.

[6] Aïtcin P-C, Neville A, Acker P. Les différents types de retrait du béton. Bulletin des laboratoires des Ponts et Chaussées 1998;215.