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A fiber optic smart sensor for studying the setting characteristics of various grades of cement

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Abstract

A simple, effective and inexpensive fiber optic sensor for investigating the setting characteristics of various grades of cement is described. A finite length of unsheathed multimode optical fiber laid inside the cement mix, is subjected to stress during the setting process. The microbends created on the fiber due to this stress directly influence the intensity of light propagating through the fiber. Continuous monitoring of such variations in the light output transmitted through the fiber gives a clear measure of the setting characteristics of the cement mix, thus providing a simple and elegant technique of great practical importance in the field of civil engineering. The smart fiber optic sensor described above can be incorporated into a building during the construction process itself so that continuous monitoring of the deterioration process for the entire life time of the building can be carried out.

Keywords: Smart sensor; Cement; Setting characteristics; Microbends; Stress

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1. Introduction

Over the last century, concrete [1,2] has changed the way we dwell on this planet. It has been established as the most popular building material with unmatched properties. It is such a familiar material that quite often we ignore the remarkable process by which cement and water are mixed with a wide range of aggregates to form a plastic mass which ultimately sets into a strong and durable material.

Moisture or water plays an important role in the setting and strength development of concrete. The cement hardening is due to the chemical process called hydration. This means that the silicate and aluminate [3] minerals in the cement react and combine with water to produce the 'glue' that holds together the aggregate which forms the concrete. The water–cement ratio is always much in excess of that required for hydration of the cement in the attainment of its final form in the concrete. The excess water used for workability will be lost as the cement gradually attains its final form. The cement paste has several other important properties such as strength and porosity, which are determined by the ratio of water to cement in the original mix. The water–cement ratio is an index of strength and design of cement mixes. The lower the water cement ratio, the higher will be the strength of the hardened paste and that of the concrete.

Many studies have been done in the past for the optimization of cement paste used for civil structures [4–6]. Conventional techniques for the measurement of setting time of cement mix are by using the Vicat and Gillmore needles [1,2]. These measurements can provide only the initial and final setting time. Since the characteristics may change from batch to batch of the same grade of cement it is very important to study the setting behavior of the cement paste. There are many chemical and physical reactions taking place during the setting of concrete, which are not fully understood till now. This is due to the fact that wide ranges of chemical substances exist in the cement. The chemical reactions may continue slowly over a long period of time and others may be initiated by elements in the environment in to which concrete is subsequently exposed. For these studies, continuous measurement of these settings and curing characteristics of cement are very important. Conventional methods do not provide continuous measurement of setting characteristics. But with the present fiber optic sensor we can continuously monitor setting and hardening pattern of different grades of cement.

Optical fiber sensors are capable of playing an important role in the health monitoring of civil structures such as bridges [7], dams [8], buildings and so on. The main features of the optical fiber sensor are its immunity from electromagnetic noise, very good sensitivity and compactness [9]. Since optical fibers are very sensitive to strain and bending losses, a variety of intensity modulated sensors can be used to carry out in situ studies of civil structures [10]. Studies have been carried out to determine the cracks in concrete structures using displacement techniques [11]. Moreover, many interferometric sensors based on Bragg gratings have been developed for more sensitive measurements, such as vibrations and strain [12,13]. Distributed fiber optic sensors can also be used as smart sensors for the determination of cracks in concrete structures [14,15]. The optical fiber sensor can be incorporated into such structures during their construction or can be adhered to them after the completion of construction. The sensitivity of the sensor largely depends on the bonding properties of the construction materials [2].

The main advantage of the present method is that no mechanical parts are involved in the measurements, and this reduces the instrumental error to a great extent. Moreover, the experimental setup is very simple and straightforward and this can be installed at the work site with no sophisticated instruments for measurements. Commonly available high-luminescent LEDs and photodiodes can be employed for these studies, which make the sensor very cost effective. The use of plastic optical fiber will further reduce the cost considerably.

2. Setting and hardening of cement paste

Setting is described as the stiffening of the cement paste, i.e. setting refers to a transition from fluid to a rigid state. In current practice, the terms 'initial setting' and 'final setting' are used to describe the stages of setting, which take place within 10 hours. The setting process is accompanied by temperature changes in cement paste. Initial set corresponds to a rapid rise in temperature and final set to a peak in temperature. The usual method for finding the setting time of cement is by Vicat apparatus. Usually a measure of the above-said two setting times, viz the initial and the final setting times follow a definite procedure. The period elapsing between the time when water is added to the cement and the time at which the Vicat needle fails to pierce the test block by 5 ± 0.5 mm is taken as the initial setting time [2]. The period elapsing between the time when water is added to the cement and the time at which the needle makes an impression on the surface of the test block while the attachment fails to do so is taken as final setting time [2]. Typically, the initial setting value for ordinary porcelain cement should be higher than 30 min while final setting time should be less than 600 min [2].

This means that in the usual description, the setting of the cement will be completed within 600 min. However, the dynamics of cement setting continues with time to more than 600 min, the characteristics of which cannot be studied using the Vicat apparatus. This is one of the important drawbacks of the vicat-based measurements. Since the Vicat measurements provide only the information about the setting times within 600 min, the curing and rapidity with which cement achieves hardness with different environmental conditions cannot be studied. Although, during the setting process, the paste acquires some strength, for practical purposes, it is the hardening, which indicates the gain of strength of set cement paste. The speed of setting and rapidity of hardening are entirely independent of one another. Using conventional techniques, the speed of setting and hardening cannot be traced. The fiber optic-based measurements will be helpful to study the complete setting characteristics of the cement paste.

3. Principle

The basic principle underlying the sensor is that as the cement sets, it exerts a stress on the sensing fiber, which is laid within the cement paste. This stress induces strain on the optical fiber, which can be thought of as a series of aperiodic microbends on the surface of the fiber. This in turn changes the characteristics of the light signal transmitted through the fiber and can be viewed as stress-induced modulation of light in the fiber. By monitoring the intensity variation with time we can accurately determine the cement setting rate. This can be used as an effective tool for quality testing of commercially available cements of different grades.

Microbends on the fiber arise as the variable pressure exerted on it distorts the fiber [16–18]. These bends are so small that the bend radii are of the order of the diameter of the fiber. If the mechanical perturbation is severe, a major part of the light is coupled to the cladding and is lost as radiation modes. Essentially, a continuous succession of such small bends may cause a significant enhancement of attenuation in the fiber (Fig. 1) .The small variations in the core diameter due to stress-induced deformation on the fiber during the setting of the cement mix, give rise to a scattering mechanism, which accounts for part of the loss. The microbends formed cause the coupling of energy between various guided modes and leaky modes (both cladding and radiation modes), the latter giving rise to a loss during transmission of light.

4. Experimental setup

The experimental setup essentially consists of a super luminescent LED source, a certain length of multimode plastic clad silica fiber (200/230 μm) and a photo detector. The epoxy lens of the commercially available LED ($\lambda = 670$ nm.) is

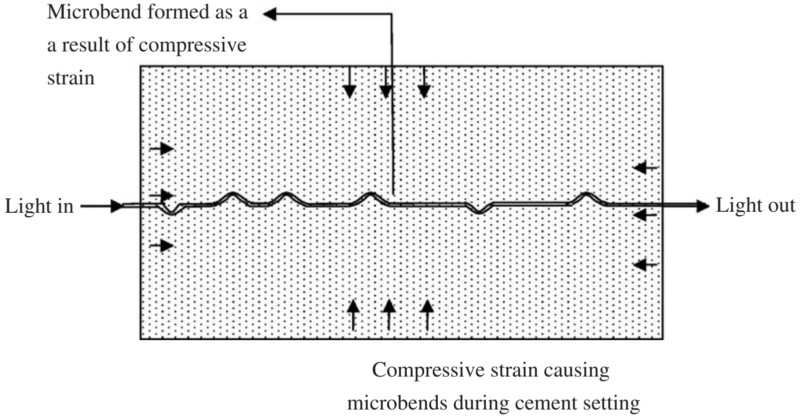

Fig. 1. Stress-induced microbends in an optical fiber.

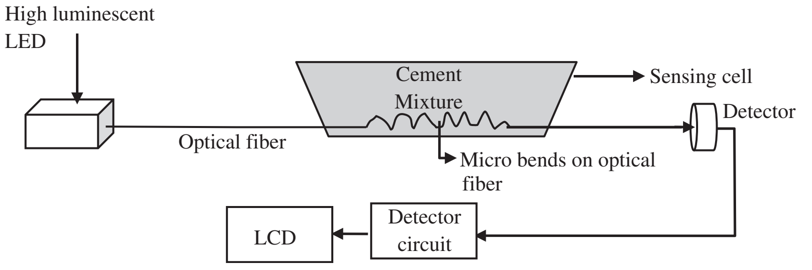

Fig. 2. Experimental setup.

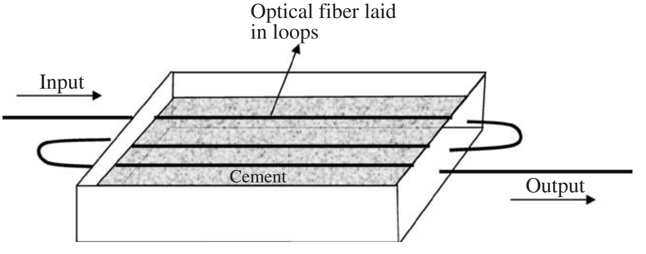

Fig. 3. Schematic of the sensing head.

removed and the end face is thoroughly polished, so as to help to make a very efficient coupling to the fiber. The experimental setup is as shown in Fig. 2.

Initially the sheath in the sensing region of the fiber is removed. This ensures the development of microbends on the fiber due to local strain. The ends of the fiber are polished to obtain efficient coupling to the LED and the power meter. The whole setup is aligned perfectly with one or two loops of the fiber residing in the cement container (size 12 cm × 9 cm) as shown in Fig. 3. The total length of the fiber within the cement mix is around 15 cm. This looping provides a greater surface area so as to enhance the sensitivity. The fiber is placed in such a manner that its unsheathed sensing region is well within the container. A cement mixture with a specific water cement ratio (cement:water is 4:1) is made and it is poured into the container such that it fully covers the sensing region. Only a small quantity of the cement mix is required for this purpose. The output power measurements are taken at regular intervals of time using a Newport 1815C power meter. Data acquisition and processing are done using a Labview card and a PC.

5. Results and discussion

The output variations with time for cement mix prepared for three different grades of cements are studied. Typical plots of power vs. setting time are shown in Figs. 4a–c. As can be clearly seen from the figure, the dynamics of the setting of cement mix involves three phases, viz., an initial slow phase, the second rapid phase

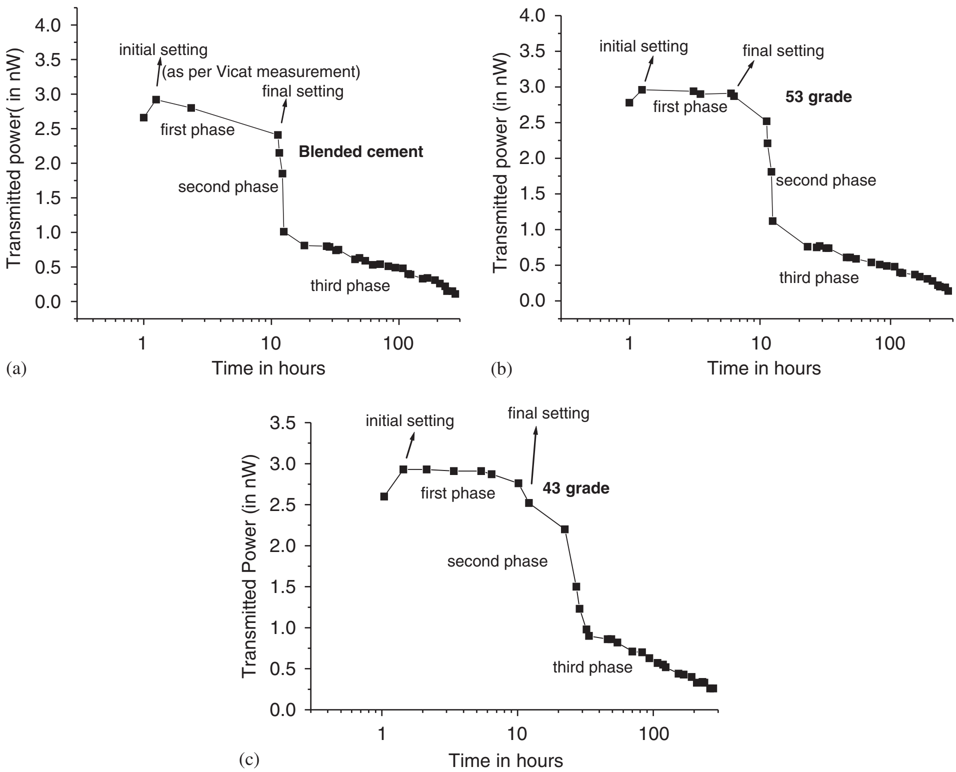

Fig. 4. A typical graph showing time vs. intensity of a cement sample.

and the final slow setting phase [2]. During the initial phase, the cement loses its plasticity and becomes a thick paste. Here, we can infer that the cement mix starts the process of setting. During this phase, the cement passes through the initial and final setting processes as described in literature [1,2]. Then it enters the second phase, which is the most important and the fastest process in the whole phenomenon of setting of cement. For example the log–log plot of transmitted power vs. the setting time in the second phase (Fig. 5) provides the following information. In the case of blended and 53-grade cements, a power law behavior can be obtained as, viz. $I(t) = C_1 t^{-0.96}$ and $I(t) = C_2 t^{-0.93}$, respectively, while in the case of 43 grade the corresponding relation is $I(t) = C_3 t^{-0.12}$, where C_1, C_2, C_3 are constants. The setting times for the 53 and the blended grades are lower than that in the case of 43-grade sample. The commercial specifications also show that 53-grade and blended grade cements have similar setting properties. As per commercial specification, the 43-grade cement is slow setting, which is confirmed by our investigations [19]. In summary, by evaluating the setting properties of the second stage, one can determine whether the sample in question is showing the properties of the required grade. Thus, for verifying the data provided by the manufactures, we can determine the setting

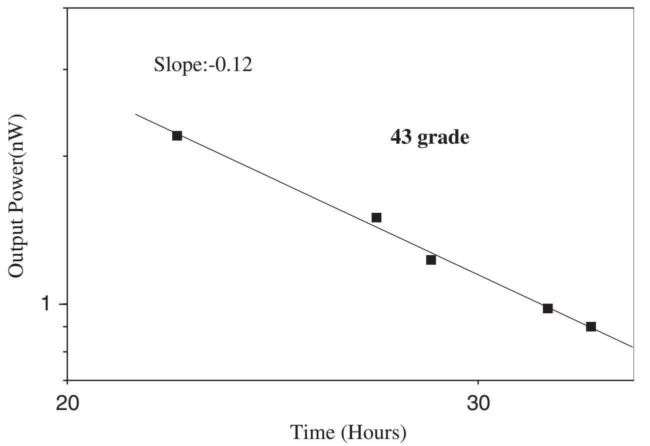

Fig. 5. Log (t) vs. log (I) plot showing the power law dependency.

times and hence the quality of the cement samples. Observation during the third and final setting phase reveals that the cement mix attains its full strength in almost a month's time.

As mentioned before, the results from the Vicat experiment provides the details of the initial and final setting times. However, the results from the fiber optic smart sensor show the setting times given by Vicat apparatus but also the setting characteristics extending up to a few weeks. The so-called initial and final setting times are 160 and 420 min, respectively, for 43-grade cement, which agrees with the Vicat test.

The differences in setting behavior of cement mix have far reaching implications in civil works related to building constructions. A carefully incorporated fiber optic sensor during building construction will be helpful in identifying proper phases of concrete mix and the whole curing process, in general.

6. Conclusion

In conclusion, we have described an optical fiber smart sensor that can be used to monitor the setting characteristics of cement mix during civil construction activities. The optical fiber sensor described here is inexpensive and simple to implement. The sensor can be incorporated during the construction process and it has the advantage of being nonobtrusive while providing the possibility for continuous measurement during the entire lifetime of civil structure. Detailed analysis of the results with special reference to civil construction is in progress. Continuous monitoring of the civil structures using the embedded fiber optic sensor as described in this paper will be helpful in the deterioration measurements of the concrete structures as well.

Acknowledgments

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