High-performance Concrete - Cement Paste Optimization with Fiber-optic Sensors

Wolfgang R. Habel[1], Detlef Hofmann[2],
Federal Institute for Materials Research and Testing (BAM) Berlin/Germany

Geraldine Buchenau[3], Bernd Hillemeier[4]
Technische Universität Berlin, Institute of Civil Engineering

Abstract

Increasing demands on concrete require the need to clarify the causes of its detrimental properties. Almost all types of high-performance concrete (HPC) show problems concerning the shrinkage at early ages and are very susceptible to curing. Because the binder agent is considered to be responsible for the early cracking of HPC paste deformations at very early ages are measured with matrix embeddable fiber-optic microstrain sensors. Two fiber sensor types (Bragg grating sensors and a compliant Fabry Pérot sensor type - EFPI sensor) have been compared and reason for the choice of the EFPI-sensor is given. Results obtained from several cement paste mixtures, referenced by externally fixed displacement sensors are presented.

Introduction

Newly mix-designs for fresh and hardened concrete are developed, in order to create construction materials with high performance. The optimization of mix-designs requires detailed knowledge of concrete properties. Low water cement ratios leads to increased strength, but negatively will lead to an accelerated and higher shrinkage /1/. Apart from the larger deformations the acceleration of hydration and strength will cause cracking at early ages.

Usually, the porosity of HPC is very low. For this reason, drying shrinkage is partially smaller than that of normal concrete /2/. The high shrinkage of HPC is essentially attributed to shrinkage due to the chemical reaction of cement. This causes a contraction of the cement gel due to physical reaction normally called autogenous shrinkage. The chemical as well as the autogenous shrinkage of fresh and hardened cement paste leads to volume changes, which take place at the beginning of hydration reaction without moisture exchange to the environment.

Contact measurements are often proposed for the determination of shrinkage behavior of paste, mortar or concrete specimens. The length changes of the investigated samples are measured by using measurement cone fixed in the cement matrix or attached on the surface. This measuring method requires a stiff sample. The stiffness as a function of the hydration kinetics of the binder agent determines the beginning of the displacement measurement. For such uniaxial measurements the specimens must be removed from the mould. This means, the initial setting process of the paste was already

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[1] Dipl.-Ing., Leader of the Fiber sensor group (to whome the correspondence should be addressed).
BAM Berlin, Lab. S.12; Unter den Eichen 87, D - 12205 Berlin/Germany.
[2] Dipl.-Ing., Scientific employee
[3] Dipl.-Ing., Research Assistant
[4] Prof. Dr.-Ing., Chair of Building Materials and Building Materials Testing.

finished before measurement can be carried out. However, the deformation behavior during rigidity and setting process of the binder agent has to be known. In order to solve the problem, very small embedded sensors could be used. Compliant fiber-optic micro-strain sensors have been used for measurement of chemical as well as autogenous shrinkage of cement pastes with different water-cement ratios. This measuring method is compared with an externally fixed uniaxial displacement sensor.

Measuring Deformation: Using Fiber Bragg Grating or Fabry-Pérot Sensors?

In order to measure deformations in a cementitious matrix at early ages, two fiber-optic sensor types can be embedded: fiber Bragg grating sensors and fiber Fabry-Pérot sensors. The significant characteristics of Bragg grating sensors is their long-term stable absolute strain resolution in the range of a few microns (με). Fiber Fabry-Pérot sensors, in contrast to Bragg gratings, can be designed as flexible sensors - like a micro dis-tometer. Such sensors do not prevent the surrounding plastic matrix from deformation and only require a force of about 150 µN to react to the deformation. Bragg grating sensors are not able to measure matrix deformations reliably in the first period of the hardening process. Fig. 1 gives an impression from what time during the hardening process, stiff sensors become able to measure the deformation. In this example of a Portland cement mortar, stiff gratings did not follow the real deformation until 4 hours after starting the hydration reaction process. In the setting period, between 4 hours and 7.5 hours, the measured deformation should follow approximately the cement paste deformation. Such behavior is expected and additionally it is possible to determine at which point this sensor can be used for matrix deformation measurement. And this is the reason for using flexible Fabry-Pérot sensors to measure deformation at very early ages.

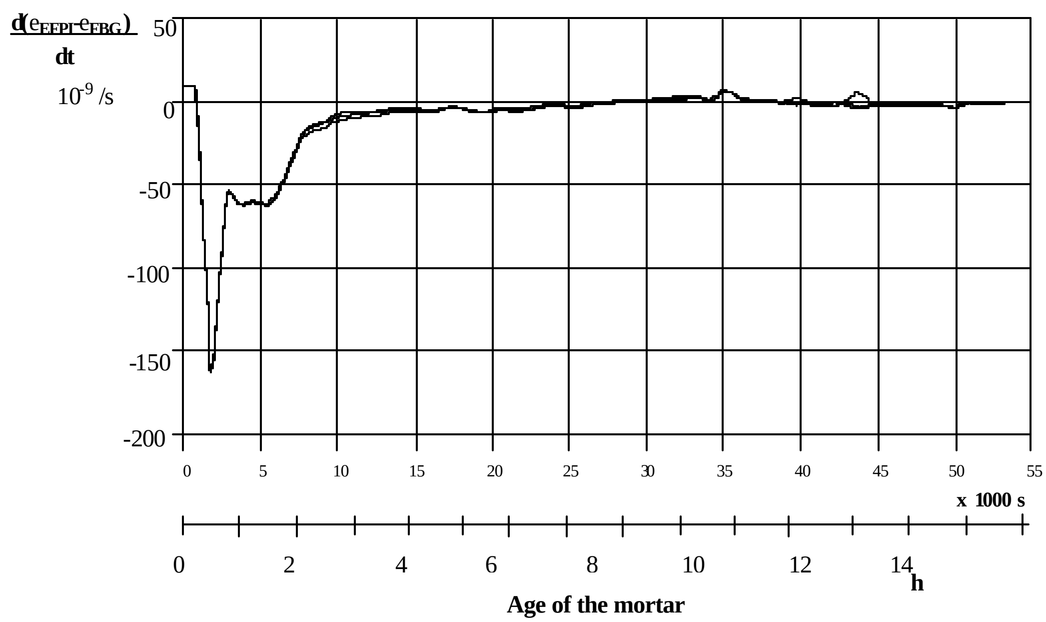

Fig. 1: Velocity of alignment of the matrix deformation measured by stiff Bragg grating sensors with those measured by compliant (EFPI) fiber sensors (beam: 80cmx8cmx4cm).

Flexible Sensor Methodology

The function of the fiber-optic sensor has been described in detail elsewhere /3/. The tubular sensor (length about 15 mm, outer diameter 0.35 mm) is connected with the leading optical fiber (diameter 0.25 mm). The leading fiber links the sensor to the instrument. In order to create a compliant sensor, the end of the leading fiber is able to slide inside the glass tube. The glass tube itself and the fiber near the tube are not additionally protected so that they are intimately washed by the cement paste. In order to achieve a reliable bonding between sensor and lime matrix as soon as it sets and to define the gage length, small ceramic punched discs (inner diameter 0.3 mm, outer diameter 2 mm, thickness 0.25 mm, see fig. 3) are fixed at the end of the tube as well as at the leading fiber just where it enters the tube. This sensor design enable displacement measurements caused by an applied axial force of 150 µN. Thus, the sensor is able to measure deformation immediately after finishing the casting of the material. The *measuring range* in terms of axial displacement depends on the material to be measured. It can be adjusted by the distance between the two punched discs. For the measurements described here a range from - 2500 µε to + 5000 µε has been set. A *sensitivity* (primarily determined by the wavelength of the laser source l_S and the data recording device) in the range of 0.1 µε can be achieved. It should be noted that for strain evaluation of hardened matrices smooth sensors (such as fiber Bragg grating sensors) can be used. In such cases the adhesion between sensor and cementitious matrix is of great importance. Experience and results are reported elsewhere /4/.

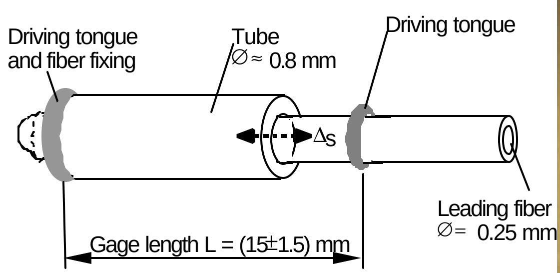

Fig. 2: Principle of compliant EPFI-sensor.

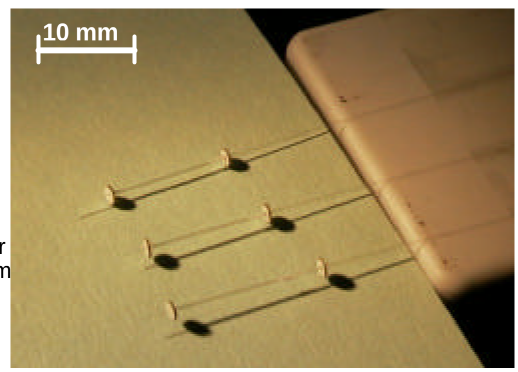

Fig. 3: Flexible EFPI sensors (fiber micro-distometer) prepared for embeddment (the driving tongues are designed as disks).

Durability of Fiber-optic Sensors in a Cement Matrix

In order to achieve minimal perturbation of the lime matrix, the sensor is principally embedded without coating. This make sense because commonly used fiber coatings are not stable when they are exposed to alkaline environment over a longer period of time. Alternatively, sensing elements could be coated with very thin coatings (<< 1 µm thick) deposited onto the sensor in a gas plasma. This makes the embedding procedure more practical and decelerates crack growth in the fiber surface, when the glass material is strained due to stress arising in the matrix. Since the pore solution might reach the surface of the leading fiber during the measuring time, the strength behavior of chemically attacked optical glass fibers had to be estimated. Long-term investigations of optical fibers stored in alkaline pore solution as well as static and dynamic fatigue tests have been carried out. Table 1 shows results obtained from dynamic fatigue tests with glass fibers attacked in an alkaline environment (pH = 13.9). It was surprising that the fiber tensile strength did not change significantly when fibers were stored in highly alkaline pore solution for several days. This seems to be caused by the high purity of the Si-O lattice of synthetic optical fibers. (The content of impurities is < 1 ppm.) Moreover, with regard to the average value, a small increase in the fiber strength due to the attack could be detected. One reason should be the 'polishing effect' of alkaline solutions, which results in smoothing of the crack tips of existing microcracks at the fiber surface. On the other hand, pore solution aging products produce adhesive forces between the crack sides. Long-term tests could prove that embedded optical fiber sensors or long-gage length sensor fibers are able to survive the deformation of cement materials.

Table 1: Strength of chemically decoated optical fibers stored in artificial pore solution (pH = 13,9), obtained from dynamic strain test.

Duration of attack	Tensile force when crack occurs [N]	Ultimate strain [‰]	Ultimate stress[5] [MPa]
1 hour	3,05 ± 0,59	4,04 ± 0,84	247,61 ± 48,27
24 days	3,05 ± 0,34	4,06 ± 0,69	248,07 ± 36,25
14 days	3,20 ± 0,18	4,32 ± 0,24	260,35 ± 14,97

Experimental Investigations and Results

Cement pastes with different water-cement ratios have been cast in standard moulds. In one case fiber-optic sensors have been embedded in the specimens, and in another, samples were equipped with inductive displacement transducers. Fig. 4 shows the measuring frame consisting of quartz glass and aluminum with the inductive displacement transducers on the top. In order to avoid temperature-induced deformations of the frame, quartz glass has been chosen as frame material. The specimens are fixed at the measurement cone, protruding from the rectangular specimen at both ends. Fig. 5 shows the sensors during embeddment in cement paste. The sample mould has the same standard dimension. After having completed the casting, three sensors are positioned in the core of one sample. In both cases the samples have been stored under the same conditions. The frames with casted paste have been protected against drying-out by a cover.

Portland cement CEM I 42.5 R-NA and water have been stored at a temperature of 20 °C before mixing them. In order to adjust a defined consistency, a superplasticizer (Polycarboxylatether) was added to the pastes with low water-cement ratios.

The specimens had achieved enough stiffness between four and six hours after mixing. At this time the form can be removed to start the measurements with the inductive displacement transducers in the quartz glass frame. The same methodology has been used for the samples equipped with fiber sensors. In order to prevent drying shrinkage, in both cases the specimens have been sealed immediately after form removal. The temperature of the investigated mixtures and of the ambient air have been measured throughout the whole test time.

[5] Calculated from the measured tensile force.

Fig. 4: Cement paste specimens fixed in the frame and equipped with inductive displament transducers.

Fig. 5: EFPI sensors during embeddment into cement paste (bodies: 4 cm x 4 cm x 16 cm).

Fig. 6 shows the mean deformation obtained from three specimens and the hydration reaction process, as indicated by the beginning of rapid temperature rise. Fig. 7 shows the measured values averaged from six sensors. The time axis begins with the start of cement hydration reaction. In order to evaluate the shrinkage behavior, the point with the expansion $e(t_0) = 0$ has to be defined in relation to the degree of hydration reaction. Here, the time t_0 has been defined corresponding to the point of maximum temperature. The main peak of the heat evaluation curves (shown in fig. 6) corresponds to a defined degree of hydration reaction.

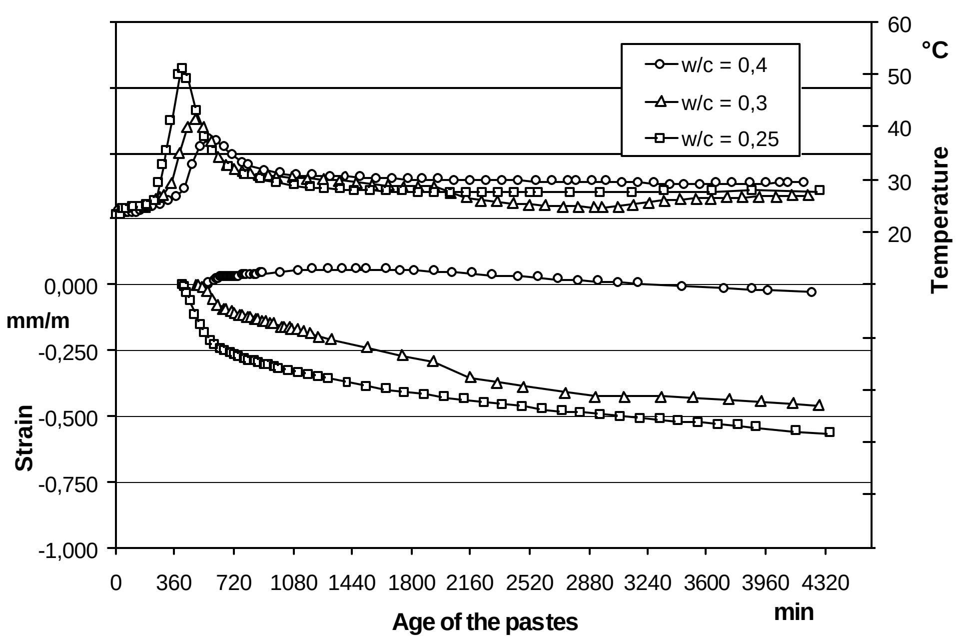

Fig. 6: Length changes of cement paste specimens depending on the w/c ratio uniaxially measured in the frame, temperature measured in the core of the specimen. (The length changes show temperature-influenced deformations).

Comparing the measured results obtained from both methods (shown in figs. 6 and 7) a satisfying qualitative correspondence could be ascertained. While the measurement method using inductive displacement transducers can only be used after removal the form, the embedded compliant fiber sensors provide measuring results immediately after finishing the casting of the cement paste. On the other hand, such compliant microstrain sensors do not react to the measuring zone and thus, do not influence the deformation behavior of the matrix to be measured.

However, only very small deformations have been observed in the time range between rigidity process and form removal. One reason could be the resistance to deformation of a small cement paste volume due to the mould, especially for the pastes with a swelling behavior at early ages. In the cement pastes with a w/c ratio 0.25 the sensors already measure shrinkage before removal from the form (fig. 7).

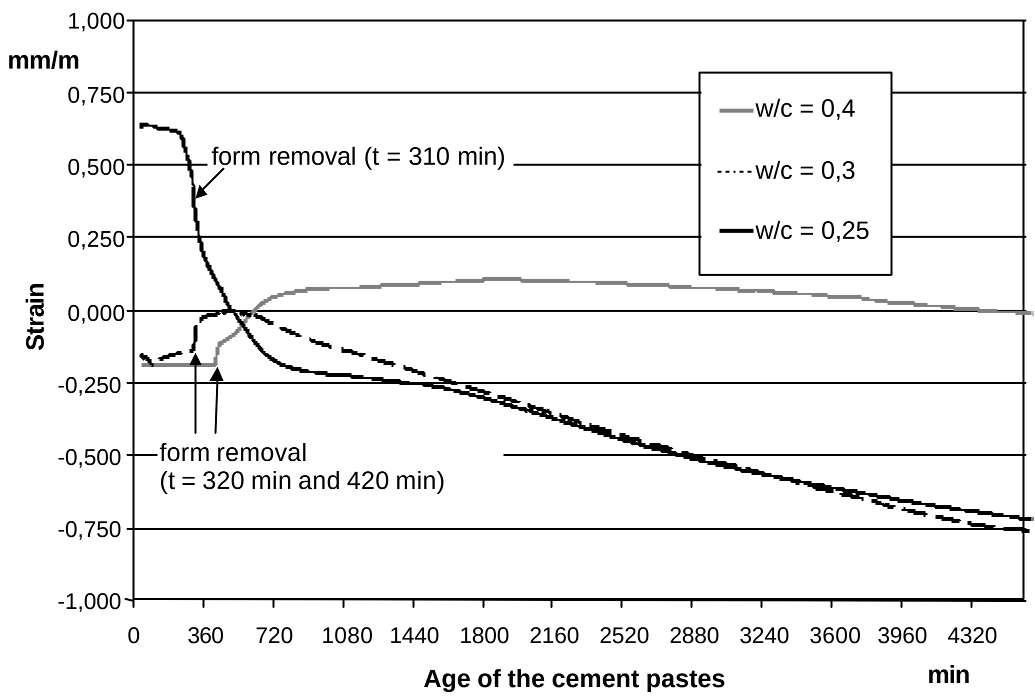

Fig. 7: Influence of water-cement ratio on deformation of Portland-cement paste (CEM I 42,5 R-NA) at early ages (in comparison with fig. 6), The length changes show temperature-influenced deformations.

Conclusions

Deformations of different cement paste specimens at early ages have been measured by using two methods: externally fixed inductive displacement transducers and embedded compliant fiber-optic micro strain sensors. Qualitatively good correspondence of the results could be observed from the point where the specimens have been removed from the form. Because externally fixed displacement sensors can only be used after form removal, embedded compliant fiber sensors provided measuring results immediately after finishing the casting. Thus, the opportunity to achieve measurements in fresh cement pastes make the extended range of application of the EFPI-sensors obvious. Deformation measurement of the fresh binder agent of HPC represents an important application field due to its high deformation at early ages. The comparison of the obtained measurement in pastes with low w/c ratio indicated a deficit of externally uniaxial measuring methods.

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