The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

HEALTH MONITORING OF FIBER-REINFORCED CONCRETE OVERLAYS AT THE CHEMBIOE BUILDING, VANCOUVER, CANADA

Nemkumar Banthia
The University of British Columbia, Canada

Rishi Gupta
The University of British Columbia, Canada

Phil Dyer
Propex, Inc., USA

Abstract

Cement-based materials shrink due to loss of moisture and due to self-desiccation arising from internal consumption of free water during hydration. Shrinkage develops compressive strains, which manifest themselves as tensile stresses under conditions of restraint. When tensile stresses exceed the tensile strength, cracking occurs. Cracking causes debonding makes concrete more permeable and adversely affects its long term durability.

Amongst various solutions proposed for mitigating plastic shrinkage cracking in concrete including the use of shrinkage reducing admixtures, reinforcement of concrete with fibers is undoubtedly the most effective. A field study was conducted where the role of fiber reinforcement was assessed when used in slabs-on-grade at the new Chemical and Biological Engineering building at the University of British Columbia. In this study, results from an unreinforced concrete placement were used for comparison with fiber-reinforced concrete. Three sections were casted using synthetic fiber and their performance was monitored by reading strain signals from embedded sensors. Both traditional (electrical) and state of the art optical (Fiber Bragg Grating) sensors were used. Strain measurements from the field overlays indicated that in fiber reinforced overlays, there was a decrease in the shrinkage-induced strains. This is expected to reduce the risk of cracking in FRC overlays and enhance their durability in service. Performance of the slabs-on-grade was further investigated using Non destructive tests.

INTRODUCTION

Loss of moisture due to evaporation and self desiccation of cement (internal consumption of moisture) cause cement-based materials to shrink. This shrinkage is more pronounced during early ages and leads to development of compressive strains, which manifest themselves as tensile stresses under conditions of restraint. Cracking occurs when tensile stresses exceed the material tensile strength. Cracking causes debonding, makes concrete more permeable, and adversely affects its long term durability. This issue is far more pronounced in overlays, repairs and slabs-on-grade where exposed surface areas are large.

Several solutions have been proposed for mitigating plastic shrinkage cracking in concrete including the use of shrinkage reducing admixtures (SRAs), reinforcement of concrete with fibers is undoubtedly the most effective (1, 2). Fibers are known to reduce the settlement of aggregates, and decrease bleeding. This, in turn, is expected to reduce the formation of bleed channels and decrease the ease with which flow can occur through the material. Secondly, fibers engage water in the mix and reduce the overall early age shrinkage. This is expected to produce a more 'in-tact' material with less internal cracking. Clearly, the ability of a given fiber to control plastic shrinkage cracking will depend among other things on the mix design, fiber type and dimensions, hydrophilic/hydrophobic nature of the fiber, concrete conditioning, placement details and the severity of the environment. This paper describes a field demonstration project where the role of fiber reinforcement was assessed when used in slabs-on-grade. The slabs were casted at the new ChemBioE (Chemical and Biological Engineering) building located at 2360 East Mall at the University of British Columbia, Vancouver. A 6.6 m x 6 m concrete slab was casted for the loading dock located near the south entrance of the building. The slab is located in the loading bay of the building and is expected to experience large loads during its service life. The slab was subdivided into five sections: four of size 3.3 m x 2 m each, and the fifth one of size 6.6 m x 2 m. (Figure 1). Two of the five sections (P1 and P4) had plain concrete with no fibers. P1 was controlled with no fly ash and P2 was one with a high volume (40%) of fly ash. F2, F3 and F5 were reinforced with a polymeric fiber (Hybrid Fiber Novomesh 950® produced by Propex, Inc., Figure 2). F2 and F3 had 7.5 lbs/yd^3 and 5 lbs/yd^3 of the fibers, respectively (see Table 1). Section F5 was designed to study the effect of not having any construction joints in a slab for more than 6 m. Section F5 had 7.5 lbs/yd^3 of the fiber (same as F2). All placements were 150 mm (6") thick and had no steel reinforcement. In each section, two electrical strain sensors (one along the long and short direction) and one optical strain sensor in the short direction were placed (Figure 1).

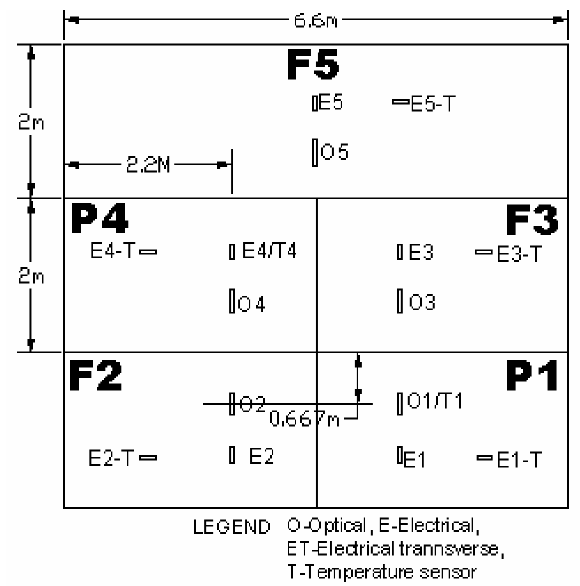

Figure 1. Five Sections of the Loading Dock (P1: Control; P4: HVFA; F2: FRC (7.5 lbs/ yd^3); F3: FRC (5 lbs/ yd^3); and F5: Joint-Free FRC Floor (7.5 lbs/ yd^3))

Figure 2. Novomesh 950® (Produced by Propex, Inc.)

Table 1. Concrete Placement Details

Notation	Admixture	Concrete Type	Remarks
P1	None	32 MPa (No fly-ash)	Control (Plain Concrete)
F2	Fiber		Novomesh 950 (7.5 lbs/ yd^3)
F3			Novomesh 950 (5 lbs/yd^3)
P4	Fly ash	32 MPa	High Volume Fly Ash (40% cement replacement)
F5	Fiber	32 MPa (No fly-ash)	Novomesh 950 (7.5 lbs/yd^3)

CONCRETE PLACEMENTS

Ready-mix concrete was used for the project and the fibers were pre-mixed at the plant, as recommended by the manufacturer. The mix design for the various concretes has been described elsewhere [3]. Since four different concrete mixes were used, concrete placement was spread over 3 days. Concrete with 70±20 mm slump was poured and broom finished (Figure 3). No external vibration was utilized for compaction and the slabs were protected with a plastic sheet for a couple of days to avoid excessive loss of moisture.

STRAIN MONITONRING

Embedded Sensors

Strain gauges were mounted on specially designed chairs (Figure 4), 25 mm below the top finished surface and equidistant from the slab edges (Figure 1). Every section contained two electrical (long and short direction) and one optical strain sensor along the short direction. Two temperature sensors were also installed alongside sensors 'O1' and 'E4' in placements P1 and P4 respectively, to monitor temperature changes. This allowed for any temperature correction to the strains.

(a)

(b)

Figure 3. (a) Concrete Placement and (b) Finishing [Notice the sensors in (a)]

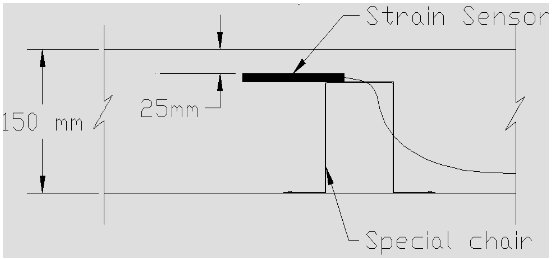

Figure 4. a) Specially Designed Chairs for Sensors

Figure 4. b) A Sensor Before Placing Concrete

For the optical sensors, a Fiber Bragg Grating (FBG) was installed at mid-length of a 250 mm long GFRP rebar (Figure 5). The modulus of elasticity of the GFRP rebar was 42 GPa and that of the electrical sensor as reported by the manufacturer was 2.75 GPa. A single mode fiber optic patch cable was used with the fiber optic sensors and a FC/APC (angle polished connector) was used at the ends to extend the length of the cable. For additional protection, the embedded portion of optical cables and electrical wires were covered in a vinyl tubing.

Figure 5. An FBG Optical Sensor

Data Acquisition System

The entire data acquisition system (Figure 6) was installed on-site. For the fiber-optic sensors (FBGs) a data acquisition system manufactured by Iders, Inc. was used. The advantage of the system is that it monitors all FBG channels on a common time base, which simplifies post-acquisition processing of the data. The unit used in this study had a total of 8 channels. A custom software was used to acquire data onto a PC. For the electrical sensors, an acquisition system designed and built at UBC was used. The 13 channels system is configured to enable data monitoring via the Internet using a Web-based data acquisition called “WebDaq”.

RESULTS

Strain Readings

Data were collected from optical and electrical sensors at 100 Hz and 0.01 Hz, respectively.

(a) Optical Sensor Readout Device

(b) Data Logger for Electrical Strain Gauges including WebDaq

Figure 6. On-Site Data Acquisition Systems

A high acquisition frequency resulted in an enormous amount of data acquired over a relatively short period of time especially in the case of the optical sensors. These data were analyzed and condensed by proper averaging techniques. Data were acquired in two sets. One prior to setting (this included the initial temperature rise) and one after setting (this included acquisition after proper bonding). At the start of both of these stages, all sensors were "zeroed" to have a fair comparison between different strain sensors. Further, in the case of the electrical sensors, the signals from the gauges in longitudinal and transverse direction in each placement were very similar; indicating that strain in all directions of the placement was similar. For simplified comparison, strains recorded from the two electrical sensors in each placement were averaged (except E5-T).

Figure 7 shows the presetting strains recorded with the electrical sensors. Notice that these sensors recorded a tensile strain during the first few hours after casting. This is expected as the temperature of concrete will increase due to the generation of the heat of hydration.

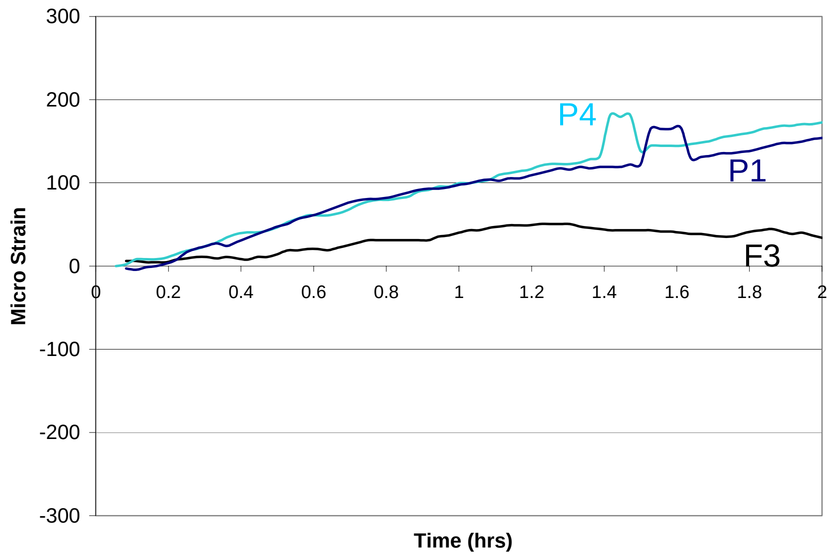

Figure 7. Averaged Pre-Setting Signals from Electrical Sensors (Tensile +ve, Compression –ve).

Figure 8 shows the average post-setting signals from the electrical sensors. Notice that the sensors in F2 and F5 (fiber reinforced concrete with a higher fiber dosage rate) recorded low values of strains implying a reduced potential for cracking. P1, P4 and F3, on the other hand, recorded greater strains than those in F2 and F5 placements, and these strain were compressive in nature. As will be noted later, unfortunately, the compressive strength of concrete in placement F3 was abnormally low, which may explain the highs strains noted in this placement. The strain results of placement F3 may also indicate that a fiber dosage of 5 lb/yd^3 is not sufficient to bring about a notable reduction in the measured strain.

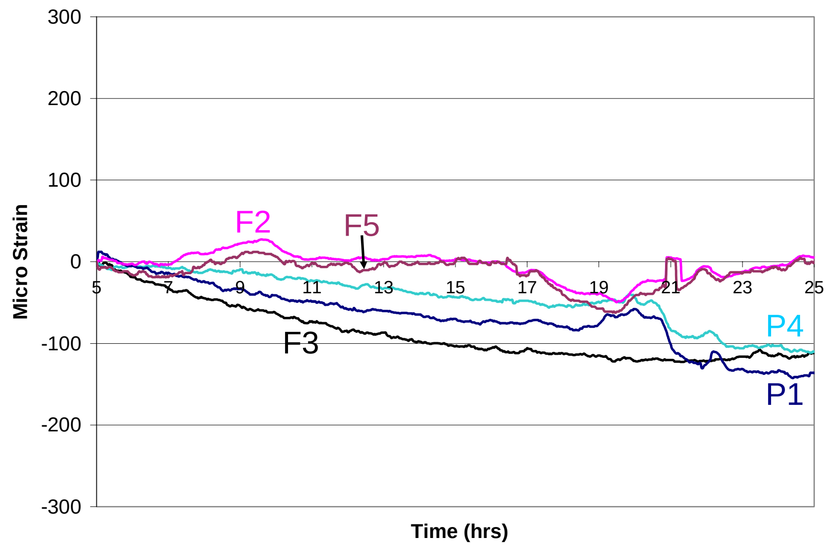

Figure 8. Averaged Post-Setting Signals from Electrical Sensors.

The similar magnitude of strains in P1 and P4 is somewhat surprising as one would expect the placement with high fly-ash content (P4), to record somewhat higher strains due to reduced bleeding and greater potential for subsequent water loss. The reduced nature of strains in F2 and F5 is encouraging as it implies that a joint-free placement (F5) does not necessarily increase the risk of cracking. Post-setting strain increment data is given in Table 2.

Table 2. Post-Setting Strain Increment Data (Electrical Sensors)

Placement	Short direction	Long direction	Average
P1	-134	-146	-140
F2	-61	-24	-42.5
F3	-12	-37	-24.5
P4	-146	-122	-134
F5	-12	-	-12

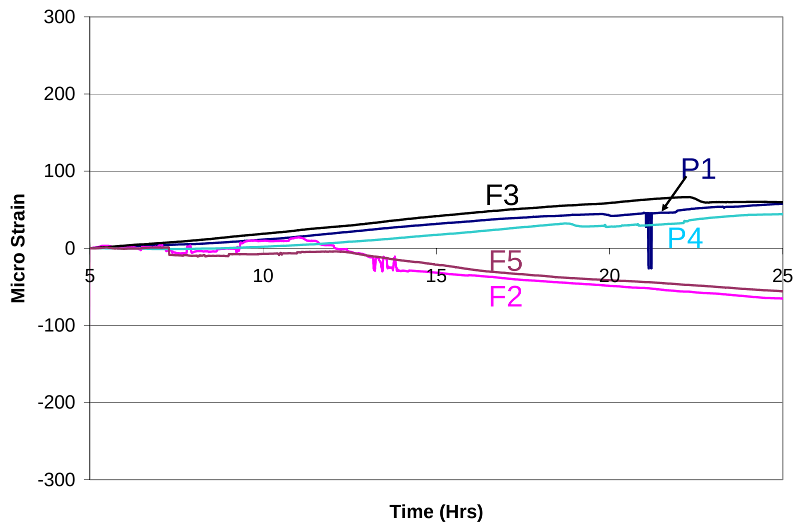

Figure 9. Average Post-Setting Signals from the Optical Sensors

The post-setting data from the optical sensors are plotted in Figure 9. As seen in Figure 9, the strains recorded in all optical gauges were very low. To protect the FBG mounted on the GFRP rebar, a rubber tape was used which unfortunately appears to have prevented the development of bond between the sensors and concrete.

Materials Tests

Material tests were conducted to evaluate the performance of the different concrete mixes and non destructive tests (NDTs) were conducted to further study the performance of various slabs. Due to the limited scope of this paper, these results are not presented here but are only briefly discussed. Cylinders and prisms were casted to determine the compressive strength (ASTM C 39) and flexural toughness according to ASTM C 1609 [4]. Results from toughness tests were analyzed using Post Crack Strength method [5]. Specimens casted using concrete mix type F2/F5 with a high fiber dosage had significantly higher toughness than the mix with a lower fiber dosage (F3). The un-reinforced concrete specimens (P1 and P4), as expected, did not have any post crack toughness and hence only peak load values could be recorded.

NDTs included Schmidt hammer rebound measurements and Electrical Impedance (EM) measurements were conducted. The slabs were divided into a 0.3 x 0.3 m grid for these measurements. On a comparative basis, the relative values of the compressive strengths measured using the Schmidt hammer correlated well with the results obtained from compression tests. Average resistivity values recorded for all slabs were lower than 1.34KΩ·cm and values were very similar for different concrete types. In the context of the joint-free floor, this meant that there was no adverse effect of increasing the joint spacing.

CONCLUSIONS AND RECOMMENDATIONS

The project presented here is one of the first attempts at measuring internal strain developed in slabs-on-grade at early ages with the help of traditional and fiber optic sensors. Data indicate that the strains developed in fiber reinforced concrete placements are lower than those developed in the plain placements. This implies that in-service cracking potential in FRC placements is lower and one can expect a better long-term durability. The project also investigated joint-free flooring and determined that there is no increased cracking potential in such floors as long as appropriate amount of fiber reinforcement is present. Embedded strain gauges can be used to study the early age performance of concrete. Electrical strain gauges are effective in measuring early age strain due to their low elastic modulus and bond between the FBG sensors and concrete is critical to record meaningful strain values. Since limited data was collected from this study, where sensors were measuring local strains, it is recommended that further research be conducted to verify the trends observed in this project. Use of long gauge sensors or mounting FBGs on low modulus rebars should also be considered in future projects.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of Propex, Inc., ISIS Canada Research Network, Rempel Concrete (Mr. Irv Lenz), APSC Dean's Office (Ron Loewen), and Civil Engineering technicians (especially John Wong) for their help. Thanks are due to Andy Vizer of Cement Association of Canada and the on-site staff of Stuart Olson, Inc.

REFERENCES

1 Banthia, N. and Gupta, R., Influence of Polypropylene Fiber Geometry on Plastic Shrinkage Cracking in Concrete, Cement and Concrete Research, 36 (7), July 2006, pp. 1263-1267.
2 Banthia, N., Gupta, R. and Mindess, S., Development of Fiber Reinforced Concrete Repair Materials, Canadian J. of Civil Engineering, 33 (2), February 2006, Pages 126-133.
3 Gupta, R., Banthia, N. and Dyer, P. "Field Application and Monitoring of Crack Resistant FRC Overlays," *Symposium on Fiber Reinforced Concrete - Past, Present & Future,* ACI Fall Convention, Denver, 2006 (Accepted September 2006).
4 ASTM 1609/C, "Standard test method for Fiber-Reinforced Concrete (Using beam with Third-Point Loading)"
5 Banthia, N. and Trottier, J.-F., "Test Methods of Flexural Toughness Characterization: Some Concerns and a Proposition", American Concrete Institute, Materials Journal, 92(1), 1995, pp. 48-57.