Electrical Monitoring of Concrete Using A Novel Structural Sensor Based on Conductive Cementitious Mortar

Emma Qingnan Zhang[1], Sotirios Grammatikos[2*], Ingemar Löfgren[3], Luping Tang[1], Lilei Ye[4], Johan Liu[5]

[1]Department of Architecture and Civil Engineering
Chalmers University of Technology, Sweden
Email: emma.zhang@chalmers.se; tang.luping@chalmers.se

[2]Department of Manufacturing and Civil Engineering
Faculty of Engineering, Norwegian University of Science and Technology, Norway
Email: sotirios.grammatikos@ntnu.no

[3]Thomas Concrete Group AB, Gothenburg, Sweden
Email: ingemar.lofgren@thomasconcretegroup.com

[4]SHT Smart High Tech AB, Gothenburg, Sweden
Email: lilei@sht-tek.com

[5]Department of Microtechnology and Nanoscience
Chalmers University of Technology, Sweden
Email: johan.liu@chalmers.se

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Abstract

This paper presents the development of a durable structural sensor based on cement-mortar modified with graphene and other carbon-based fillers. The purpose of the structural sensor is to indirectly monitor curing and service performance of concrete via electrical resistivity measurements. Electrical resistivity is an efficient parameter which can non-destructively capture intrinsic structural features of cementitious materials. The developed structural sensor is used to record electrical resistivity as a durability indicator during the whole service life of the concrete structure. To date, performance monitoring systems usually fail in the long-run before the failure of the actual monitored structure. The proposed sensor is embeddable in the interrogated structure and ensures sustainable consolidation with appropriate physico-chemical adherence and mechanical interlocking. This allows the monitoring system to surpass the expected service life of the parent concrete. Within this on-going work, the effects of different concentrations of carbon fillers on the electrical properties of cementitious mortars are reported. After an initial investigation to select the appropriate synthesis, the ability of the sensor to monitor the development of resistivity during setting and hardening was tested and the results are presented herein. Finally, the durability of the sensor was tested via electrical stability measurements under freeze-thaw cycles.

1 Introduction

Cement-based composites are the most widely-employed materials on earth in a range of civil engineering applications. Concrete structures are typically designed for a service life of more than 100 years. It is well understandable that efficient and dependable long-term performance monitoring is of primary importance in order to secure for safe infrastructure [1].

Conventional metallic monitoring systems often fail in the long-run, mainly due to the failure at the interface between the sensing material and concrete, because of the high alkaline environment in concrete [2]. Moreover, very few can actually monitor the porosity development and the initial curing [3]. Actually, most monitoring systems for the construction stage are purely based on the temperature development and models for maturity and strength development, which do not provide any information about the properties that influence durability, such as freeze-thaw weathering conditions [4].

Extensive research on the electrical property measurements reveals that conventional metallic electrodes have been largely used [8]. In the nature of high alkalinity and aggressive exposure condition of concrete structures, metallic electrodes are prone to deterioration, which will influence the stability and accuracy of the electrical measurements.

Therefore, there is a strong need for durable sensing systems that are compatible with the concrete environment from a long-term perspective. Hence, we report an on-going development of a structural sensor based on carbon-filler modified conductive cementitious mortars (CCM). Carbon fillers such as carbon fibres, graphite and graphene, have excellent electrical conductivity and can effectively 'short-cut' the tortuous pore structures to increase the total electrical conductivity of the cementitious materials [9, 10].

In this study, two different mixtures of CCMs were tested during setting and hardening stages, in comparison with the conventional metallic electrodes. The conductive mortar was embedded in plain parent mortar, functioning as a transition phase between the metallic electrodes and the parent mortar. The present study focuses on the electrical measurement and the stability of the innovative structural electrode under freeze-thaw thermal cycles during the initial setting and hardening stage.

After an initial investigation to select the appropriate synthesis, the ability of the sensor to monitor the development of resistivity during setting and hardening was tested and the results are presented herein. Lastly, the durability of the sensor was tested via electrical stability measurements under freeze-thaw thermal cycling. The development of the structural sensor paves the way towards the realization of a compact wireless system/device avail to provide remote indication of setting and hardening of concrete and long-term service performance.

2 Experiments

2.1 Materials

Table 1 gives the mixture design of CCMs. CEM I 42.5N-SR3 MH/LA Portland cement (Cementa, Sweden) was used and the water/cement (w/c) ratio was 0.4. For the parent mortars, CEM II/A-V 52.5 N Portland-fly ash cement was used (Cementa, Sweden). The w/c ratio was

0.5 and the cement to sand (0-2 mm) ratio was 1 : 3. After casting, all specimens were stored in lime-water to prevent carbonation.

Table 1: Mixture proportions of investigated CCMs

	CCM1	CCM2
Cement I 42.5N-SR3 MH/LA (kg/m^3)	980	980
Sand (0.125-0.5 mm) (kg/m^3)	785	785
water (kg/m^3)	392	392
Graphite (kg/m^3)	20	–
Graphene suspension (kg/m^3)	500	500
Carbon fibres (3mm) (kg/m^3)	12	12
Superplasticizer (Glenium51) (kg/m^3)	10	10

Figure 1 shows a schematic illustration of the developed sensor. The sensor consisted of four metallic electrodes embedded in four cylinder-shaped CCMs, each of which was formed in a polyvinyl chloride (PVC) holder.

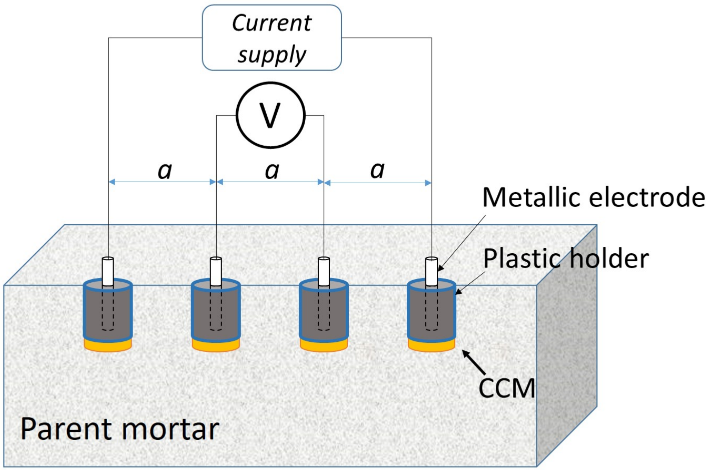


Figure 1: Schematic illustration of the graphene-based structural sensor configuration.

2.2 Electrical measurements

Electrical resistivity was recorded by making use of a Keithley (2750 series) multimeter continuously for a total period of 28 days, directly after casting. A 4-point resistance test was conducted for the curing and durability monitoring. The electrical resistivity was calculated by a simplified Wenner's approach:

$$\rho = 2\pi a R \tag{1}$$

2.3 Freeze-thaw thermal cycles

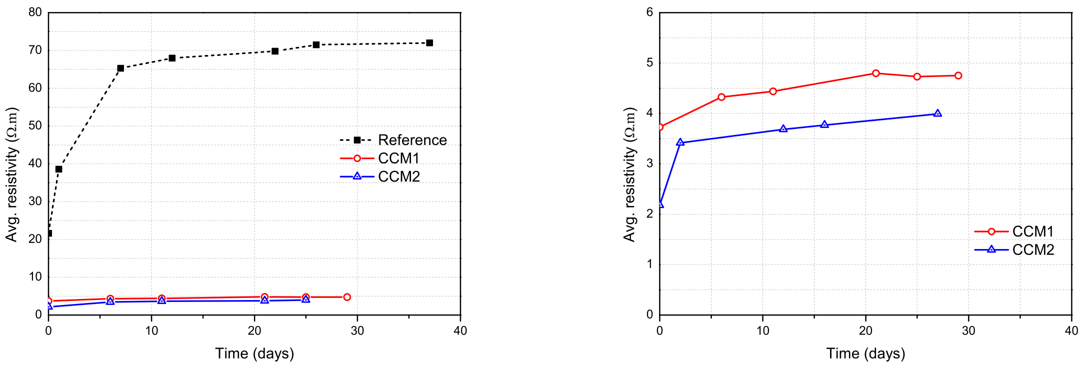
A daily freeze-thaw thermal cycle was set between 20 °C for approximately 12 hours and -20 °C for approximately 12 hours. The resistivity of both the reference and CCM specimens was monitored from day 1 to day 28.

The resistance of the conventional metallic electrode (referred as the reference specimen) and the developed sensor with CCM embedded (referred as CCM specimen) was then monitored and compared under freeze-thaw thermal cycles. The results were presented as a relative resistance $((R - Ro)/Ro)$ and normalized to a scale from zero to one, which zero indicated failure of the sensor system.

3 Results and discussions

3.1 Development of resistivity

Figure 2 shows the variation of electrical resistivity values throughout a period of approximately a month. In particular, Figure 2a illustrates the development of resistivity of a reference sample (parent mortar as reference sample) as well as two types of CCMs over a period of a month. As it can be seen, the addition of carbon nano-fillers and carbon fibres significantly suppresses the electrical resistivity values of about an order of magnitude difference. Figure 2b, the resistivity of two CCM specimens were plotted over time. It is worth mentioning that the addition of 20 g graphite in the mixture of CCM1 induced a small increase in the electrical resistivity. This may be attributed to the extra porosity, due to potential agglomeration, developed by the presence of the extra carbon phase.

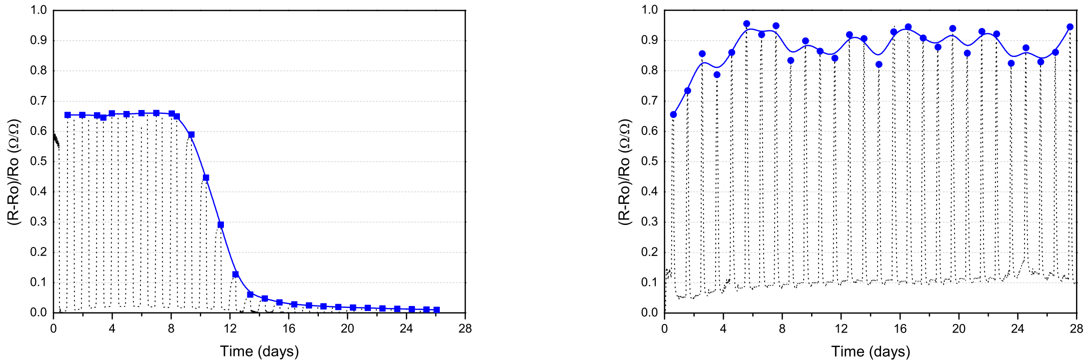


(a) Reference and CCMs (b) CCMs

Figure 2: Development of resistivity during curing.

3.2 Durability of freeze-thaw thermal cycles

Figure 3 shows the changes of relative resistance of the reference and CCM2 specimen. The calculated relative resistance was normalized to the scale from zero to one. As shown in Figure 3a, the normalized resistance of reference specimen decreased at about day 9 and then followed by a rapid drop to almost zero within several days. The reduction in resistance implied the performance of the sensor have been compromised and eventually failed due to the freeze-thaw thermal cycles. As for the CCM2 specimen in Figure 3b, during the 28 days monitoring, the normalized resistance was kept in a relative stable range without showing sign of sudden reduction of monitored values. This indicated the performance of CCM2 sensor was stable and functioning during the 28 days freeze-thaw thermal cycles.



(a) Reference (b) CCM2

Figure 3: Development of relative resistance under freeze-thaw thermal cycles.

4 Conclusions

This study presented the design of a durable sensor based on graphene modified mortar for the monitoring of structural performance of concrete. The developed sensor was able to record electrical resistivity as a durability indicator during both setting and hardening stage, as well as the whole service life of the concrete structure. In this study, setting and hardening of concrete was monitored by inherent electrical resistivity. The proposed sensor was properly embedded in the structure to ensure sustainable consolidation via physico-chemical adherence and mechanical interlocking. This led to an efficient performance monitoring system that could be able to surpass the service life of the parent concrete structure. The effects of different concentrations of graphene and other fillers on the electrical properties of concrete were studied and presented. After an initial investigation, the ability of the sensor to monitor the development of resistivity during setting and hardening was tested.

In conclusion, it was found that the graphene suspension with carbon fibers significantly increased the electrical conductivity of the cement paste. This conductive cement paste was then capable of being used as a sensing element embedded in the parent structure. The performance of the CCM sensor under freeze-thaw thermal cycles was stable and showed no sign of failure during the 28 days monitoring, while the conventional metallic sensor failed at about day 9.

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References

[1] F. Rajabipour, "Insitu electrical sensing and material health monitoring in concrete structures," Ph.D. dissertation, Purdue University, 2006.

[2] W. McCarter, T. Chrisp, G. Starrs, A. Adamson, E. Owens, P. Basheer, S. Nanukuttan, S. Srinivasan, and N. Holmes, "Developments in performance monitoring of concrete exposed to extreme environments," *Journal of Infrastructure Systems*, vol. 18, no. 3, pp. 167–175, 2011.

[3] W. McCarter and A. Afshar, "Monitoring the early hydration mechanisms of hydraulic cement," *Journal of materials science*, vol. 23, no. 2, pp. 488–496, 1988.

[4] W. McCarter, T. Chrisp, G. Starrs, and J. Blewett, "Characterization and monitoring of cement-based systems using intrinsic electrical property measurements," *Cement and Concrete Research*, vol. 33, no. 2, pp. 197–206, 2003, papers presented at the Fall 2001 Materials Research Society Symposium on Design, Characteristics and Properties of Cementitious Materials.

[5] B. J. Christensen, T. Coverdale, R. A. Olson, S. J. Ford, E. J. Garboczi, H. M. Jennings, and T. O. Mason, "Impedance spectroscopy of hydrating cement–based materials: Measurement, interpretation, and application," *Journal of the American Ceramic Society*, vol. 77, no. 11, pp. 2789–2804, 1994.

[6] W. McCarter, G. Starrs, and T. Chrisp, "Electrical conductivity, diffusion, and permeability of portland cement-based mortars," *Cement and Concrete Research*, vol. 30, no. 9, pp. 1395–1400, 2000.

[7] K. A. Snyder, C. Ferraris, N. Martys, and E. J. Garboczi, "Using impedance spectroscopy to assess the viability of the rapid chloride test for determining concrete conductivity," *Journal of research of the national institute of standards and technology*, vol. 105, no. 4, p. 497, 2000.

[8] W. McCarter, T. Chrisp, G. Starrs, P. Basheer, and J. Blewett, "Field monitoring of electrical conductivity of cover-zone concrete," *Cement and Concrete Composites*, vol. 27, no. 7, pp. 809–817, 2005.

[9] P. T. Dalla, K. G. Dassios, I. K. Tragazikis, D. A. Exarchos, and T. E. Matikas, "Carbon nanotubes and nanofibers as strain and damage sensors for smart cement," *Materials Today Communications*, vol. 8, pp. 196–204, 2016.

[10] D. Chung, "Electrically conductive cement-based materials," *Advances in Cement Research*, vol. 16, no. 4, pp. 167–176, 2004.

[11] S. Grammatikos, G. Gkikas, and A. Paipetis, "Monitoring strain and damage in multi-phase composite materials using electrical resistance methods," in *Smart Sensor Phenomena, Technology, Networks, and Systems 2011*, vol. 7982. International Society for Optics and Photonics, 2011, p. 79820K.