Monitoring the durability of marine concrete structures

New techniques based on embedded sensors have been developed for monitoring reinforced concrete structures to assess their durability, which can be used instead of the conventional non-destructive testing techniques. The continuous monitoring of concrete for its durability using various types of sensors allows not only early assessment of the potential durability of structures, but also a prediction of their service life. ***Effrosyni Tzoura*** *and* ***Muhammed Basheer*** *of* ***University of Leeds****,* ***Sreejith Nanukuttan*** *and* ***Danny McPolin*** *of* ***Queen's University Belfast****,* ***John McCarter*** *of* ***Heriot-Watt University****,* ***Ken Grattan*** *and* ***Tong Sun*** *of* ***City University London*** *and* ***Sudarshan Srinivasan*** *of* ***Mott MacDonald*** *report.*

Reinforced concrete is the main structural material used in marine structures. One of the key requirements for the design of these structures is that they should resist the aggressive marine environment and provide the expected service life.

The design codes[1] specify different methods by which the durability of concrete in marine environments can be assured, but despite all these precautionary measures marine structures frequently suffer from premature deterioration due to a combination of physical and chemical effects on concrete. The physical durability of concrete is strongly dependent on cyclic freezing and thawing action and temperature stresses, while the chemical durability is mainly dependent on chloride ingress, sulfate attack, alkali–aggregate reaction, corrosion of reinforcement and the delayed ettringite formation. Therefore, both the macro- and micro-environments to which the concrete is exposed play an important role in the durability of concrete in marine structures.

Need to monitor

Coastal and marine structures deteriorate primarily due to sulfate attack and chloride-induced reinforcement corrosion. Although the performance of concrete in marine structures has improved with the use of high-performance concretes (HPC), the life-cycle performance of marine concrete structures can be improved significantly by focusing on measures to improve their durability. According to recent research[2], the effect of micro-cracking on the corrosion of steel in concrete is more important than macro-cracks when considering the durability design of reinforced concrete structures in chloride-exposed environments. A crucial parameter is the concrete cover zone because it protects the reinforcing steel from the external environment. Therefore, the ability to assess and continually monitor the integrity of the cover zone concrete would lead to a more accurate assessment of the future performance of marine structures and their service life[3,4].

Structural health monitoring

Implementing a damage detection and characterisation strategy by employing an array of sensors is referred to as structural health monitoring (SHM). Detecting changes to the micro-structure and/or damage to concrete at an early stage facilitates timely interventions leading to less costly and time-consuming maintenance. Consequently, the service life of structures could increase.

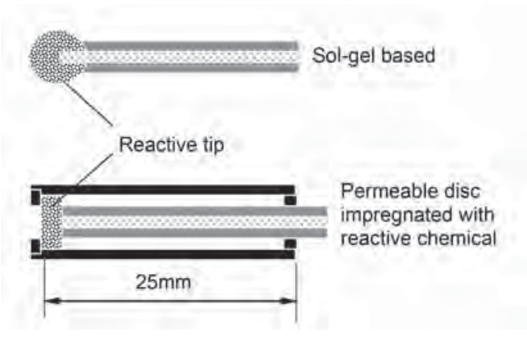

Figure 1: Generic design of sol-gel based fibre-optic pH sensor.

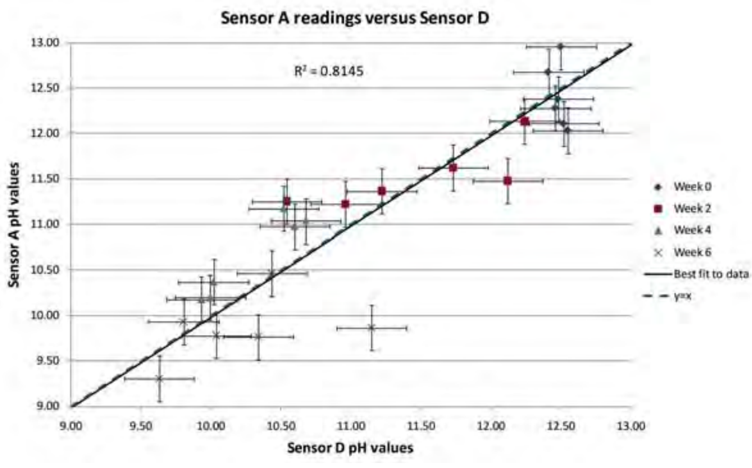

Figure 2 (below): pH readings obtained from sol-gel-based fibre-optic sensor (Sensor A) compared with those from a commercial capacitance-based pH sensor (Sensor D) for a concrete sample subjected to accelerated carbonation for six weeks.

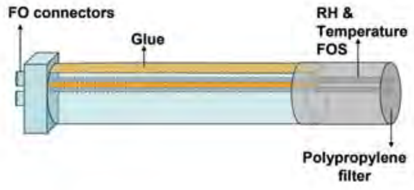

Figure 3 (above): Schematic of a fibre-optic humidity sensor.

Figure 5 (right): Refractive index based fibre-optic chloride sensor.

Figure 6 (far right): Electrical resistance sensors for concrete and corrosion monitoring.

During the past decade, the research community has put much effort into developing numerous SHM techniques. The application of various types of sensors has been proposed in combination with assorted measurement systems.

Initially, externally bonded sensors were used on concrete structures for SHM; however, these are unable to identify micro-damage at an early stage and hence have limited use for assessing durability. More recently, embedded sensors made of SHM 'smart' materials have emerged as a promising technique.

Embedded sensors

Fibre optic, piezoelectric and electrical resistance sensors are the most commonly used types of embedded sensor. They measure variations in the electrical properties (electrical resistivity, electrical admittance/impedance) of concrete with depth from the surface, relative humidity (RH), temperature, chloride ion concentration and/or pH values. The variation of these parameters from the healthy state (uncracked – early age) to the damaged state (fractured – micro, meso and macro) is associated with the damage evolution and propagation resulting from the progressive penetration of aggressive substances into the concrete through its cover zone.

The fibre-optic sensors shown in this article were designed and developed as part of various research projects funded by the Engineering and Physical Sciences Research Council. Figure 1 shows the design of the sol-gel-based fibre-optic pH sensor developed by some of the authors. In an experimental investigation, the effect of progressively increasing carbonation on pH was measured using this sensor (Figure 2). These data show the viability of using pH sensors for monitoring concrete in marine environments.

Figure 3 shows the design of the fibre-optic RH and temperature sensor developed by some of the authors and Figure 4 is a comparison of its performance with a commercially available capacitance-based sensor in an absorption test.

The above two types of sensor could be used along with the fibre-optic chloride sensors (Figure 5) developed by some of the authors, for monitoring marine concrete structures.

With the specific purpose of continually monitoring electrical properties of concrete from the time of its pour in formwork, the electrical resistance sensor system shown in Figure 6 was developed. This sensory system not only gives the electrical properties but can also be used to identify the time to onset of corrosion as well as the rate of corrosion of steel in marine concrete structures. One such application was the performance monitoring of different types of concrete at the service station in Hangzhou Bay Bridge in China (Figure 7).

The electrical sensor system shown in Figure 6 was installed at various locations, as shown in Figure 8, to monitor the performance of concrete with time in this marine environment. Figure 9 shows the early-age data, highlighting the difference between normal concrete (NC) and HPC, in which the electrical resistivity of the latter continually increased, whereas it reached a maximum value after a short period for the former.

Data was also collected of the atmospheric temperature, RH and other weather parameters, using a weather station (Figure 10). All the data at the monitoring station were collected using the instrumentation system shown in Figure 11 for remote access from the UK and further analysis.

Life cycle of marine structures

One of the main aims of monitoring concrete structures for durability is to

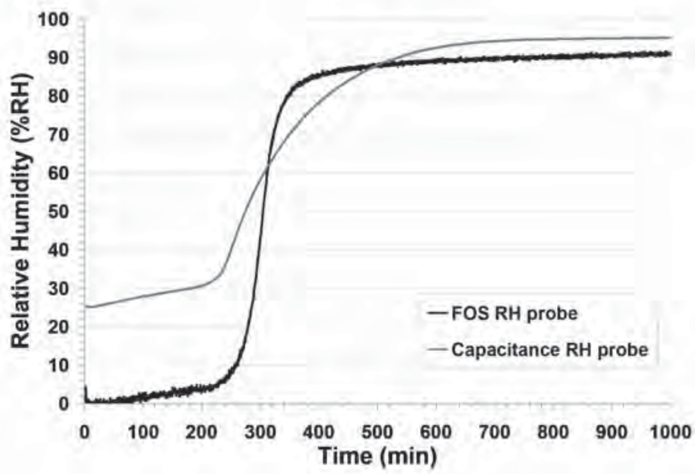

Figure 4 (left): Comparison of RH values between fibre-optic RH sensor and commercial capacitance-based RH sensor in a capillary absorption test.

Figure 7: Hangzhou Bay Bridge service station.

predict the service life using service life models (SLM). By developing more accurate mathematical models, decisions on the time and type of interventions for maintenance could be identified, which would lead to less costly solutions and of course an extended service life of the structures as previously mentioned.

Future research

Unfortunately, unlike the prediction of structural performance from SHM data, durability monitoring has not been widely used to predict the service life of structures. The monitoring stations established by the authors, along with parallel laboratory investigations, are expected to address this drawback so that life-cycle assessment models for structures in marine environments can be developed. By correlating durability monitoring of marine structures with SLMs, not only will the lifespan of these structures be extended but also the level of safety, health, security, quality of environment and economy will be increased. ■

References:

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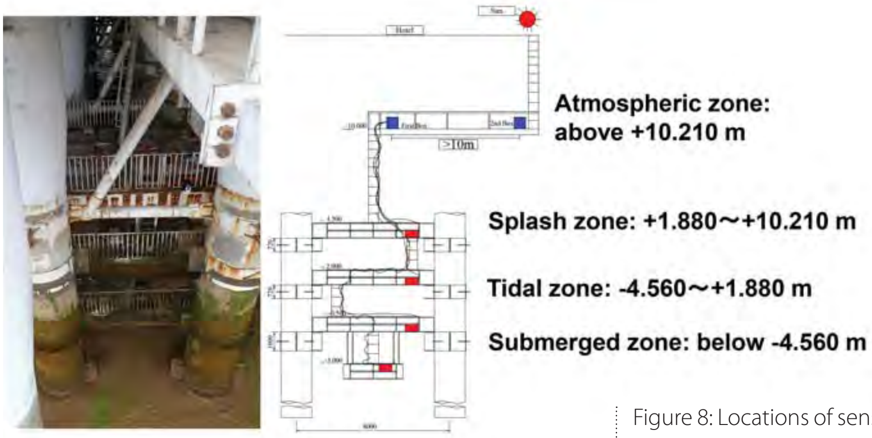

Figure 8: Locations of sensors.

Figure 10: Weather station.

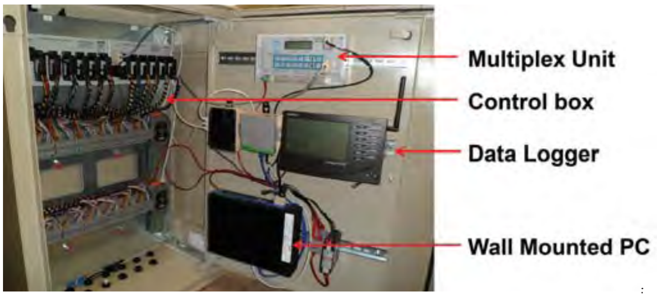

Figure 11: Instrumentation.

Figure 9: Performance of (a) NC and (b) HPC.