A sensor apparatus for embedding in construction material, comprises a sensor electrode array comprising at least one pair of electrodes connectable to an electrical signal source for measuring at least one electrical property representative of electrical resistivity or conductivity between the pair of electrodes, and an anode and cathode connectable to form a cell.
A sensor apparatus and method

Field of the invention

The present invention relates to a sensor apparatus, for example a sensor apparatus for embedding in construction material, such as concrete or other cement-based material.

Background to the invention

The premature deterioration of reinforced concrete structures is a major and growing world-wide problem; in the UK alone, in general around half of construction budgets are devoted to repair and maintenance, with over 30% on concrete structures. There are also the hidden costs of road and bridge closures due to traffic disruption caused by maintenance programmes. Traffic delay costs due to inspection and maintenance programmes are already estimated to be between 15%-40% of the construction costs. Effective methods of monitoring deterioration would provide early warning of serious problems and enable planning and scheduling of remedial measures. However, at present very little (in-situ) monitoring of the deterioration of concrete structures is undertaken, primarily due to the lack of reliable methods that provide the detailed information that will allow estimation of residual service life.

The main deterioration process in concrete structures is chloride-induced corrosion of steel reinforcement embedded within the concrete, particularly for those structures located in, or near, the marine environment or subjected to deicing salt during the winter months. A thin 'skin' of concrete (usually approximately 50-75mm thick) protects the steel from the external environment and hence provides the only barrier to aggressive agents such as chlorides. This 'skin' is called cover-zone concrete and has a major influence on the deterioration of reinforced concrete structures. It is important to understand the protective qualities of cover-zone concrete when attempting to predict in-service performance of a structure, addressing issues such as likely deterioration rates for a particular exposure condition, compliance with specified design life and an early warning indicator of incipient problems. To this end, embedding sensor systems within the cover-zone could potentially provide important information on the state of the structure.
Currently, the most notable embedded sensor system in use in the field is an 'anode-ladder' system manufactured by Sensortech, which employs macrocell current measurements between small diameter, mild-steel bars (anodes) embedded at selected locations within the cover-zone and a stainless steel bar (cathode), using a low impedance ammeter. When the electrical current measured between a mild steel bar and the stainless steel bar starts to rise significantly it can be inferred that passivity of the steel surface has been lost (caused, for example, by chloride ingress). In the course of time, the anodes will be depassivated sequentially, allowing monitoring the advance of a corrosion-front through the cover-zone.

However, as the mild steel bars of the system of the preceding paragraph corrode they can cause significant damage to the concrete. The products of corrosion of the mild steel anodes positioned nearest to the concrete surface can cause cracking and spalling of the concrete (since the products of corrosion occupy a greater volume than the mild steel they replace) and further encourage the ingress of chloride ions thereby exacerbating the situation, making measurements by the system unrepresentative of the corrosion present in the structure as a whole and potentially rendering the system ineffective. Furthermore, it is questionable whether measurement of corrosion activity on the mild steel anodes embedded within the cover-zone is useful in representing the corrosion of a full-size reinforcing bar.

It has been suggested to measure electrical resistance (hence resistivity) of concrete itself within the cover zone, and to monitor the temporal variation of measured electrical resistance, as an indicator of the moisture state and the concentration of deleterious ions within the concrete. Since the flow of water under a pressure differential (hence permeability) or the movement of ions under a concentration gradient (hence diffusion) is analogous to the flow of current under a potential difference (hence electrical resistance) then the measurement of the electrical properties of concrete may provide a methodology for assessing cover-zone performance. Further, once steel passivity is lost, research indicates that the single most important factor affecting the corrosion rate of the reinforcing steel within a reinforced concrete structure is the electrical conductivity of the surrounding concrete (the electrical conductivity being the reciprocal of the electrical resistivity).

A system for measuring electrical resistance of concrete within the cover zone has been described, for example, in McCarter et al, Concrete in Aggressive Aqueous Environments, Performance, Testing and Modeling, 3-5 June 2009, Toulouse,
France. The system comprises an array of 8 electrode pairs mounted on a plastic former and embedded in the surface region of reinforced concrete specimens. The pairs of electrodes are positioned at discrete depths from the exposed surface ranging from 5mm to 50mm. The plastic former is attached to a support structure of stainless steel bars, which are attached the steel reinforcement structure of the concrete specimens using cable ties. The electrode arrays were calibrated prior to installation in solutions of known conductivity to allow a measured resistance between each electrode pair to be converted to a conductivity of the material between the electrodes of the pair. Electrical resistance measurements were performed at a frequency of 1kHz using a portable battery operated data logging system. The various samples were exposed to different environmental conditions over a period of 18 months and variations in conductivity were measured that were consistent with various effects to which the samples were subject, including the ingress of chloride ions.

The system of the preceding paragraph is suitable for performing experimental measurements under controlled conditions. Although it provides a viable means for measuring electrical properties within the cover zone of concrete reinforced structures, the use of such systems in practice for lifetime monitoring of concrete structures presents various practical issues, including ensuring consistency of measurement between different sensors, whilst keeping any initial calibration procedures within reasonable time and cost limits, and ensuring the reliability and accuracy of the sensors over the lifetime of a concrete structure.

It is an aim of the present invention to provide an improved, or at least alternative, sensor apparatus and method.

**Summary of the invention**

In a first, independent aspect of the invention there is provided a sensor apparatus for embedding in construction material, comprising:- a sensor electrode array comprising at least one pair of electrodes connectable to an electrical signal source for measuring at least one electrical property representative of electrical resistivity conductivity between the pair of electrodes; and an anode and cathode connectable to form a cell. The cell may comprise a corrosion cell.
The construction material may comprise a cement-based material, for example concrete. The sensor apparatus may be for embedding in a concrete or other cement-based structure, for example a reinforced concrete structure. The sensor electrode array may be referred to herein as a resistivity sensor electrode array or a conductivity sensor electrode array. A resistivity sensor may also be referred to as a conductivity sensor and vice versa, as resistivity is the reciprocal of conductivity and a measure of resistivity is also a measure of conductivity.

The measured at least one electrical property representative of electrical conductivity between the pair of electrodes may be used to detect the penetration of fluid and/or ions, or other material that may cause deterioration of the construction material. The measured at least one electrical property may be used to predict when corrosion (for example corrosion of reinforcement elements of a reinforced concrete structure) may occur and/or when a cover zone or other part of the structure should be replaced, repaired or treated. The measured at least one property is also representative of electrical resistivity (as resistivity is merely the reciprocal of conductivity).

By providing an anode and cathode connectable to form an electrical cell in the structure, a back-up to the predictive or other measurements obtained using the electrode array may be provided. The cell may be a corrosion cell. Even if the electrode array or associated circuitry suffers a fault and stops working or begins to operate unreliably or at reduced accuracy, the anode and cathode arrangement may, for example, provide for detection of significant corrosion. That can be particularly useful if the sensor apparatus is intended for monitoring penetration of fluid, for example liquid containing dissolved ions, or other material that may cause corrosion, over a long period of time (for example, years or decades).

The ability to measure actual corrosion, as well as electrical properties that may be predictive of corrosion can be particularly useful if the sensor apparatus is embedded in a structure for which safety is particularly important or for which replacement of corroded structures once significant corrosion has occurred is difficult or expensive, for example bridges, tunnels or tall buildings such as skyscrapers.

The sensor apparatus may form part of an integrated monitoring system to provide long-term information on the performance of the structure. In one example, the sensor apparatus may be operable to provide continuous, real-time information of the performance of cover-zone concrete from initial placing.
The anode and cathode may be formed and arranged so that in operation, when the anode and cathode are connected to form the electrical cell, an electrical output, for example a macrocell current, provided by the cell is dependent on the passivity and/or corrosion of at least one of the anode and the cathode. The anode and the cathode may be integral to the structure of the sensor apparatus.

The apparatus may further comprise a support structure, and at least one of the anode and the cathode may form part of the support structure. That can provide for a particularly compact apparatus. The support structure may be for supporting the sensor electrode array.

The anode and the cathode may each comprise a bar forming part of the support structure for supporting the sensor electrode array. The anode and the cathode may form part of the same bar forming part of the support structure.

At least one of the anode and cathode may be arranged to be a load-bearing part of the support structure. Thus, the anode and/or cathode may be subject to similar conditions to parts of a reinforcing structure that may be subject to corrosion (for example reinforcing bars of a reinforced concrete structure).

The sensor apparatus may be for embedding in a reinforced concrete structure that comprises concrete and a framework of reinforcement bars within the concrete, and one of the anode or cathode may be formed of substantially the same material as the support bars of the reinforced concrete structure. Thus, the presence (or absence) of corrosion in the anode or cathode may be a good indicator of the presence (or absence) of corrosion in the reinforcement of the concrete structure.

At least one of the anode and cathode may have at least one dimension (for example, width or radius) that is similar to a corresponding at least one dimension of the reinforcement bars of the structure. Again, the presence (or absence) of corrosion in the anode or cathode may thus be a good indicator of the presence (or absence) of corrosion in the reinforcement of the concrete structure. One of the anode and the cathode may comprise mild steel. The other of the anode and the cathode may comprise a noble metal, for example the cathode may comprise stainless steel or titanium.
If both the anode and cathode comprise steel (for example, one comprising mild steel and one comprising stainless steel) a particularly strong support structure that is straightforward to produce can be provided.

The sensor apparatus may be for embedding in a reinforced concrete structure that comprises concrete and a framework of reinforcement bars within the concrete, and the sensor apparatus may comprise attachment means for attaching the sensor apparatus to at least one reinforcement bar of the framework.

The attachment means may comprise at least one part of the apparatus that is formed and arranged for resting on and/or being fixed to at least one reinforcement bar. That at least one part of the apparatus may comprise at least one part of the or a support structure.

The length of the sensor apparatus may be greater than the separation of at least two reinforcement bars of the concrete structure. Thus, the sensor apparatus may rest on or beneath the at least two reinforcement bars, and may be particularly easy to install within a reinforced concrete structure. The length of the support structure may be greater than the separation of the at least two reinforcement bars.

The sensor apparatus may be arranged so that it is maintained at a selected depth within the concrete structure and/or at a selected position relative to the framework of reinforcement bars by attachment to the at least one reinforcement bar of the concrete structure using the attachment means.

The attachment means may be arranged so that the support structure of the sensor apparatus can be held at a selected depth within the concrete structure and/or at a selected position during the forming of the concrete structure, for example prior to the pouring of the concrete into the concrete structure. The attachment of the support structure to the reinforcement bars may comprise resting the support structure on the reinforcement bars and/or fixing the support structure to the reinforcement bars. The attachment means may comprise clamping or tying means.

The anode and cathode may be arranged so that if the sensor apparatus is at the selected depth and/or selected position, for example by way of attachment to the at least one reinforcement bar, at least one of the anode and the cathode is at substantially the same distance from a surface of the concrete structure (for example,
at substantially the same depth within the concrete structure) as the or a reinforcement bar of the concrete structure. Thus the anode and/or cathode may be subject to substantially the same conditions as the at least one reinforcement bar. The anode and/or the cathode may be located at a base portion of the support structure.

The apparatus may further comprise a four-point resistance sensor, comprising four further electrodes connectable to an electrical signal source for performing a four-point measurement of resistance.

That feature is particularly important and so in a further independent aspect of the invention there is provided a sensor apparatus for embedding in construction material to measure at least one property of the construction material, comprising:- a sensor electrode array comprising at least one pair of electrodes for measuring at least one electrical property representative of electrical resistivity or conductivity between the pair of electrodes; and a four-point resistance sensor electrode arrangement, comprising four further electrodes connectable to an electrical signal source for performing a four-point measurement of resistance. The resistance obtained from the four-point measurement can be converted to resistivity (or conductivity) using standard techniques.

The use of a four-point technique may enable the measurement of the electrical resistivity/conductivity of the material, excluding the effects of contact resistances and other surface effects between the electrodes and the concrete. For example, the four-point measurement technique can allow for the measurement of electrical resistivity/conductivity whilst excluding or at least reducing electrode polarization effects. That can be particularly important as the such polarization effects can have a significant effect on two-point measurements, such as those that may be performed using the pairs of electrodes of the electrode array, in concrete or other cement-based structures. Two point measurements are generally less complex to perform, and require less wiring to be present, which is an important practical consideration. By using a combination of two-point measurements with four-point measurements for checking or calibration, a combination of accuracy, reliability and efficiency can be obtained.

The sensor electrode array may comprise an array of pairs of electrodes, and the four further electrodes may be located outside the array.
The four-point resistance sensor may be arranged so that the four further electrodes are further away from a surface of the concrete than at least one pair of electrodes, or all pairs, of the sensor electrode array, for example when the sensor apparatus is held at the selected depth and/or selected position within the concrete structure by attachment to the at least one reinforcement bar of the concrete structure. For example, the four further electrodes may be below the pairs of electrodes of the sensor electrode array, if the surface in question is an upper surface of the concrete structure.

Thus, any fluid, ions or other material that may penetrate the concrete or other construction material will not reach the four further electrodes before the array of electrode pairs. Measurements using the four point sensor may be used to benchmark and/or recalibrate the electrode pairs positioned with the cover-zone.

In another arrangement, the four further electrodes may be nearer to a surface of the concrete than each pair of electrodes of the sensor electrode array, for example when the sensor apparatus is held at the selected depth and/or selected position within the concrete structure by attachment to the at least one reinforcement bar of the concrete structure. For example, the four further electrodes may be above the pairs of electrodes of the sensor electrode array, if the surface in question is an upper surface of the concrete structure. In that case, if measurements using the four point sensor do not indicate the penetration of fluid, ions or other material then it may be the case that changes in measurements using the electrode array may be due to extraneous effects (for example, electrode polarization effects) rather than due to the penetration of fluid, ions or other material.

In another independent aspect of the invention there is provided a sensor system comprising a sensor apparatus as claimed or described herein and a controller comprising at least one electrical signal source for connection to the at least one pair of electrodes of the sensor electrode array to form a conductivity sensor and means for measuring the at least one electrical property representative of electrical conductivity between the pair of electrodes.

The controller may comprise means for applying an electrical signal (for example from the electrical signal source) to the at least one pair of electrodes and for measuring a response to the applied signal. The electrical signal may be an a.c.
(alternating current) signal and may have a frequency in the range from 100Hz to 10,000Hz, for example around 1KHz. The signal amplitude may be in the range 100mV to 1V.

The controller may further comprise means for measuring the current or voltage provided by the electrical cell. The means for measuring the current or voltage may comprise, for example, a low impedance ammeter, or high impedance voltmeter.

The controller may comprise means for determining the presence of corrosion at the anode or cathode in dependence upon the measured current or voltage provided by the electrical cell.

That at least one electrical signal source may be for connection to the four further electrodes and the controller may further comprise means for performing the four-point measurement of resistance.

The controller may be configured to perform a comparison of measurements obtained using the four-point resistance sensor and measurements obtained using the conductivity sensor. The controller may be configured to modify a calibration of the conductivity sensor in dependence on the comparison. The controller may be configured to apply an offset to measurements using the conductivity sensor in dependence on the comparison.

In another independent aspect of the invention there is provided a method of monitoring the penetration of fluid (for example water) and/or ions into a structure, using a sensor apparatus as claimed or described herein installed in the structure, comprising measuring at least one electrical property representative of electrical conductivity between the pair of electrodes of the sensor electrode array of the sensor apparatus, and monitoring changes in the measured electrical property.

The method may further comprise installing the sensor apparatus in the structure.

The measured electrical property may comprise electrical resistance. The measured electrical resistance may be subsequently converted to conductivity (or its reciprocal resistivity), to provide a measure that may be substantially independent of the volume of concrete or other material between the electrodes.
The method may further comprise measuring the current or voltage provided by the electrical cell of the sensor apparatus, and monitoring changes in the measured current or voltage.

The structure may be a reinforced concrete structure comprising at least one reinforcement bar, and the installing of the sensor may comprise arranging the sensor so that at least one of the anode and the cathode is at substantially the same distance from a surface of the structure (for example, at substantially the same depth within the concrete) as the or a reinforcement bar of the concrete structure.

The installing of the sensor apparatus may comprise arranging the sensor so that is adjacent to the or a reinforcement bar. The or a reinforcement bar may be that reinforcement bar of a framework or reinforcement bars which is closest to the surface of the concrete. The installing of the sensor apparatus may comprise installing the sensor apparatus in a cover zone of the structure.

The method may further comprise measuring resistance using the or a four-point resistance sensor.

The installing of the sensor apparatus may comprise arranging the sensor apparatus so that the four further electrodes of the four point resistance sensor are further away from a surface of the concrete structure (for example, at a greater depth within the concrete structure) than the at least one pair of electrodes of the sensor electrode array.

The installing of the sensor may comprise arranging the sensor so that each of the four further electrodes are at substantially the same depth within the concrete structure and/or so that, for each pair of electrodes of the sensor electrode array, the electrodes of the pair are at substantially the same depth within the concrete structure.

The method may further comprise comparing measurements obtained using the four-point resistance sensor and measurements obtained using the sensor electrode array.

The method may further comprise modifying a calibration of the conductivity sensor in dependence on the comparison.
The method may further comprise applying an offset to measurements using the conductivity sensor in dependence on the comparison.

In one mode of operation, short term accurate monitoring of setting, hardening and strength development of concrete, may be provided. In another mode of operation, long term durability monitoring can be provided, enabling the assessment of the condition of a concrete structure as it ages using automated monitoring techniques.

A multi-electrode probe for monitoring time-variant processes in structural concrete may be provided. Real-time monitoring and measurement of chemical and physical changes within the cover zone of reinforced concrete structures may be enabled.

An embeddable sensor system for in-situ, non-destructive, continuous and quantitative measurement of changes occurring within the surface region of reinforced concrete structures may be provided. The sensor system may measure variations in electrical conductivity measured at multiple locations within the aforementioned surface region, and may also measure macrocell current and temperature.

In another independent aspect of the invention there is provided a ruggedized, multi-purpose unit enabling evaluation of electrical conductivity or resistivity (the reciprocal of conductivity) and temperature at discrete points within a concrete cover zone. Discretized conductivity measurements may allow the integrated quality of the cover-zone to be assessed as conductivity is related to diffusivity, permeability and corrosion activity. The unit may also have the facility to monitor macrocell current, which can be used to indicate loss of passivity of mild steel.

There may be provided an integrated monitoring system for new or existing reinforced concrete structures that includes a sensor apparatus as claimed or described herein. Such a system may reduce costs by allowing a more rational approach to the assessment of repair options, and scheduling of inspection and maintenance programmes thereby minimising traffic delays resulting from road closures. The ability to continuously monitor covercrete and steel - in real time - may allow a more informed assessment of the current and future performance of the structure. Sensor systems, such as those described, deployed for the assessment of
covercrete and steel performance may provide or form a component of an integrated monitoring system.

In another independent aspect of the invention, there is provided a sensor apparatus or system substantially as described herein with reference to the accompanying drawings.

In a further independent aspect of the invention there is provided a method substantially as described herein with reference to the accompanying drawings.

Any feature in one aspect of the invention may be applied to other aspects of the invention, in any appropriate combination. For example, apparatus features may be applied to method features and vice versa.

**Detailed description of embodiments**

Embodiments of the invention are now described, by way of non-limiting example, and are illustrated in the following figures, in which:

- Figure 1 is an illustration of a sensor apparatus;
- Figures 2 to 4 are illustrations of a metal bar forming part of the sensor apparatus of Figure 1 and comprising anode and cathode components;
- Figure 5 is a schematic illustration of the metal bar of Figures 2 to 4 in cross-section, showing electrical connections to components of the metal bar;
- Figure 6 is an illustration of a conductivity sensor included in the sensor apparatus of Figure 1;
- Figure 7 is a schematic illustration, in cross-section, of a sensor apparatus embedded in a reinforced concrete structure;
- Figures 8a and 8b are graphs of complex and real electrical impedances of concrete; and
- Figure 9 is an illustration of a conductivity sensor for inclusion in a sensor apparatus according to a further embodiment.

A sensor apparatus 2 for embedding in building material, for example for embedding in and measuring properties of a concrete structure, for example a cover zone of the concrete structure, is illustrated in Figure 1. The sensor comprises a conductivity sensor 4 (which may also be referred to as a resistivity sensor) that comprises an
electrode array 6 mounted on a PVC former 8. The former 8 of the embodiment of Figure 1 is T-shaped, but any suitable shape of former can be used. The electrode array 6 comprises pairs of electrodes arranged vertically at intervals thus enabling electrical measurements to be taken at discrete depths within the concrete cover-zone. The electrode array 6 and PVC former may be similar to those described in McCarter et al, Concrete in Aggressive Aqueous Environments, Performance, Testing and Modeling, 3-5 June 2009, Toulouse, France, the content of which is hereby incorporated by reference.

The conductivity sensor 4 is mounted onto two metal bars 10, 12 (each of approximately 12mm diameter and approximately 350mm long), with an additional PVC separator 14 connecting the metal bars 10, 12 and providing rigidity. The size, structure and arrangement of the bars 10, 12, together with the additional PVC spacer ensure that the sensor assembly is rigid and can be tied to reinforcement. A ruggedized unit is important in practice for use on site.

The metal bars 10, 12 are illustrated in more detail in Figure 2, in which the electrode array 6 has been removed from the PVC former 8. Each bar 10, 12 comprises two stainless steel tubes 20, 22 separated by a mild-steel tube insert 24. The mild-steel and stainless steel are, themselves, separated by PTFE spacer rings 26, 28. The bars 10, 12 are shown detached from the system in Figure 3 and 4, with the component parts of the bars 10, 12 connected together to form a continuous tube and with the component parts separated.

For each bar electrical connections are made by attaching wires 32, 34, 36 to the stainless steel tubes 20, 22 and to the mild steel tube 24, these connections being made on the inside surface of the tubes, with the cabling taken ducted out through the tube, as illustrated schematically in Figure 5. After electrical connections have been made by attaching wires to the tubes, the bars are filled with a potting compound, for example epoxy resin, to provide rigidity and to provide that moisture cannot penetrate, or condense in, the tube. The stainless steel tubes 20, 22 are partially sleeved with heat-shrink sleeving 30. This construction allows macrocell current measurements to be made between the exposed stainless steel and mild steel (in the illustrated embodiment the ratio of the cathode area to the anode area is, approximately 4:1 but this can be varied).
In order to install the concrete sensor 2 in a concrete structure, the metal bars 10, 12 are rested on steel reinforcement bars 32, 34 of a reinforcing framework. A portion 32, 34, 36, 38 of such a framework is illustrated in Figure 1. The metal bars 10, 12 can be tied to the framework using, for example, cable ties. The sleeving 30 on the stainless steel tubes 20, 22 ensures that the metal bars 10, 12 remain electrically isolated from the steel reinforcement bars 32, 34.

The conductivity sensor 4 is illustrated in more detail in Figure 6. Each of the pairs of electrodes in the electrode array 6 comprises a stainless steel pin 40a, 40b (1.2 mm in diameter) which is sleeved with heat-shrink sleeving 42a, 42b to expose a 10mm tip 44a, 44b. Marine grade stainless steel is used for the electrodes to ensure long term durability. For each electrode pair, the pins have a (horizontal) centre-to-centre spacing of, for example, 10mm.

The electrode pairs are off-set from each other in the horizontal direction, and the exposed tip of the electrodes 44a, 44b are positioned remote from the PVC former (usually at distances greater than a maximum expected aggregate size, for example 10mm so that any problems of interference with the distribution of aggregate in the concrete can be reduced). This arrangement is adopted in the embodiment of Figures 1 to 6 in preference to a vertical stack of electrode pairs mounted close to the PVC former (although such a vertical stack can be used in alternative embodiments) as it can reduce interference with the natural distribution of aggregate within the concrete and wall-effect type problems against the PVC former. Grooves 46 are provided at locations between the electrode pairs to ensure intimate bond with the concrete.

In the current embodiment of Figures 1 to 6, electrode pairs are positioned at, for example, 10, 20, 30, 40, 50 and 75mm from the base of the former 8. Other inter-electrode spacings are used in other embodiments, and the number of electrode pairs can also be varied in such other embodiments.

Thermistors 46, 47, 48 can be mounted on the former 8 at discrete depths, for example at distances of 10, 20, 30 and 40mm from the base of the former 8 to facilitate temperature measurements, and to enable the temperature profile through the cover region where the resistance measurements are performed to be evaluated. Resistance measurements can be standardised to a reference temperature in dependence on the temperatures measured with the thermistors.
The sensor apparatus 2 is shown in cross-section embedded in a concrete structure 50 in Figure 7 (not to scale). The sensor apparatus 2 rests between steel reinforcement bars 32, 34 of a reinforcing structure 52, and lies in a cover zone 53 of the structure. Cabling 54 (for example, colour coded multi-core cable) is provided that passes through the concrete structure 50 and links electrical connections for the electrode pairs, the metal bars 10, 12 and the thermistors to a control unit 56 located at the exterior of the concrete structure 50.

The control unit 56 comprises a microprocessor control unit for applying an a.c. electrical signal to the electrode pairs and for measuring the response from the electrode pairs. The measurement circuitry is also operable to measure the resistance of the thermistors; this resistance measurement can be converted to a temperature. The control unit can be programmed to initiate a measurement cycle at predefined time intervals (for example, to take a measurement cycle once every 24-hours, once every week, or once every month). A measurement cycle comprises a set of resistance measurements taken from the electrode pairs and thermistors.

The control unit is interfaced to a multiplexing unit. All cabling from the electrode pairs and thermistors is connected back to the multiplexing unit. The multiplexing unit switches sequentially between the electrode pairs and thermistors during the aforementioned measurement cycle. The control unit comprises a memory for storing measurement data and a connection (for example a RS232 connection) enabling measurement data to be downloaded from the control unit. The control unit can also include a transmitter/receiver unit (for example a modem) and aerial for transmitting wirelessly measurement data from the control unit to a remote location, for example to a control centre for processing. The transmitter/receiver unit and aerial can also be used to receive instructions from the remote location, for example instructions to alter the time interval between measurement cycles, perform measurements or to transmit data. Thus, the sensor apparatus can be interrogated remotely.

A separate low impedance ammeter is used to measure the macrocell currents generated between the metal bars 10, 12. Macrocell current measurements are usually only taken when measurements from the electrode pairs indicate that chloride ions, for example, have penetrated to a sufficient depth as to depassify the mild steel.
Prior to installation, the electrode-pairs are calibrated in solutions of known conductivity thereby to obtain a calibration factor, $k$, for the array. This procedure allows the measured resistance or conductance ($G$, in Siemens, S) of the concrete to be converted to conductivity ($\sigma$ in S/m) using the equation, $\sigma = G*k$. The resistivity, $\rho$, reciprocal of conductivity, can also be obtained (in ohm-m).

In operation, the control unit applies an a.c. current or voltage at a selected frequency to the electrodes of each electrode pair and measures the resulting a.c. voltage or current across the electrodes. Usually the selected frequency is in the range 1kHz-10kHz and is selected to be a frequency at which the influence of electrode polarisation effects is minimized. The complex impedance response of hardened concrete is illustrated in Figure 8a, which is a graph of imaginary versus real impedance for hardened concrete. Figure 8b is a schematic diagram showing the bulk and electrode contributions to the complex impedance response illustrated in Figure 8a whereby the electrical response from concrete is represented by a parallel combination of resistance, $R$, and capacitance, $C$. The frequency at the cusp point between the bulk and electrode responses represents the optimal frequency for a.c. measurements (at which point electrode polarisation effects are substantially eliminated). The cusp point is usually in the region 100Hz to 10kHz, for example around 1kHz.

In the embodiment of Figures 1 to 6, the selected frequency is around 1 kHz, but the optimum frequency can vary in dependence on the properties of the concrete and the properties and arrangement of the electrodes.

The sensor 2 is usually arranged so that each pair of electrodes is arranged horizontally, usually parallel to the concrete surface. Thus, measurements at each pair of electrodes can be used to determine the conductance, in a horizontal direction, at a respective depth beneath the surface of the concrete structure.

A separate measurement unit is also operable to measure the current generated by the metal bars 10, 12. The electrical connections to the stainless steel tubes 20, 22 and to the mild steel tube 24 are arranged such that the tubes form an electrochemical cell, and the control unit is arranged to measure the macrocell current generated between the stainless steel and mild steel tubes. The level of current is indicative of the passivity of the mild steel tube 24.
Various modes of operation of the sensor 2 are provided. In a first mode of operation, resistance measurements are performed on a regular basis (for example daily or weekly) over a long period of time (for example over years or decades) after setting of the concrete in the structure. At the time of each measurement, the resistance is measured between each pair of electrodes in turn. The resistance data are logged and converted to conductivity data representative of the conductivity of the concrete at each depth beneath the surface at which an electrode pair is present. The logging and conversion can be performed at the control unit 56 or at a control centre or other remote location.

The determined electrical conductivity is directly related to those properties which are of importance in relation to reinforced concrete durability (for example, diffusivity, permeability, sorptivity). As fluid, and for example chloride ions, penetrate the concrete structure over time the conductivity between the electrode pairs increases. The onset of an increase in conductivity can be indicative of the ingress / arrival of significant amounts of fluid and, for example, fluid containing dissolved chloride ions or other deleterious ions substances that can cause deterioration of reinforced concrete. As the pairs of electrodes are arranged at different depths, the onset of an increase in conductivity occurs at different times for the different electrode pairs, and the progress, and rate of progress of fluid and, for example, chloride ions through the concrete can be tracked.

By determining when significant amounts of fluid, and, for example chloride ions, have penetrated to different depths within the cover zone, it is possible to make predictions as to when the fluid and, for example, chloride ions will reach the steel reinforcing framework of the concrete structure and thus when there is a risk that significant corrosion will begin to occur. Thus, the cover layer can be replaced or treated before significant corrosion of the reinforcing framework occurs. Once corrosion of the reinforcing framework has occurred, remedial action is usually significantly more complex, expensive and time consuming and may require replacement of portions of the supporting framework.

It is a significant feature of the embodiment of Figures 1 to 6 that the supporting structure for the electrode array of the conductivity sensor includes mild steel and stainless steel components arranged as a macrocell that can be used to measure the level of corrosion of the mild steel. The apparatus 2 is intended to be embedded in
the concrete structure for significant lengths of time (years or decades) and it is important that the apparatus continues to operate reliably throughout that time, as replacement of the apparatus 2 would require breaking open of the cover layer. Furthermore, even if the apparatus 2 were replaced it could not then provide measurements representative of the state of the rest of the cover layer, as the concrete surrounding the apparatus 2 would then be of a different age and condition.

By providing the mild steel and stainless steel components arranged as a macrocell, the apparatus is also able to determine when corrosion of the mild steel begins to take place. In the embodiment of Figures 1 to 6 the mild steel tubing 24 is selected to be similar to the material of the supporting framework and, as it is also located at the same depth as the top-most (or bottom-most) bars of the supporting framework, any corrosion detected using the macrocell arrangement provides a good indication that corrosion of the supporting framework has started or is about to start. That can provide a useful back-up to the predictive measurements obtained from the conductivity sensor. Even if the conductivity sensor suffers a fault and stops working or begins to operate unreliably or at reduced accuracy, the macrocell arrangement can provide for detection of significant corrosion, and can avoid the need to replace the apparatus.

It can be understood from the preceding few paragraphs that the first mode of operation can provide for a suite of measurements are taken which are directly related to concrete performance and state of the steel surface. They allow virtually continuous real-time monitoring of cover-zone concrete properties and also has the facility for monitoring macrocell current, indicating loss of passivity of mild steel. The method is non-destructive with measurements taken in-situ. As the sensor 2 can be embedded within the fresh concrete, it is suited for measurements on new-build structures or structures which are undergoing repair; it therefore allows monitoring of the concrete from time of construction.

Alternatively to the embodiment of Figures 1 to 6 provide for further conductivity measurements to be taken, which can allow for in-situ calibration or adjustment of the conductivity sensor, and detection of faults or drift in operation of the conductivity sensor. One such alternative embodiment is illustrated in Figure 9 (not to scale) in which the former 8 includes a further two horizontal rows 60, 62 of pin-electrodes, with each row comprising 4 electrodes of the same form as those illustrated in Figures 1 and 6. In the embodiment of Figure 9, the horizontal rows are positioned
50mm and 75mm from the base of the former 8, and thus above the electrode pairs of the electrode arrays. Each of the electrodes in the two horizontal rows is connected to the control unit via cabling to enable, for each row, electrical measurements between the four electrodes of the row. Usually the control unit is configured to apply electrical signals to the four electrodes to perform a four-point measurement of electrical resistance, in accordance with known four-point measurement techniques. In such a configuration, two of the electrodes are arranged to be current terminals and the control unit applies a current between those terminals and measures the corresponding voltage on the other two electrodes, located between the current terminals. In the embodiment of Figure 9, the current and voltages used can be either d.c. current and voltages or a.c. currents and voltages.

As mentioned above, the operating frequency for measurement of the resistance using the pairs of electrodes is selected in order to minimize such electrode polarization effects. However, it has been found that such electrode polarization effects can vary significantly over time, particularly over the years or decades for which the apparatus 2 is intended to be used in situ. Other extraneous contributions to the resistance measurements, for example arising from other contact resistance effects, can also vary significantly over those time scales. By periodically measuring the resistance using a four point measurement on the horizontal rows of four electrodes it can be determined whether any significant variation of the resistance measured by the pairs of electrodes in the electrode array is due to a genuine variation in the resistivity of the concrete or a variation in electrode polarization or other extraneous effects.

In the embodiment of Figure 1, the horizontal rows of four electrodes are placed farther from the concrete surface than the array of electrode pairs of the conductivity sensor, and will thus usually remain unaffected by wetting or drying action at the surface. The four point measurements obtained from the rows of four electrodes can thus be taken as representative of concrete unaffected by fluid or ion ingress from the surface and thus used as a benchmark. The concrete surface in question may be the concrete surface that is closest to the apparatus and/or a concrete surface from which the ingress of fluid, for example ion-containing fluid, may be expected. The concrete surface may be an upper or lower surface of the concrete structure.
The four point measurements can be used to provide an in-situ calibration of the electrode pairs of the electrode array. For example, a variable offset can be applied to measurements by the electrode pairs in dependence on the four point measurements, to compensate for any drift due, for example, the electrode polarization or other extraneous effects over time.

In a variant of the embodiment of Figure 9, the metal bars 10, 12 are stainless steel throughout and do not include the mild steel components arranged to form a macrocell.

The first mode of operation of the embodiment of Figures 1 to 6, described above, can be used to monitor the condition of, and penetration of fluid into, concrete or other building material. In a second mode of operation, the apparatus is used to monitor in-situ the condition of concrete after it is deposited, and can follow the setting and hardening of concrete from the time of placement.

Since the electrical conductivity of cement (hence concrete) is directly related to its degree of hydration, which, in turn, is related to strength, the measurement of electrical conductivity of the concrete using the electrode pairs can be used to monitor the increase in strength of concrete following deposition. The increase in electrical resistivity (reciprocal of conductivity) with time after deposition of concrete follows the same profile as its strength development curve for the concrete. Thus, the conductivity measurements can be used to ensure that the in-situ strength of the concrete is developing in a satisfactory manner. The resistivity measurements can be performed using the same techniques as described in relation to the first mode of operation. Usually the resistivity measurements would be performed more frequently (for example, hourly or daily) when monitoring the setting and drying of concrete than when measuring the penetration of fluid, although in both cases measurements can be repeated at any desired interval.

In using the sensor apparatus 2 to measure the setting and hardening of concrete, it may be located at any suitable depth within the concrete, and does not need to be within the cover zone. For example, it could be rested on steel bars within the body of the reinforcing framework, rather than resting on the top-most steel bars of the reinforcing framework. Several sensor apparatus 2 can be provided to monitor in situ the setting and hardening of the concrete, each located at different depths.
As well as using the sensor apparatus 2 to measure the setting and hardening of concrete structures in the field, it can also be used as a tool to measure the influence of, for example, chemical and mineral admixtures in concrete on setting and hardening of the concrete.

In addition to monitoring fluid and ionic movement within the cover zone of reinforced concrete structures (or other locations within such structures) which is of considerable importance with regard to long-term concrete durability, the sensor apparatus can be used to evaluate the performance and efficacy of surface treatments on concrete (it is now a statutory requirement that the concrete in all highway structures on motorways and trunk roads is surface treated).

The sensor apparatus could also be used to study migration of contaminants through landfill liners, or the movement of radionuclides which have been encapsulated in cement matrices.

The sensor apparatus described in relation to Figures 1 to 9 represent only certain possible embodiments, and details of the sensor apparatus can be varied in other embodiments. For example, the number, arrangement and structure of the electrodes can be varied, and the structure and form of the former can be varied, as can the support structure and the arrangement of the anode and cathode. One or more sets of four electrodes can be provided for the performance of four-point measurements.

It will be understood that the present invention has been described above purely by way of example, and modifications of detail can be made within the scope of the invention.

Each feature disclosed in the description, and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination.
**Claims**

1. A sensor apparatus for embedding in construction material, comprising:-
   a sensor electrode array comprising at least one pair of electrodes connectable to an electrical signal source for measuring at least one electrical property representative of electrical resistivity or conductivity between the pair of electrodes; and
   an anode and cathode connectable to form a cell.

2. Apparatus according to Claim 1 wherein the anode and cathode are formed and arranged so that in operation, when the anode and cathode are connected to form the cell, an electrical output provided by the cell is dependent on the passivity and/or corrosion of at least one of the anode and the cathode.

3. Apparatus according to Claim 1 or 2, further comprising a support structure, wherein at least one of the anode and the cathode forms part of the support structure.

4. Apparatus according to Claim 3, wherein at least one of the anode and cathode is arranged to be a load-bearing part of the support structure.

5. Apparatus according to any preceding claim, wherein the sensor apparatus is for embedding in a reinforced concrete structure that comprises concrete and at least one reinforcement bar within the concrete, and the anode is formed of substantially the same material as the at least one reinforcement bar.

6. Apparatus according to any preceding claim, wherein the anode comprises mild steel.

7. Apparatus according to any preceding claim, wherein the cathode comprises a noble metal, for example the cathode comprises stainless steel.

8. Apparatus according to any preceding claim, wherein the sensor apparatus is for embedding in a reinforced concrete structure that comprises concrete and at least one reinforcement bar within the concrete, and the sensor apparatus comprises
attachment means for attaching the sensor apparatus to the at least one reinforcement bar.

9. Apparatus according to Claim 8, wherein the attachment means comprises at least one part of the apparatus that is formed and arranged for resting on and/or being fixed to at least one reinforcement bar.

10. Apparatus according to Claim 8 or 9, wherein the length of the sensor apparatus is greater than the separation of at least two reinforcement bars of the concrete structure.

11. Apparatus according to any of Claims 8 to 10, wherein the sensor apparatus is arranged so that it is maintained at a selected depth within the concrete structure and/or at a selected position relative to the at least one reinforcement bar by attachment to the at least one reinforcement bar of the concrete structure using the attachment means.

12. Apparatus according to Claim 11, wherein the anode and cathode are arranged so that if the sensor apparatus is maintained at the selected depth and/or selected position by attachment to the at least one reinforcement bar, at least one of the anode and the cathode is at substantially the same distance from a surface of the concrete structure as the or a reinforcement bar of the concrete structure.

13. Apparatus according to any preceding claim, further comprising a four-point resistance sensor, comprising four further electrodes connectable to an electrical signal source for performing a four-point measurement of resistance.

14. A sensor apparatus for embedding in construction material to measure at least one property of the construction material, comprising:-

   a sensor electrode array comprising at least one pair of electrodes for measuring at least one electrical property representative of electrical resistivity or conductivity between the pair of electrodes; and

   a four-point resistance sensor electrode arrangement, comprising four further electrodes connectable to an electrical signal source for performing a four-point measurement of resistance.
15. Apparatus according to Claim 13 or 14, wherein the sensor electrode array comprises an array of pairs of electrodes, and the four further electrodes are located outside the array.

16. Apparatus according to any of Claims 13 to 15 as dependent on Claim 11 or 12, wherein the four-point resistance sensor is arranged so that the four further electrodes are further than the at least one pair of electrodes of the sensor electrode array from a surface of the concrete structure when the sensor apparatus is held at the selected depth and/or selected position within the concrete structure by attachment to the at least one reinforcement bar of the concrete structure.

17. A sensor system comprising a sensor apparatus according to any preceding claim and a controller comprising at least one electrical signal source for connection to the at least one pair of electrodes of the sensor electrode array to form a conductivity sensor and means for measuring the at least one electrical property representative of electrical conductivity between the pair of electrodes.

18. A system according to Claim 17 as dependent on any of Claims 1 to 13, wherein the controller further comprises means for measuring the current or voltage provided by the cell.

19. A system according to Claim 17 as dependent on any of Claims 13 to 16, wherein the at least one electrical signal source is for connection to the four further electrodes and the system further comprises means for performing the four-point measurement of resistance.

20. A system according to Claim 19, further comprising means for comparing measurements obtained using the four-point resistance sensor and measurements obtained using the conductivity sensor.

21. A system according to Claim 20, whereby further comprising means for modifying a calibration of the conductivity sensor in dependence on the comparison.

22. A system according to Claim 19 or 20, further comprising means for applying an offset to measurements using the conductivity sensor in dependence on the comparison.
23. A method of monitoring the penetration of fluid and/or ions into a structure, using a sensor apparatus according to any of Claims 1 to 16 in the structure, comprising measuring at least one electrical property representative of electrical resistivity or conductivity between the pair of electrodes of the sensor electrode array of the sensor apparatus, and monitoring changes in the measured electrical property.

24. A method according to Claim 23 as dependent on any of Claims 1 to 13, wherein the method further comprises measuring the current or voltage provided by the cell of the sensor apparatus, and monitoring changes in the measured current or voltage.

25. A method according to Claim 23 as dependent on any of Claims 1 to 13, or 24 wherein the structure is a reinforced concrete structure comprising at least one reinforcement bar, and the installing of the sensor comprises arranging the sensor so that at least one of the anode and the cathode is at substantially the same distance from a surface of the structure as the or a reinforcement bar of the concrete structure.

26. A method according to Claim 23 as dependent on any of Claims 13 to 16, wherein the method further comprises measuring resistance using the four-point resistance sensor.

27. A method according to Claim 26, wherein the installing of the sensor comprises arranging the sensor so that the four further electrodes of the four point resistance sensor are farther from a surface of the concrete structure than the at least one pair of electrodes of the sensor electrode array.

28. A method according to Claim 26 or 27, further comprising comparing measurements obtained using the four-point resistance sensor and measurements obtained using the sensor electrode array.

29. A method according to Claim 28, further comprising modifying a calibration of the conductivity sensor in dependence on the comparison.

30. A method according to Claim 28 or 29, further comprising applying an offset to measurements using the conductivity sensor in dependence on the comparison.
31. A sensor apparatus or system substantially as described herein with reference to the accompanying drawings.

32. A method substantially as described herein with reference to the accompanying drawings.