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Distributed Water Ingress and Water Potential Measurements using Fibre Optics

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Abstract

We report on a distributed moisture detection scheme which uses a cable design based on water-swellable hydrogel polymers. The cable modulates the loss characteristic of light guided within a multi-mode optical fibre in response to relative water potentials in the surrounding environment. Interrogation of the cable using conventional optical time-domain reflectometry (OTDR) instruments allows water ingress points to be identified and located with a spatial resolution of 50 cm. The system has been tested in a simulated tendon duct grouting experiment as a means of mapping the extent of fill along the duct during the grouting process. Voided regions were detected and identified to within 50 cm. A series of salt solutions has been used to determine the sensor behaviour over a range of water potentials. These experiments predict that measurements of soil moisture content can be made over the range 0 to −1500 kPa. Preliminary data on soil measurements have shown that the sensor can detect water pressure changes with a resolution of 45 kPa. Applications for the sensor include quality assurance of grouting procedures, verification of waterproofing barriers and soil moisture content determination (for load-bearing calculations). © 1997 Elsevier Science Limited

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INTRODUCTION

The appearance of widespread failures in bridges which are 20 years of age or older[1] has highlighted the importance of effective monitoring systems which are able to identify structural problems at an early stage. In Western Europe, the annual civil infrastructure repair/maintenance costs were estimated in 1990 to be around 190 billion ECU, representing 32% of the total investment in building and construction.[2] In the United States the problems are on a similar scale.[2] Approximately 40% of all US steel bridges built before 1960 and 10% of concrete bridges are having significant problems. The potential for monitoring systems to reduce operational maintenance costs by identifying problems at an early stage and by verifying the effectiveness of repair procedures, is clearly significant. The means of installing effective monitoring equipment and processing the collected data represent a considerable challenge which is being actively pursued world-wide.

The bulk of commercialised sensing instrumentation measures physical parameters such as loads, distances or movements. In many instances these measurements are secondary indicators of other problems such as corrosion. By the time that the physical movements are such that the problem can be identified the corrosion may well be at an advanced state and expensive repairs unavoidable. In this present work we have focused attention on a means for performing distributed chemical measurements as a means of complementing the physical parameter instrumentation base.

The measurement system presented here uses optical time-domain reflectometry (OTDR) and a novel cable design which enables chemical parameters to modulate the loss of an optical fibre. To date this approach has been demonstrated as an effective method for detecting locations of water ingress,[3] with potential applications in monitoring waterproofing layers. It has also been shown to provide a useful indication of the extent of grout fill in post-tensioned reinforced concrete structure tendon ducts.[4] This paper will review these applications and will show how the sensor operation can be extended to address chemical quantities such as analogue measurements of water potential, which can be related to soil moisture content or the presence of particular solutes. Such measurements can be useful in determining the strength of soils or in detecting seepages from land-fill sites.

PRINCIPLE OF OPERATION

Hydrogel polymers are materials which are able to absorb water to produce a significant volumetric expansion without dissolving.[5] Furthermore they can be tuned to respond such that the water uptake process is inhibited unless the appropriate stimulus is present[6] (for example, that the water has a specific pH value). This swelling behaviour can be harnessed to produce work in the form of exerting a mechanical force and is the basis of the present sensor.

Acting through a periodic cabling geometry which enables the optical fibre to be mechanically stressed, the swelling of the hydrogel is used to introduce loss into the optical signal. This can be detected and localised using OTDR instruments, thus allowing the location of the swelling hydrogel (the point of chemical activity of interest) to be identified and the chemical parameter measured.

As a measurement of optical backscatter as a function of linear position, OTDR is a well-established method for examining fibre-optic cables to detect, for example, areas of high loss (excessive bends) or points of cable fracture. The technology is well developed and a wide range of instruments, able to resolve changes in the backscatter signal of less than 0.01 dB in magnitude with a spatial resolution of better than 1 m, is commercially available.

It is well known that mechanical perturbations or bends can alter locally the level of backscatter, particularly if the disturbance is periodic and equal to the modal separation between guided and radiative modes. In graded-index fibres, a maximum in mode coupling under a periodic perturbation occurs if the period of the microbend Δ_m is

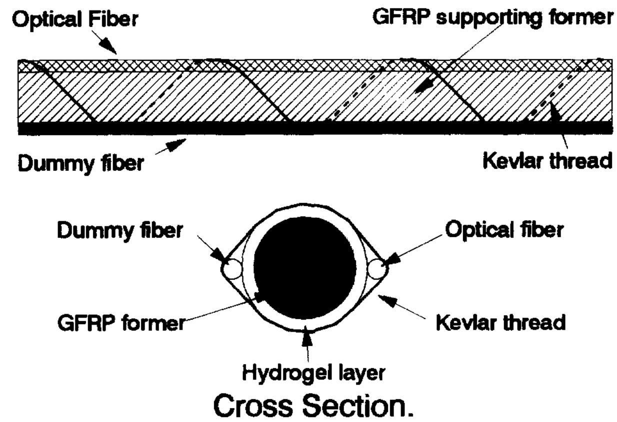

Fig. 1. Schematic diagram of water detector sensor.

$$\Delta_m = \frac{2\pi a}{\sqrt{2\delta}} \quad (1)$$

where a is the core radius and δ is the maximum refractive index difference between the core and the cladding.[7] For graded-index type fibres with a 25 μm core radius Δ_m is typically of the order of 1 mm. The sensor construction is depicted schematically in Fig. 1. A poly-(ethylene oxide)-based hydrogel polymer is dissolved in an alcohol solvent and deposited onto a central supporting former, which is then held in intimate contact with an optical fibre by a helically wound thread with a 2 mm winding pitch. In the presence of water (or the target parameter) the hydrogel swells and pushes the fibre against the thread to create local deformations or microbends. These microbends cause a loss of power in the vicinity of the water, enabling it to be detected. With the present fibre (standard graded-index fibre with a 62.5/125 μm core/cladding diameter and a 250 μm acrylate buffer layer), a hydrogel layer less than 20 μm thick was found to produce a signal loss of around 100 dB/km when the gel is in the swollen condition.

SENSOR CHARACTERISATION

Wet regions of the sensor can be detected provided that the attenuation is sufficiently high that they can be distinguished from dry areas and then spatially located using an OTDR. Figure 2 shows how the loss profile of the sensor evolves following contact with water. The wet attenuation rises to around 60 dB within a 15 s time period and continues to rise for around 45 min to reach a steady-state wet attenuation of over 100 dB/km. The evolution of the sensor loss can be directly equated to the water uptake curve of the bulk hydrogel (more details on the water uptake will be given later).

The final attenuation of the swollen sensor is a function of gel thickness, tension in the Kevlar thread, winding period and the type of thread used. Controlling the exact tension on the thread during the fabrication process is difficult but can be performed to some extent by varying the winding speed. Figure 3 shows how the wet attenuation level changes as spinning rate is increased for a range of gel coating thicknesses.

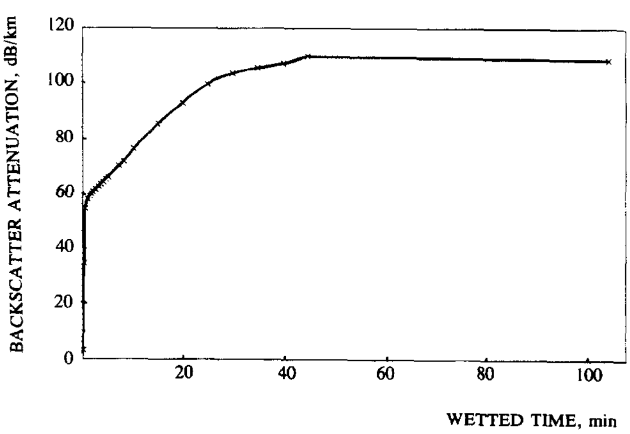

Fig. 2. Sensor attenuation in water.

When the sensor is initially manufactured the dry attenuation is generally high but can be annealed out by a wetting to a level which is comparable with that of the intrinsic loss of the multi-mode optical fibre used in the experiments. Figure 4 demonstrates this behaviour for various gel coating thicknesses and spinning speeds.

Distributed water ingress alarm

The cable as designed can be directly used as a water ingress alarm when interrogated with an OTDR unit. An example of this is shown in Fig. 5, where two wet sections are identified over a 30 m length of sensing fibre. The wetted lengths in this figure were several metres long in order to provide a clear visual image of the sensor operation but in practice they can be made much shorter, limited only by the resolution of the measurement apparatus. OTDR units are able to measure changes in signal strength with a sensitivity of 0.01 dB. To minimise the probability of falsely identifying a low-loss region as a high-loss region, it is normal practice to use 0.05 dB as a minimum measurement threshold to give an adequate signal-to-noise ratio. With the present sensor cable, which shows a wet attenuation of over 100 dB/km, such instru-

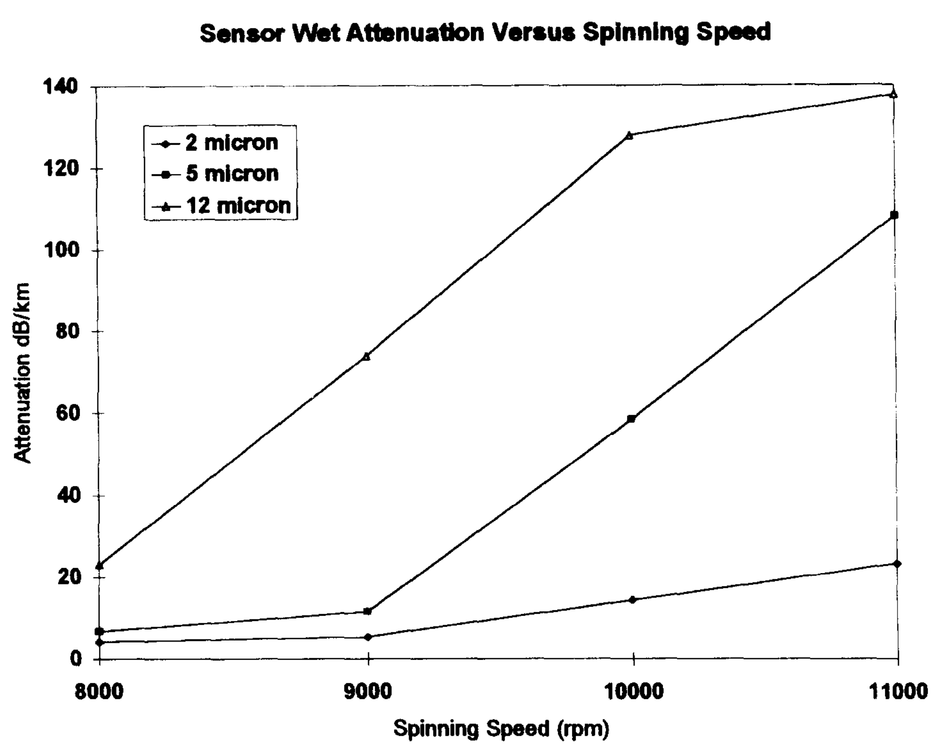

Fig. 3. Sensor wet attenuation vs spinning speed and coating thickness.

ments could be used to detect water ingress locations of less than 50 cm length.

Determination of grout fill in a reinforcing tendon duct

In many cases where locating leaks is the primary concern, a minimum detectable wet length of 1 m would be adequate. However, with improved spatial resolution, the sensor can be applied to a greater range of applications. Determining the grout distribution profile of a reinforcing tendon duct is one.

Steel tendons in post-tensioned reinforced structures are used to maintain a compressive load on the concrete throughout the structures'

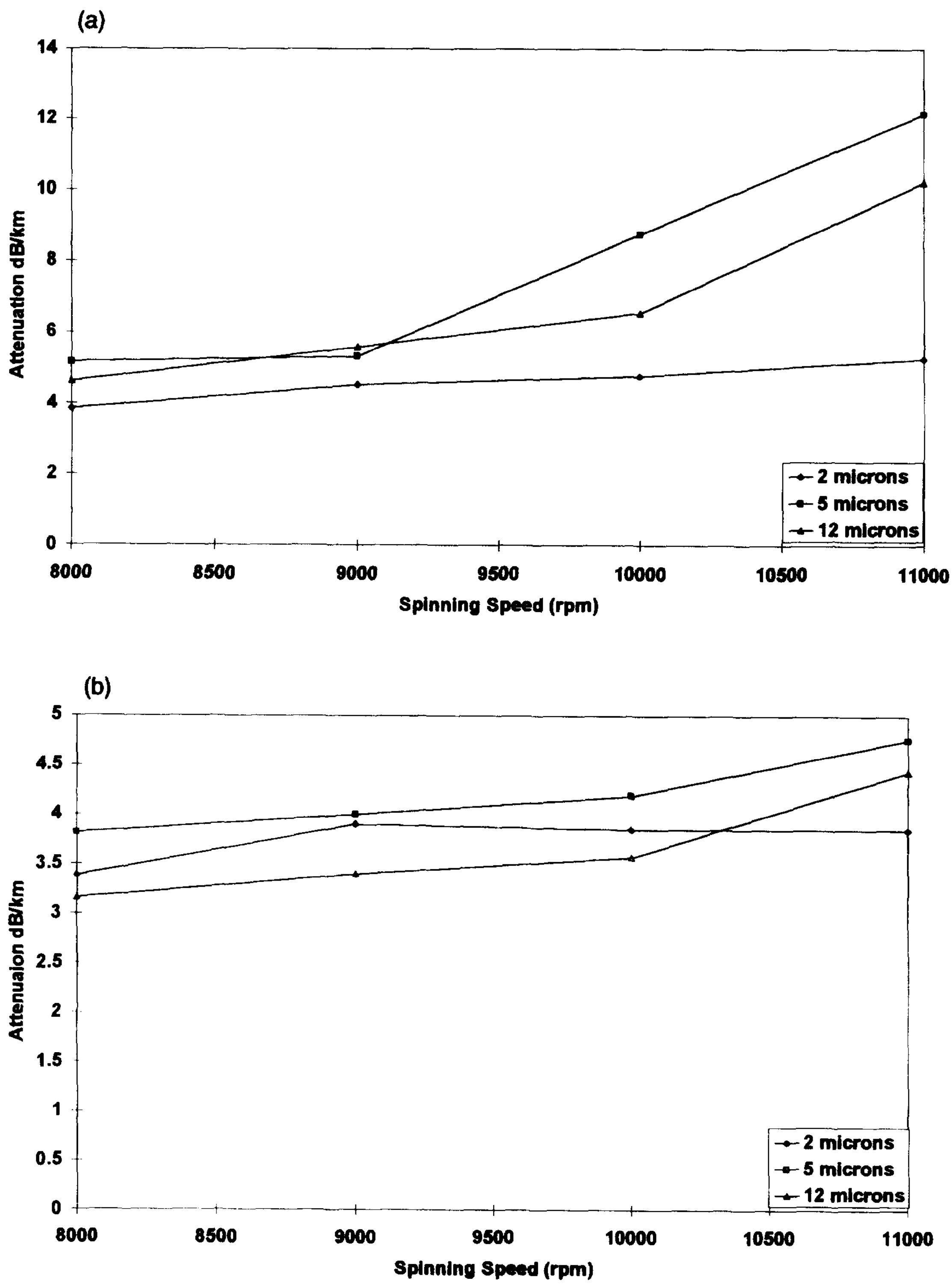

Fig. 4. Dry attenuation of sensor vs spinning speed: (a) at point of manufacture; (b) after water annealing.

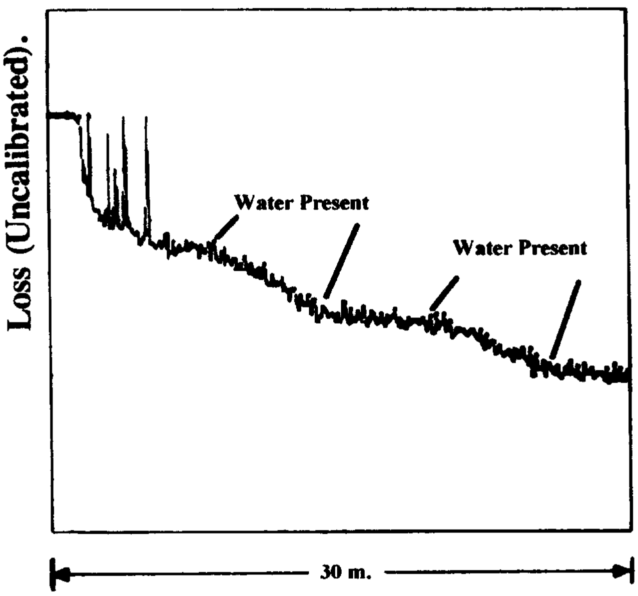

Fig. 5. OTDR trace of distributed water ingress measurement.

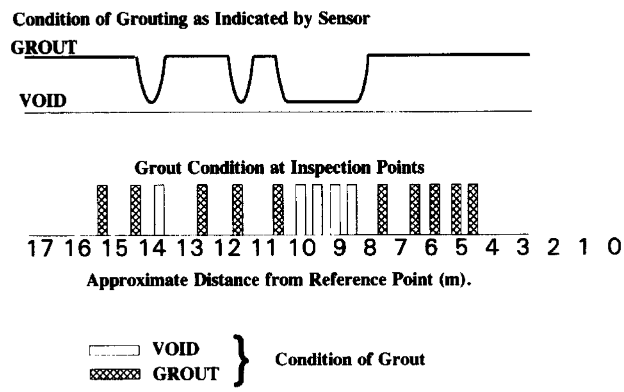

Fig. 7. Estimation of tendon duct grout fill.

lifetime. Chemical attack on the tendons, particularly pitting due to chloride ion ingress, can significantly reduce the tendon strength and have dramatic consequences on the overall structural integrity. To protect the tendons, the ducts where they are routed are usually filled with a cement-based grout to form a seal. This has been found to be effective provided that the duct is completely filled with grout along its length. Voids or poorly grouted areas leave sections of tendons which are exposed to chemical ingress. One difficulty in the use of this construction process is that it is not easy to determine whether or not the tendon ducts have been adequately grouted, since the entire duct length is contained within the concrete structure. The distributed measurement properties of the hydrogel sensor provide a potential solution to this problem.

To investigate this potential, a length of hydrogel sensor was made into a cable with a mechanically supporting inner surrounded by a porous braid as depicted in Fig. 6. This cable was inserted into a tendon duct and the grouting process carried out as normal, but with voided areas introduced at selected positions.

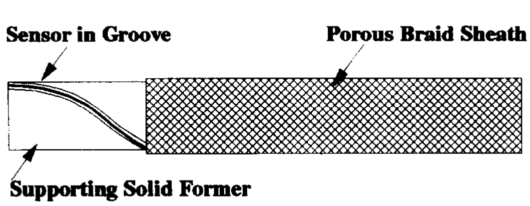

Fig. 6. Schematic of sensor cable design.

Areas of high loss, the wet areas, should correspond to positions where the grouting had been effectively carried out. Figure 7 shows a comparison of the areas of sensor identified as being low-loss (i.e. dry) regions with the voided zones, and confirms that the sensor was effective in performing this task. The dry regions, voids, were located with a spatial precision of around 0.5 m and with a success rate of greater than 85%. This preliminary work was extremely encouraging because of the fact that the voided areas were identified by using a sensor which was not optimised for the measurement purpose (the wet loss gradient limited the spatial resolution to around 0.5 m) and a minimal signal process was used to identify the areas of low loss.

SOIL WATER POTENTIAL MEASUREMENTS

Clearly the signal attenuation within the sensor is directly related to the amount of water that the hydrogel absorbs to swell and deform the optical fibre. This in turn depends upon the ability of the water to diffuse into the gel material. Under conditions where the gel is not fully saturated, the sensor should therefore show a varying degree of loss. This has been examined using a variety of salt solutions of different concentrations to produce a curve of the sensor response as a function of water potential. A distributed water potential measurement device would be a useful tool in analysing the strength of soils where moisture content is a critical component. Other applications, such as the monitoring seepage from land-fill sites, may also be possible.

Equilibrium water uptake

The equilibrium water uptake, *EWU*, of a hydrogel polymer is the standard means of determining the ability of the hydrogel to absorb water (and hence swell) in a particular environment and is defined as:

$$EWU = \frac{SW - DW}{DW} \times 100 \qquad (2)$$

where *SW* is the swollen weight of the gel and *DW* is its dry weight. As it takes on water the hydrogel material expands volumetrically and this expansion can also be directly related to the *EWU* by

$$EWU = \frac{V_f - V_i}{V_i} a \qquad (3)$$

where V_i is the initial volume of the gel and V_f is the final volume, and a is a scaling factor which relates the expansion of the material to the water uptake. The *EWU* of a gel can be directly related to the water potential of the surrounding environment. The presence of solutes in an aqueous solution tends to decrease the water potential.[8] Thus in a solution of increasing concentration we would expect the hydrogel to absorb a smaller amount of water and the sensor to display a reduced signal attenuation.

The easiest way to determine the water potential of a solution is through the osmotic coefficient, which has been extensively evaluated and tabulated for a range of salts. The water potential of a solution is related to the osmotic coefficient by:[9]

$$\Psi = -\nu RT\phi \qquad (4)$$

where ν is the number of ions from one molecule of the salt (in the case of NaCl, $\nu = 2$) and ϕ is the osmotic coefficient (the osmotic coefficients for NaCl solutions were taken from Ref. 8). Equilibrium water uptake studies for samples of hydrogel were conducted in distilled water and NaCl solutions. The *EWU* and volumetric expansion were estimated by periodically removing the gels from the solutions to be weighed and measured. The water uptake of the gel samples was recorded as a function of increasing concentration of the NaCl solution. All of the curves (shown in Fig. 8) follow the same general shape (as does the sensor loss characteristic shown in Fig. 2) but as the concentration of NaCl is increased, the *EWU* decreases. The minimum *EWU*, which is approximately two-thirds that of the distilled water treatment, is that of the most concentrated salt solution. This corresponds to the 'driest' environment, i.e. that with the most negative water potential.

The sensor loss was determined as a function of solution concentration by immersing a length of the sensor in the same solutions as those used above. This characteristic is displayed in Fig. 9. Clearly, as the water potential is reduced by increasing the salt concentration, the attenuation of the sensor (a measure of the hydrogel swelling) decreases. As the solution concentration is increased towards the 6 M

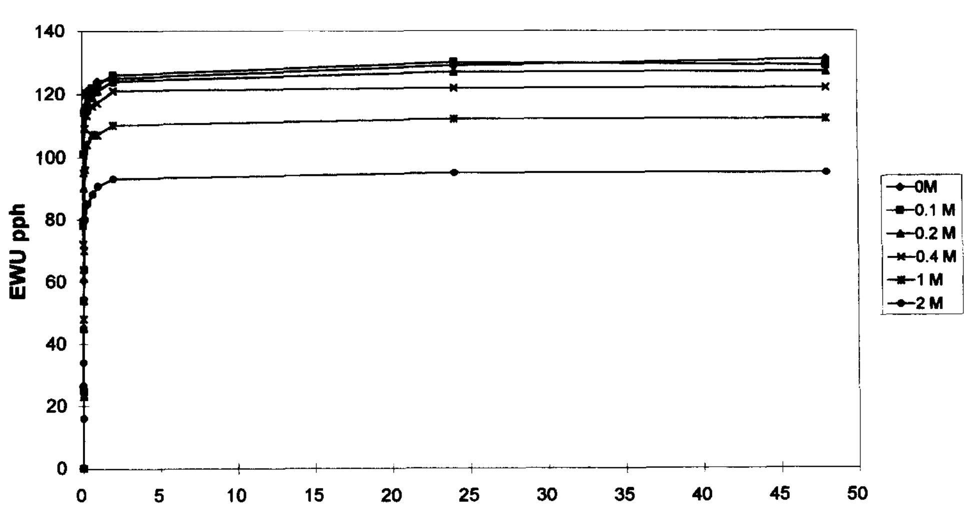

Fig. 8. Equilibrium water uptake (*EWU*) vs NaCl concentration.

level, the signal attenuation approaches that of the dry sensor. Also shown in Fig. 9 is the variation of the sensor attenuation as a function of water potential (calculated from the data in Ref. 9).

The experiments show clearly that the sensor can detect changes in the water potential of the surrounding environment. The full implications have not been evaluated to date but there are some promising indications. The response curve of Fig. 9 shows that the sensor can detect the presence of dissolved salts in an aqueous solution with a high degree of sensitivity. As the concentration of the NaCl solution increases from 0 to 1 mol/l, the signal attenuation decreases by over 60 dB/km, implying that a measurement resolution of around 0.05 mol/l could be obtained using a 10 m length of sensor. The resolution can be increased by using longer lengths of sensor or increasing the gel thickness. Similar responses have been obtained using a range of salt solutions, which implies that the sensor may be usefully applied to the monitoring of seepage from land-fill sites.

In situ measurements of soil moisture contents are not easy to perform, particularly on a distributed basis. Clearly the sensor shows a high degree of sensitivity to changing water

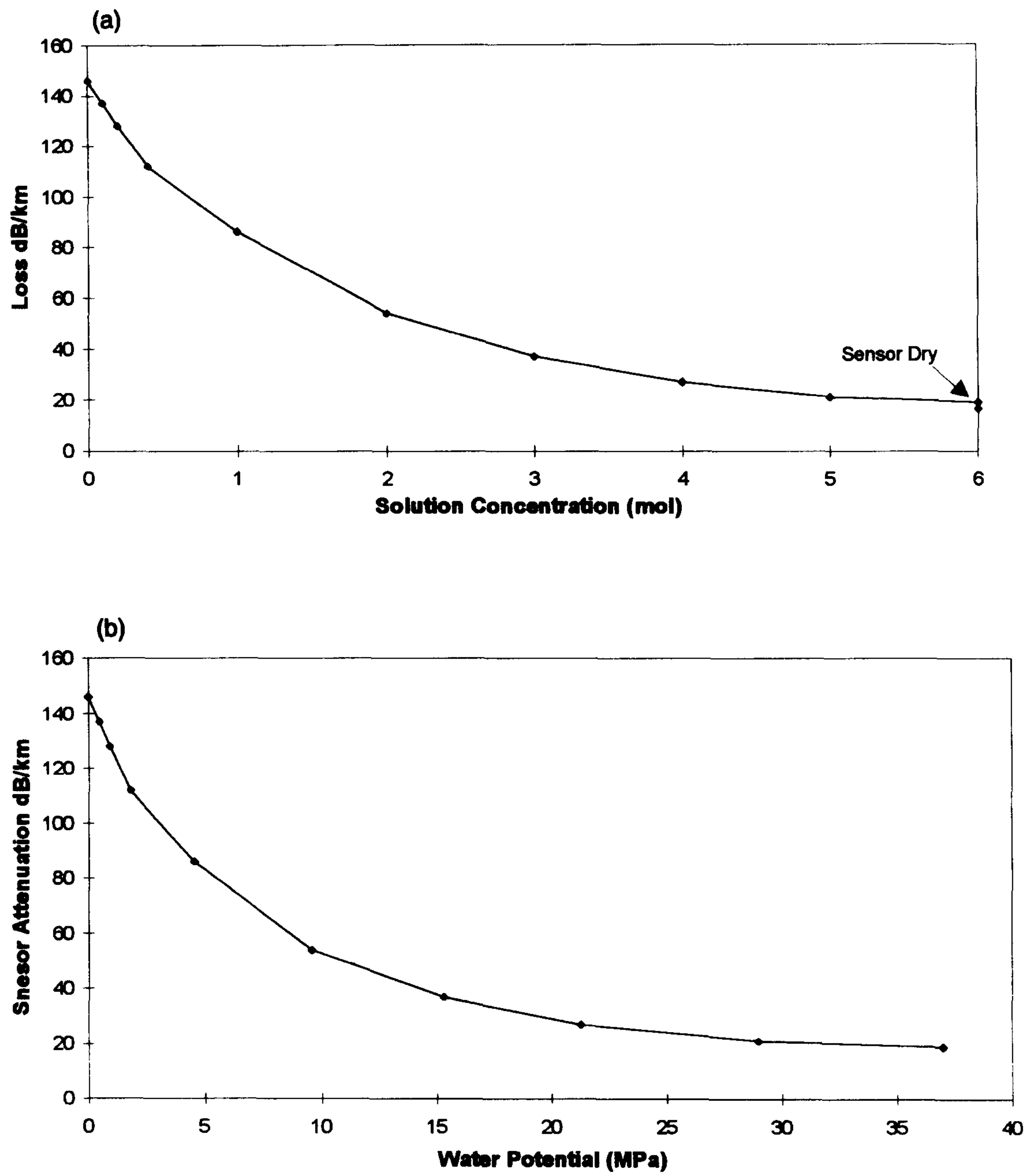

Fig. 9. Sensor signal loss variation: (a) NaCl solution concentration; (b) water potential.

potential. From measurements of water potential it is possible to estimate the water content of the soil provided that the water release curves are known. This can be determined experimentally at a range of water potentials using sintered plate funnels and pressure plates. A fuller investigation of this will be reported in the near future, some preliminary evaluation data are shown below.

A 34 m length of coiled sensor was placed in fine sand in a sintered plate funnel and water was added until saturation. At equilibrium the attenuation was measured using an OTDR and estimated to be 113 dB/km. The funnel was hermetically sealed and a hydrostatic pressure of −45 kPa (suction) was applied and found to reduce the attenuation to 110.7 dB/km. The measurement traces corresponding to these conditions are shown in Fig. 10.

While a more detailed and refined set of experiments are necessary to fully analyse and validate the sensor performance, the immediate conclusion that can be drawn is that the sensor is able to discriminate soil water potentials over the range applied during this test, implying that the minimum resolution is 45 kPa. The measurements made in NaCl solutions enable the operational range of the sensor to be estimated to lie in the region 0 to −1500 kPa.

Sensor loss as a function of *EWU*

To develop a fuller understanding of the behaviour of the sensor, an attempt was made to relate the expansion of hydrogel to the loss experienced by the sensor. To perform this comparison the *EWU* measurements for gel

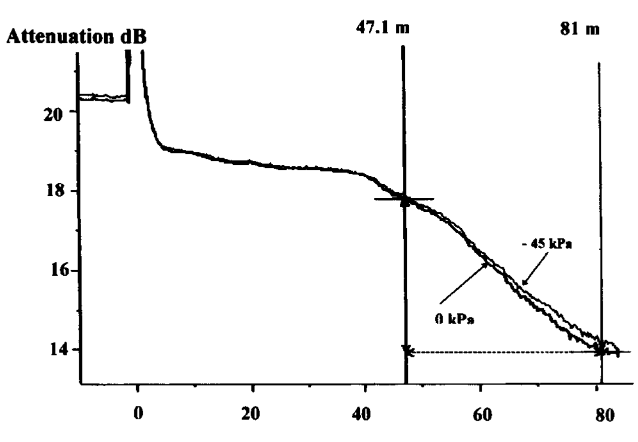

Fig. 10. OTDR trace of soil water potential measurement.

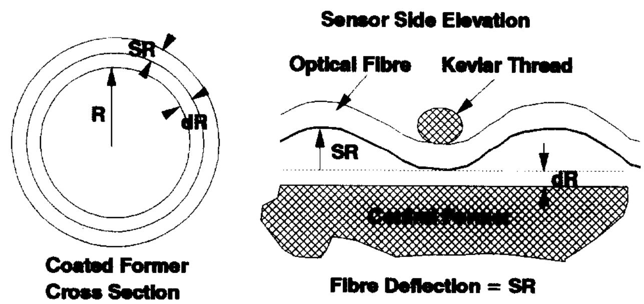

Fig. 11. Model of gel swell vs fibre deflection.

samples immersed in the NaCl solutions were equated to the volumetric expansion of the gel. From these calculations the change in effective radius experienced by the gel/carrier combination during the swelling process was calculated (see Fig. 11). It was assumed that virtually all of this expansion would be available for introducing microbends into the fibre and hence the magnitude of the deflection produced on the fibre, as a function of sensor loss, was estimated. This was then compared with a previous estimation of the fibre deflection/loss characteristic as follows.

Using the representation of the gel/carrier combination shown in Fig. 11 and assuming that the expansion is isotropic, the change in thickness of the central former carrying the gel can be calculated as

$$SR = \sqrt{\frac{EWU}{a}\left[(R+\delta R)^2 - R^2\right] + (R+\delta R)^2} - (R+\delta R)$$

where R is the radius of the supporting former, δR is the thickness of the hydrogel and SR is the amount by which the hydrogel swells. The dry thickness of the hydrogel in the present sensor was measured to be between 12 and 14 μm and the radius R of the supporting former was 240 μm. The swelling characteristics of a film of hydrogel have been calculated for a range of *EWU* values from the zero swell (dry) condition up to the case which corresponds to the fully swollen state. This has been plotted against the loss which the sensor experiences for each swell state in Fig. 12. Drawn alongside this is the estimated deflection which the fibre undergoes to produce a given loss (taken from previous analysis[10]). Good agreement is observed between the swell of the hydrogel and the expected fibre deflection for a given loss. The swelling behaviour of the gel exceeds that of the

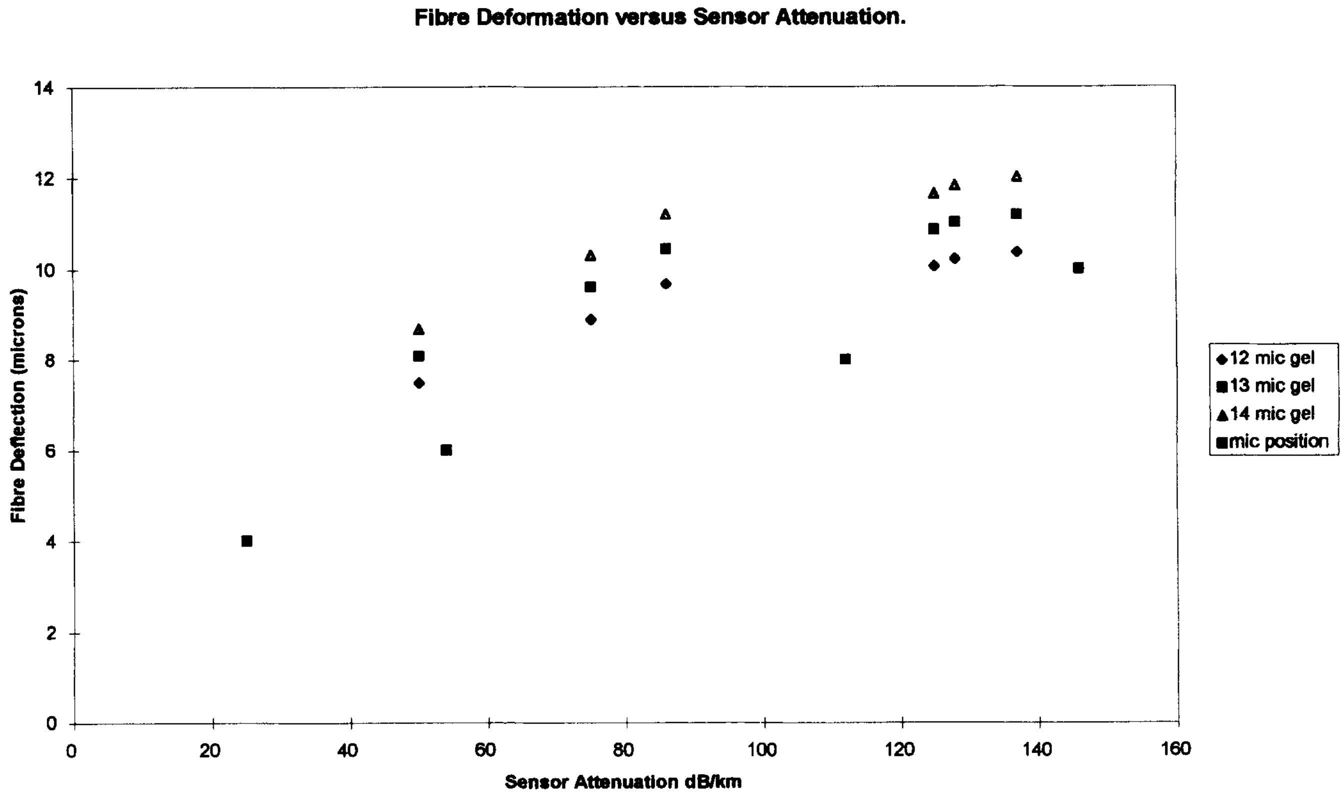

Fig. 12. Sensor signal loss vs fibre deflection.

calculated fibre deflection for all loss values by between 2 and 3 μm. This is not surprising since it would be expected that a portion of the swelling would be accommodated in the process of tensioning the Kevlar thread. Furthermore, since the gel softens as it takes on water, it is expected that the optical fibre and the thread will bed in to some degree. Taking these factors into account, the estimated gel swelling and the calculated fibre deflection are in good agreement.

CONCLUSIONS

A fibre-optic measurement technique using water-swellable polymer materials (hydrogels) to modulate the backscatter signal in an optical fibre has been developed. This sensor enables water ingress points to be detected and located with a spatial resolution of less than 1 m. The sensor has been tested during the grouting operation in a reinforced tendon duct, and it has been shown to be effective in detecting and locating voided regions where the grouting process has not been adequately performed. This could be developed as a means of providing some quality assurance for the grouting process during the construction phase of a large structure.

Preliminary investigations of the sensor response to different water potentials have been carried out. These show clearly that a strong correlation between the sensor loss and the solute concentration of aqueous solutions can be obtained. The *EWU* of bulk hydrogel material samples immersed in these solutions was equated to the loss experienced by the hydrogel sensor and equates well with previous theoretical analyses. An extension of the above measurements to equate the water potential to soil moisture content has been proposed and preliminary data suggest that the sensor will be capable of measuring changes in soil water potential over the range 0 to −1500 kPa with a resolution of at least 45 kPa. A distributed measurement sensor of this type would have a range of applications in civil engineering, agriculture and soil sciences.

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