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An in-situ monitoring system for natural temperature and relative humidity

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ABSTRACT: Oxidation of pyrite-rich, carbonaceous mudrocks used as fill beneath ground bearing floor slabs is currently causing significant problems to domestic and other properties in Ireland. Due to the precipitation of gypsum and other minerals the fill expands and this causes heave of slabs, together with distortion and cracking of the structure. Temperature is known to have an effect on both the rate and amount of this expansion; however, the full impact of human habitation on this process is not fully understood. The paper gives details of the development and testing of a system for monitoring temperature, humidity and pressure conditions within the material. This system is designed to minimise cost and disruption to the homeowner, whilst facilitating reliable measurements over period of 3 to 12 months.

1 INTRODUCTION

Oxidation of framboidal pyrite is known to be the cause of several problems in ground engineering. A particular problem occurs when sulfuric acid produced as part of the oxidation process reacts with calcium-bearing minerals also present in the parent rock. This can eventually lead to the expansive precipitation of sulfate minerals such as gypsum..

In Ireland, particularly in the Dublin area, pyrite-rich, Carboniferous age mudstone was extensively used in the late 20th Century as fill material beneath the ground supported concrete floor slabs of residential properties. Many of these properties are now showing evidence of damage such as uplift and cracking of the floor slab, which is attributed to heave of the fill material.

Although laboratory tests studying the nature and behaviour of the material are ongoing, little data currently exists detailing the behaviour of the material under field conditions. Information about the temperature and humidity conditions, both of which are recognised as key controlling factors of the reaction process, will assist with the interpretation of the lab tests and the relationships In addition the monitoring of temperature and humidity at various depths in the fill, it is also possible to record vertical stress conditions in the fill for periods between 3 and 12 months duration.

2 PROBLEM IN IRELAND

It is currently estimated that as many as 60,000 residential properties in Ireland are, or may potentially be, subject to damage caused by expansion of pyritic fill. Although the damage seen is varied, including sticking of doors, bulging of internal walls, cracking of wall and floor finishes; in the majority of cases these effects can be attributed to heave of the floor slab caused by the expansion of the underlying fill.

3 CAUSE OF THE PROBLEM

3.1 *The pyrite reaction process*

The form of pyrite most prevalent in these problematic mudrocks is small disseminated grains commonly between 0.1 and 0.5 μm in diameter or larger clusters of grains known as framboids, which are often between 2 and 40 μm in diameter and are shown in Figure 1. Both have a large specific surface and are therefore more reactive than other forms of pyrite (Hawkins & Pinches 1992). When exposed to oxygen and water, oxidation readily occurs leading effectively to production of sulfuric acid and eventual precipitation of gypsum.

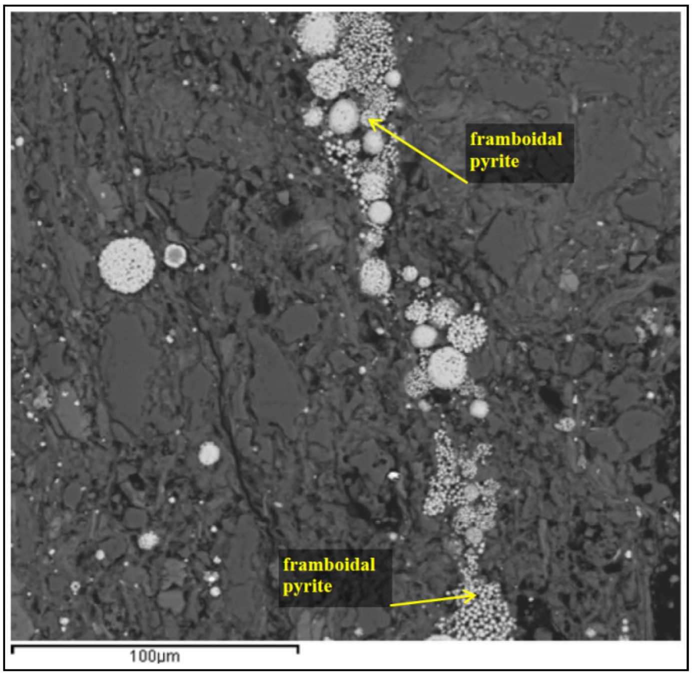

Figure 1. Horizon of pyritic framboids found in an Irish mudrock (image used with permission of Sandberg Consulting Engineers, London)

The initial reaction between pyrite, water and air leads to the production of $SO4^{2-}$, Fe^{2+} and H^+ ions, which in turn react to form sulfuric acid and ferrous sulfate, as represented by reaction 1.

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4 \qquad (1)$$

Although the reaction can continue naturally from this point, it is typically slow but can be catalysed by the presence of bacteria of the species *Thiobacillus ferrooxidans*, which aids the conversion of Fe(II) to Fe(III) as well as the conversion of sulfides to sulfates, as is shown in reaction 2. These bacteria thrive in warm, acidic environments, such as that found beneath the floor slab of a domestic property once sulfuric acid has begun to be produced by phase one of the reaction process (Hawkins & Pinches 1987b; Hawkins & Pinches 1992).

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \qquad (2)$$

The ultimate result of these reactions is that the water present within the system is now low in pH and rich in sulfates. Movement of this water, even over small distances, allows it to react with other minerals, such as calcite ($CaCO_3$), or with engineering materials such as concrete, leading to sulfate attack. It should be noted that at the time of writing, very little evidence of chemical attack on concrete has been found at the sites in Ireland.

The reaction with calcite results in the precipitation mainly of gypsum, as is summarised in equation 3.

$$H_2SO_4 + CaCO_3 + 2H_2O \rightarrow CaSO_4.2H_2O + H_2O + CO_2 \qquad (3)$$

Although workers in Canada studying similar problems with expansion of pyrite-rich mudrocks have discovered cases of jarosite precipitation leading to expansion, this is only rarely found in Irish cases and never in large amounts. This is believed to be due to the presence of calcite in the Irish mudrocks.

The gypsum formed by the reaction process precipitates between and within the laminae and fractures in the fill particles. Studies in Canada (Penner et al 1973) and the UK (Nixon 1978, Hawkins & Pinches 1987a) confirm that this process can result in a net increase in volume of the fill and thus be the cause of expansion and heave. Example of gypsum crystals apparently formed by this process in Irish fills is illustrated in Figure 2.

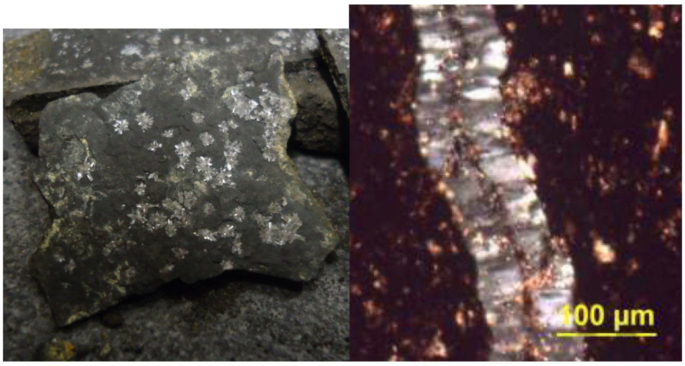

Figure 2. Occurrences of gypsum crystals in Irish mudrocks. Left: gypsum rosettes on the surface of a mudrock particle. Right: gypsum growth along a fracture in a mudrock particle (image used with permission of Sandberg Consulting Engineers, London).

The precipitation and growth of these crystals within the rock causes an increase in pressure within the system. The amount of heave is influenced by several factors, most notably precipitation location and crystal habit. For example a needle-like, acicular crystal forming within a laminated mudrock particle will exert more pressure than a flat, tabular crystal developing upon the surface of the particle. Although this pressure has not yet been measured directly under laboratory conditions, as summarized in Table 1, various workers have back-calculated values from site measurements and other tests.

Table 1. Implied pressures induced within systems showing expansion of pyritic mudrock.

	Pressure
Lutenegger et al (in Bérubé et al, 1986)	28 kPa
Quigley et al (in Bérubé et al, 1986)	72 kPa
Quigley & Vogan, 1970	74 kPa
Fasiska et al (in Bérubé et al, 1986)	500 kPa
Maher et al, 2011	600 kPa

The results presented by Bérubé et al (1986) and Quigley & Vogan (1970) are back-calculated from damage seen on sites in Canada, where the material was pyritic bedrock. The value presented by Maher et al (2011) is from a test carried out with Irish mudrocks re-compacted into a concrete tube, and is the value estimated to be required to cause cracking of the tube as seen during testing. It is unclear from the evidence presented whether or not changes in the stress on the outside of the tube was accounted for when calculating this value, and the figure should, therefore, be considered an upper value for pressure induced by pyritic expansion.

3.2 *Factors affecting expansion*

As can be expected from processes described above, there are many factors that affect the reaction process and pressures produced. These include, but are not limited to:

- Rock lithology/composition
- Depth/amount of fill
- Temperature
- Density of fill - amount and availability of void space
- Ground pressures
- Water content
- Grading of fill

Although it is understood, from both site observations and ongoing laboratory testing, that many of these factors play an important part, especially in the rate of the reaction, research into how much of an impact each factor has on both rate and amount of expansion is still ongoing.

Recent research by Sutton et al (2013) points to the importance of environmental conditions on the rate of heave. With reference to temperature, Sutton et al (2013) point out that in certain parts of Canada, where heave is a common problem and temperatures range from an average maximum of 27°C to an average minimum of -15°C, damage to structures is typically noted within 10-15 years or more of construction (CTQ-M200 2001). However, for many of the properties in Ireland, where the average maximum temperature is around 20°C but the average minimum is around 4°C, significant signs of damage develop over a timescale of less than 10 years, with most buildings showing signs within 5-8 years of fill placement. As noted above the availability of water is liable to be another significant controlling factor, and there is much uncertainty over the magnitude of the uplift pressure generated by the processes.

4 FIELD LOGGING

Although laboratory tests looking at the effects of factors such as temperature and density upon the rate of reaction are ongoing, the focus herein is the behavior of the material in field conditions. The investigations carried out in order to determine the cause of damage to structures in connection with insurance claims provides an opportunity to determine the conditions typically experienced within the fill placed below floor slabs. Of particular relevance are the seasonal changes in temperature and moisture content and the influence of internal and external temperatures on the variation of these conditions with depth.

To do this, monitoring systems will be installed within occupied and unoccupied properties at the time of sampling for the geological testing of the fill. As this sampling is normally carried out after a structural survey of the property, buildings that are suspected to be suffering pyritic expansion, based upon details recorded in the structural survey, will be selected.

Although the finer details vary, geological sampling usually entails forming a hole (approximately 0.4 by 0.4 meters) through the concrete floor slab, insulation and damp proof membrane/ radon barrier. Any blinding sand and then the fill material is removed. Under normal procedures, the hole is then backfilled, the damp proof membrane made secure and the insulation and concrete replaced.

As Figure 3 shows, it is proposed to install temperature, pressure and humidity sensors, housed in protective cases, into the fill material in the side of the excavated hole. The hole would then be backfilled with matching fill and the insulation and slab reinstated around a tube protecting the connecting wires. Additional sensors will be used to monitor the internal and external air temperatures and at two or three properties per development, sensors will also be placed outside the property to enable the effects of the presence of the building on the ground environment conditions to be investigated.

Typically, in proven cases of pyritic heave, remediation is carried out 6 months to one year after sampling. At present it is planned to install the system in around 12 properties, for periods of around 6 months. Installation will be staggered in time so that there is enough overlap between sites to determine how the ground conditions change over a full annual cycle.

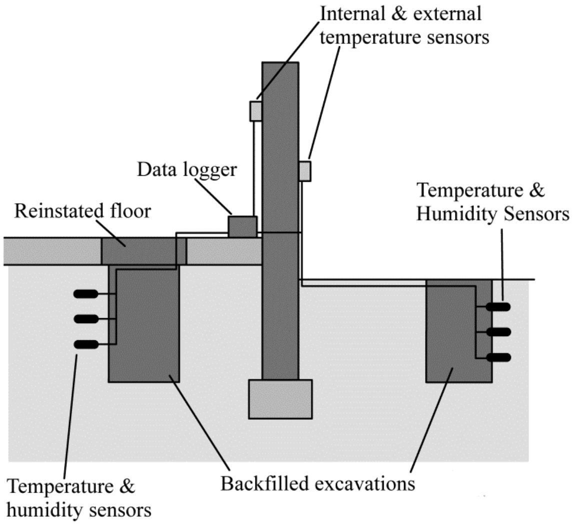

Figure 3. Basic schematic layout of sensors within a domestic property.

The equipment is designed to be easily adaptable dependent upon where within the property the excavation will be sited. The data will be recorded using a data logger that is based upon an Arduino microcontroller, shown in Figure 4. This will be programmed to log the information from each sensor at hourly intervals and record it to an SD card. If necessary this card can be retrieved by site engineers during the logging process.

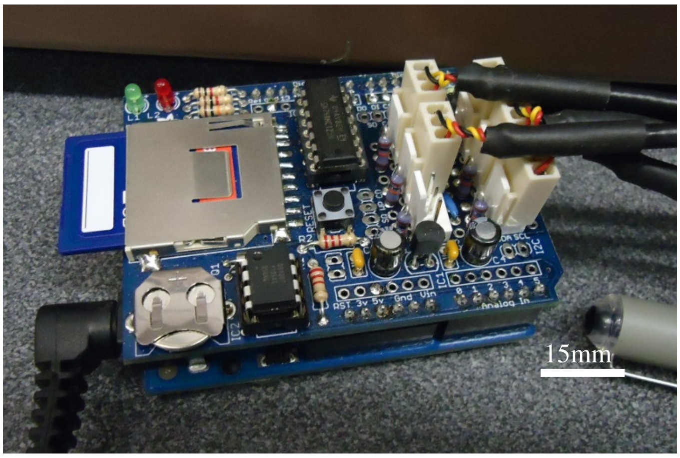

Figure 4. The Arduino microcontroller currently in use for laboratory testing.

The main criteria when selecting equipment both for the data logger and for the sensors was to minimise disruption to the homeowners when logging within an occupied property. The recording devise is small, robust, and relatively cheap and does not require frequent visits to retrieve data. The data logger in its present configuration requires mains power for use, although this power drain is low and the system could conceivably be adapted to run from batteries when used in unoccupied properties.

Removal of the sensors will take place when the properties are remediated, as this entails removal of the floor slab and all the fill material. At this time, additional characterization and testing of the fill will take place for comparison with field logging and laboratory data.

5 LABORATORY TESTING

5.1 *Test set up*

Prior to beginning field logging, the system was tested in the laboratory as part of an ongoing suite of tests on pyritic material from a housing estate just North of Dublin.

The material used in this test was removed from the foundations of a property beginning remediation in May 2012. As such it had already begun to react and was therefore anticipated to react further once set up under laboratory conditions. After removal from the property, the material was sealed in bags for transport and then stored in an outdoor, insulated storage unit whilst at the university.

The material was described during initial geological testing as being a dark grey to black, calcareous siltstone to mudstone, with the latter being clearly laminated and making up around 40% of the material. The initial tests gave a pyrite content, as of June 2009, of 1.8% by weight and a gypsum content between 1.7 and 2.5% by weight. Although chemical testing has not yet been carried out on the samples held at the university, initial assessment confirms the physical description, and testing is planned to fully characterise the material.

The swelling tests are being carried out in 850 mm high by 225 mm diameter tubes containing fill compacted in several layers, as shown in Figure 6. Hence it is easy to install the sensor system proposed for the field tests in the material being used in the laboratory experiments. The design was adapted from that used by Sutton et al (2013) and it is intended to investigate the effects of differing initial conditions on the swell process.

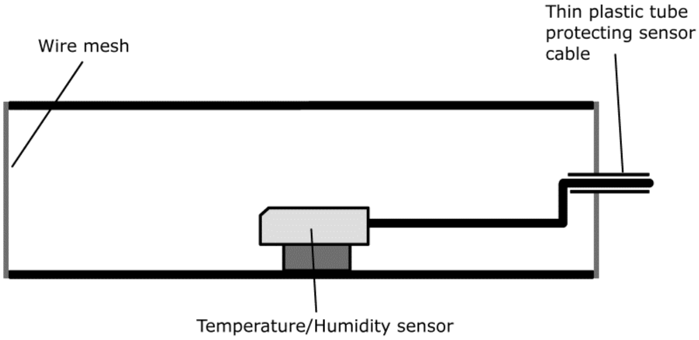

Figure 5. Schematic layout of sensor placement in protective tubes (not to scale).

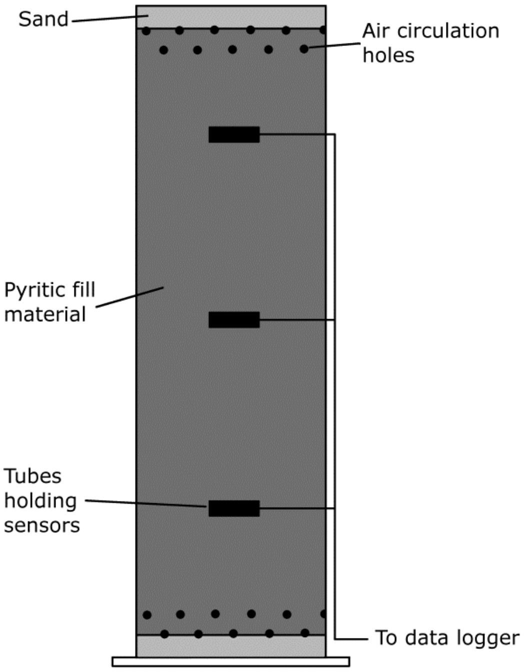

Figure 6. Schematic layout of test tube containing field logging system (not to scale).

The combined temperature and relative humidity sensors were housed within 25 mm diameter rigid plastic tubing with fine wire mesh on either end to prevent material entering the tube and still allow air circulation. These smaller tubes containing the sensors, indicated in Figure 5, were placed at three, evenly-spaced levels during the compaction process. A compacted density of 2010 kg/m^3 was achieved for the sample with an average moisture content of 8.0%.

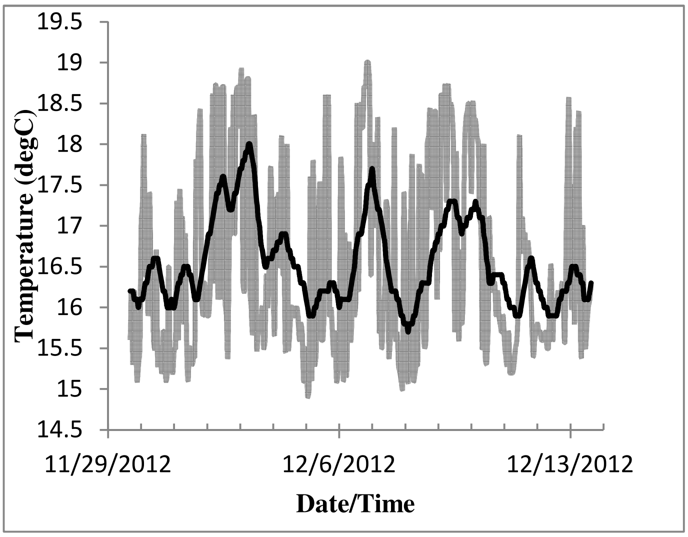

Figure 7. Temperature data obtained from laboratory tests. Pale grey represents the laboratory air temperature; black represents the data recorded from the sensor within the fill.

In both field and laboratory investigations, the sensors are connected to the Arduino, which was coded to record data from the sensors every 15 minutes. Considering the volume of data recorded, and the way that temperature and humidity were seen to change, this sampling time can be reduced to once every hour for the field measurements.

5.2 *Initial results*

Data was recorded from the sensors such that it could be accessed as a spreadsheet, from which the data could be plotted and analysed graphically. Figure 7 shows the first set of temperature data obtained.

The sensors located at the base and top of the tube recorded similar temperature values, such that only the value from the lower-most sensor is presented here for ease of viewing. The sensor placed in the middle of the fill was malfunctioning and consistently recorded temperatures higher than those recorded in the laboratory. For this reason, the results from this sensor were excluded from the initial analysis.

From Figure 7 it is possible to see that the sensors compacted within the sample mirror the temperature changes recorded in the laboratory air temperature, although at a lesser rate.

In order to look more closely at this effect, Figure 8 shows a much smaller dataset, with the laboratory air temperature and the lower-most fill sensor data obtained over two days.

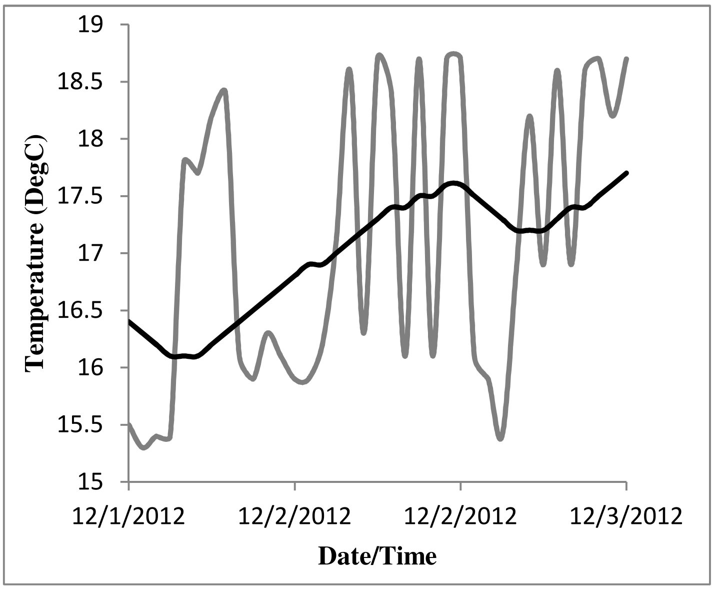

Figure 8. Data obtained over two days showing the way in which the fill temperature (black line) mirrors changes in the laboratory air temperature (grey line).

During the test period it was discovered that the sensors were returning humidity values of 100%, although the functioning temperature sensors seemed to be behaving normally. In order to determine the source of this problem the sensors were excavated from the sample.

Once two of the sensors had been removed from the sample, the other left in place as a control for temperature logging, data collection recommenced and the sensors were allowed to normalise to laboratory levels.

As the sensors recorded values consistent with laboratory humidity levels within 24 hours of removal from the fill material, it was determined that the problem was related to either the sensor set up or an excess of moisture within the sample. As the material in the laboratory test had a moisture content of 8% and many of the samples returned from affected sites show moisture content values of between 2 and 12%, this is a significant problem.

In order to improve understanding of the data, one of the sensors was placed within a modified tube in which only one end was open to air movement via a mesh, and the other end was sealed. This was then placed vertically within a dry sample, with the mesh at the base and several days logging data recorded.

Over the next several weeks water was added to the sample at intervals, with the intention of monitoring the results until a humidity reading of 100% was reached, or the moisture content exceeded 15%. The water was introduced to the surface layers of material and around the edges of the box so as to allow the moisture to move through the material while preventing it moving too close to the sensor.

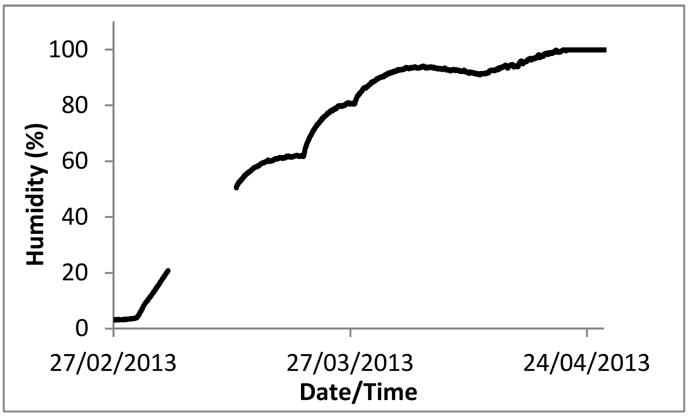

Figure 9. Humidity increases with addition of water to dry material. The gap in data collection was caused by a power cable being knocked loose. This issue has been addressed in the laboratory and the cable will be fixed more securely for field logging.

Once the humidity readings reached 100%, as shown in Figure 9, and were determined to be constant, the test was dismantled and the final moisture content of the material determined. This value was returned as 2.5%.

As this moisture content overlaps the minimum that may reasonably be expected under site conditions, it may be possible to insulate the sensors to further limit the amount of humidity that can access the sensors. Although such as system could be tested and calibrated by recording data from samples of a known moisture content, it is likely that this method would simply reduce the responsiveness of the instrumentation, thus decreasing its effectiveness. It seems unlikely that humidity sensors will prove viable for this application and small dielectric sensors are being investigated.

6 CONCLUSIONS

Although testing is still ongoing at the time of writing, and field testing has not yet commenced, initial results suggest that the temperature sensors will be a viable option for field logging purposes. The temperature values obtained from the sample clearly reflect the temperature as recorded in the laboratory and show the insulating effect of the material.

The humidity sensors, however, do not work over a sufficiently large range of moisture contents with the current set up and an alternate layout is currently being tested. Initial results confirm that humidity sensors will operate satisfactorily at very low moisture contents. However, alternative monitoring methods based on dielectric sensors are being investigated to ensure that accurate values are measured given the expected moisture content range.

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