Finite Element Modelling to Design a Concrete Dual-Probe – An Innovative Tool for Monitoring the Drying of Concrete

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Abstract

The measurement of moisture in concrete has been of interest for many years due to the potentially devastating consequences of moisture problems within buildings. A range of techniques are available to measure the moisture content of concrete floors, such as concrete moisture meters, relative humidity probes and calcium chloride tests [1]. However, all these techniques have the limitation that they either measure the moisture content of the top inch of concrete or relative humidity inside concrete or vapor emissions from the surface of the concrete floor. To measure the moisture content at any depth in the concrete floor, an innovative 'concrete' dual-probe has been developed. Essentially, a short pulse of electrical energy is applied to a wire within the 'heating' needle. A *separate* 'temperature sensor' needle, which incorporates a calibrated Pt1000, records the resulting maximum temperature rise in the concrete at a certain distance from the heating needle from which the moisture content can be deduced. The most important benefit of the concrete dual-probe approach is that it can either monitor the concrete floor's drying process during the building's construction or measure the moisture content of the concrete floor after the building has been occupied. The moisture content of the concrete floor can be measured simply by burying the concrete dual-probe inside the concrete floor during construction. Extensive finite element modelling was carried out to design the 'concrete' dual-probe and build a prototype.

Keywords: Concrete, Moisture content

Nomenclature

ΔT_m	Maximum temperature rise, ºC
ΔT_{m0}	Initial maximum temperature rise, ºC
ΔT_{mi}	ith maximum temperature rise, ºC
q	The heat input to the line source, J/m
r	Distance from the source (between the temperature sensor and the heater element), m
c_p	Specific heat capacity of soil, J/kgK
θ_0	Initial reading of moisture content, m^3/m^3
θ_i	ith reading of moisture content, m^3/m^3
q_0	Initial quantity of heat per unit length, J/m
q_i	ith quantity of heat per unit length, J/m
c_{pw}	Specific heat capacity of water, J/kgK
ρ_w	The density of water, kg/m^3
ρ	The bulk density of porous medium, kg/m^3

1. Introduction

Concrete is mixed and slabs are placed with more water than will be needed for hydration of the cement. Given the right thermodynamic conditions, slabs dry over time as the excess water evaporates. How rapidly and forcefully this occurs is determined largely by the difference between the vapor pressure in the slab and the vapor pressure in the air over the slab, as well as conditions below the slab. Vapor pressure, in turn, is affected by temperature.

Testing concrete slabs for excess moisture has become a common construction requirement, particularly where flooring or impermeable membranes are to be installed on top of the slab. Nowadays, various techniques exist to measure the moisture content of concrete floors, such as concrete moisture meters, relative humidity probes, relative humidity hoods, the plastic sheet method and calcium chloride tests [1]. However, these techniques are only able to measure the moisture content of the top inch of concrete or the relative humidity inside the concrete or vapor emissions from the concrete surface. The author has developed a concrete dual-probe to solve this problem.

Twenty years ago, a thermal dual-probe was successfully developed to measure the moisture content, thermal conductivity and volumetric heat capacity of soil both in the laboratory and field [2-4].

Applying the principle of the soil dual-probe to the field of building science, a thermal dual-probe and pad sensor were developed for measuring the moisture content of building fabrics [5-8].

In this paper, the author demonstrates the development of a 'concrete' dual-probe to measure the moisture content at any depth of the concrete floor. The concrete dual-probe approach incorporates a heating needle with a line electrical heater in parallel with a temperature sensor of a calibrated Pt1000 at a certain distance, see Fig.1. When a pulse of energy (typically 10s) is released from the concrete probe heater, the changes in temperature are detected by the temperature sensor. The volumetric heat capacity can be obtained via the measurement of temperature changes. Then, the moisture content can be deduced through incorporating the volumetric heat capacity (detailed theory in section 2).

The 'traditional' dual-probe can not be applied to measurements in concrete due to concerns regarding its ability to keep the probe spacing constant when buried into the concrete. To help keep the probe spacing constant, a holding plate was placed on the heating needle and temperature sensor at a certain distance from the end of the temperature sensor.

The aim of this project is to design a new dual-probe for the measurement of moisture content in concrete. This paper describes the techniques to develop such a concrete probe. Finite Element (FE) modeling was carried out to design the probe and build a prototype.

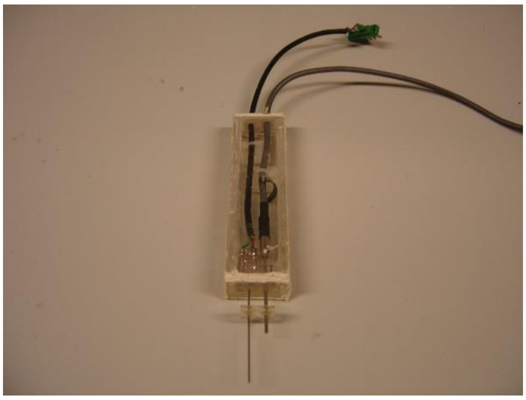

Fig.1. A photo of a prototype concrete probe

2. Theoretical Background

A dual-probe heat-pulse method was previously proposed to measure the volumetric heat capacity (ρc_p , J/m^{3}K) of soil [2]. For a given material, the volumetric heat capacity is given by:

$$\rho c_p = \frac{q}{e\pi r^2 \Delta T_m} \tag{1}$$

Volumetric heat capacity of porous media can be expressed approximately as the sum of the specific heat of water and the mineral components [3]:

$$\rho c_p \cong \rho_w c_{pw}\theta + \rho_b c_m \tag{2}$$

Substituting Equation (1) into (2), the water content (θ , m^3/m^3) can be expressed as [3]:

$$\theta = \frac{\frac{q}{e\pi r^2 \Delta T_m} - \rho_b c_m}{\rho_w c_{pw}} \tag{3}$$

Changes in water content ($\Delta\theta$, m^3/m^3) can be given as [3]:

$$\Delta\theta = \theta_0 - \theta_i = \frac{1}{e\pi r^2 \rho_w c_{pw}}\left(\frac{q_0}{\Delta T_{m0}} - \frac{q_i}{\Delta T_{mi}}\right) \tag{4}$$

3. FE Modelling

Based purely on conductive heat transfer theory, extensive FE modelling work was carried out to optimize the probe spacing, probe length, material, size and location of the holding plate. The CAE package in I-DEAS software was used. The sequence of the modeling work is: (1) the probe spacing was determined from 2D FE models and (2) based on the successfully designed 2D model, 3D FE modelling was carried out to determine suitable probe lengths, material, size, and location of the holding plate.

3.1. Probe Design Criteria and Procedures

The aim of the probe design is to obtain the *optimal* combination of probe spacing and probe length. The process considers that the probe spacing should be sufficiently small such that the energy input produces the desired temperature rise with minimum impact on the moisture field. At the same time, the probe spacing should be sufficiently large so that the effect of the metal 'needles' is negligible. For practical reasons, shorter probes are easier to insert into concrete.

The analytical solution (according to equation 1) for the maximum temperature rise of the model gives a value of 1.22°C. The criterion for a 'successful' design of the dual-probe was that the difference between the numerically predicted maximum temperature rise and the analytical solution should be less than 10%.

3.2. 2D FE Model to Design Probe Spacing

A series of 2D FE simulations for probe designs with different tube spacings was undertaken. The thermal properties of the concrete, tube material (stainless steel) and holding plate are given in Table 1.

Table 1 Material properties

Material	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)
Concrete	1890	1.60	850
Perspex	1200	0.20	1450
Stainless steel AISI 304	7900	14.90	477

A small section of a typical 2D FE model is presented in Fig. 2. Position H indicates the location of the heating needle and position T indicates the position of the temperature sensor needle. Very fine meshing can be observed around the area of the needles, with the whole model being sufficiently large to ensure that no significant temperature rise is predicted at its periphery during the simulation period. In this case, the boundary was at 45mm away from the centers of the heating needle and temperature sensor needle. The model consists of 2722 four-node quadrilateral elements and 30 three-node triangular elements, having a total of 2886 nodes. Due to the symmetry involved, it was sufficient to model only the upper half of the domain.

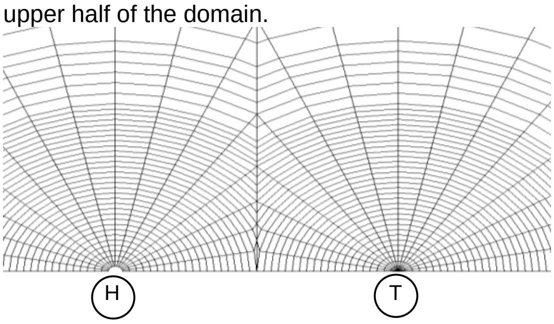

Fig. 2. Part of the 2D mesh

The energy input was modelled as a surface thermal flux applied at the semi-cylindrical surface at the position of the heating needle. This energy input was chosen for each material such that a similar temperature rise of approximately 1ºC occurred in each case. The range of the maximum temperature rise was addressed previously [4]. Work with a coupled heat and moisture transfer model [5] also verified that moisture migration within each test material under such an energy input with an approximately 1ºC maximum temperature rise was insignificant.

3.3 3D FE Model to Design Probe Length

For consistency, the 3D model's element 'lengths' in the x and y-directions were the same as for the 2D model. The element 'lengths' in the z-direction were varied. Fine meshing was used at the end, middle and front part of the needle – a balance was found between the requirements for accuracy and computational feasibility. The same basic model geometry and boundary conditions were maintained as for the 2D FE models. In an attempt to reduce the effects of the metal tubing on the maximum temperature rise, the temperature sensor needle was designed to be half the length of the heating needle. As with the 2D model, it was sufficient to model only the upper half of the actual 'wall', due to the symmetry.

The probe length and location of the holding plate were varied until the maximum temperature rise was not less than 1.10°C. An example of the 3D model simulation result is shown in Figure 3.

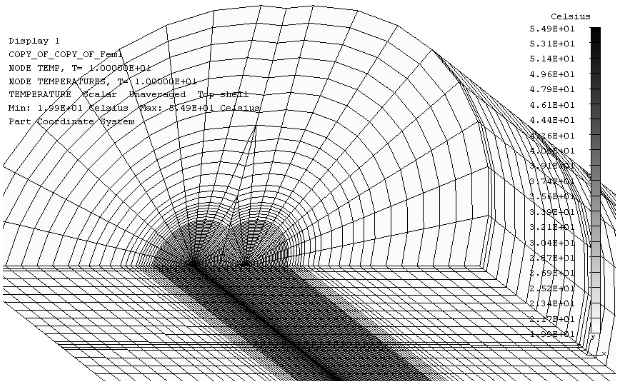

Fig.3. 3D model simulation at 10s after pulse of energy is released from heater

3.4. FE Modelling Results

The probe design results are presented in Table 2. The temperature measurement point is halfway along the length of the heater. It can be seen that suitable probe lengths and spacings are approximately 60mm and 10mm respectively. Note that the lengths are the *minimum* required, longer lengths will also be appropriate.

Table 2 Modelling results of concrete dual-probe

Model	Probel Spacing (mm)	Probe length (mm)	FE ΔT_m (°C)	Theoretical ΔT_m (°C)
3D	10	60	1.13	1.22

4. Conclusion

The work has demonstrated the initial development of the concrete probe. The device monitors the drying out process for concrete slabs/blocks. The concrete probe offers significant advantages, it is:

- capable of producing transient measurements
- capable of providing measurements without the need for field calibration
- insensitive to the movement of salts through the concrete floor
- sufficiently accurate
- relatively robust and inexpensive
- a non-destructive way for measuring moisture content of concrete floors during construction and afterwards

The most important benefit of the concrete dual-probe approach is that it can either monitor the drying process of the concrete floor during the building's construction or measure the moisture content of the concrete floor after the building has been occupied. The moisture content of the concrete floor can be measured simply by burying the concrete dual-probe inside the concrete floor during its construction. The concrete dual-probe is suitable for builders constructing buildings, it could also be very useful as a non-destructive way to measure the moisture content of concrete floors after the building is in use.

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