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A NUMERICAL SIMULATION OF MEASURED TRANSIENT HEAT TRANSFER THROUGH A CONCRETE GROUND FLOOR SLAB AND UNDERLYING SUBSTRATA

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ABSTRACT

This paper presents the results of a numerical simulation of measured heat losses from a real building. In particular, the thermal response of a concrete ground floor slab and the underlying foundation soils has been analysed and the results calibrated against data acquired from a comprehensive long term in-situ monitoring experiment. A numerical solution of a heat conduction model is obtained by use of the finite element method. Finite differences are used to accommodate the time varying nature of the problem. The model has been applied to the simulation of transient one-dimensional behaviour. Diurnal and seasonal variations in temperature are considered. Good correlation between predicted and measured thermal response has been achieved. It is, therefore, claimed that the modelling approach adopted is capable of representing real in-situ behaviour.

KEY WORDS Heat transfer Transient Concrete slabs Foundations

INTRODUCTION

The thermal behaviour of building materials is of obvious importance in the construction industry[1,2]. Accurate design values of thermal transmittance (U-values) are required to ensure that structural design is carried out in a manner that facilitates optimum energy conservation. Furthermore, recent amendments to the U.K. Building Regulations have stipulated standards of thermal insulation which require the calculation of U values for the entire structure to ensure compliance[2].

To establish U values for building materials, reliable measurement of thermal conductivity is required. This task is complicated by the fact that the thermal conductivity of a material is not necessarily constant; it is for example known to be strongly dependent on the moisture content of the material. At higher moisture content the ability of a material to insulate decreases (i.e. it's thermal conductivity increases).

Real buildings frequently encompass a variety of different materials in contact with each other. Determination of thermal properties of an entire structure will therefore often involve taking into account the presence of thermal bridges. Simple methods of dealing with nonhomogeneous structural components have been provided in the literature[2]. The numerical approach adopted here has the advantage that different material types and geometries may be readily included in an analysis.

Current design procedures consider steady state thermal behaviour of materials. However, in reality, transient temperature variations occur due to a variety of changing conditions. Temperature distributions within a building, its structural components and underlying foundation

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soils are, in fact, in a continuous state of change and are interdependent. Seasonal and diurnal climatic temperature variations and artificial internal heating systems combined to ensure that the overall pattern of heat transfer in and around a building is transient and complex in form.

Relatively simple design procedures are often adequate for the determination of the overall thermal properties of a structure. However, such methods yield no information regarding the transient behaviour of a structure subject to natural and artificial heating cycles. To this end, the work presented in this paper addresses transient temperature variations occurring within and beneath the ground floor slab of a real building. In particular details of the results from a comprehensive in-situ experiment are presented for the first time in the literature.

The time varying nature of the problem and the variety of material properties comprising a real structure renders analysis of the problem too complex for direct analytical methods. The use of a numerical modelling approach therefore becomes necessary. Such an approach has been adopted here and the resulting model is calibrated against data obtained from an in-situ experiment.

IN-SITU EXPERIMENT

A M£27 development of the site of the School of Engineering, University of Wales College of Cardiff, commenced in 1989. A number of new buildings were commissioned as part of the expansion of the School's facilities. In particular, the construction of the West Building, provided an unique opportunity to establsh an in-situ experiment to monitor the thermal performance of the building. A three year research contract was undertaken to achieve this end[3]. Attention was focused on heat losses through the ground floor slab of the building.

The structure of the West Building is typical of modern commercial construction. It comprises a steel frame with two composite suspended floors and a concrete ground floor slab, 150 mm thick on 600 mm of hard-core. The thickness of the hard-core was increased, providing additional insulation, at the time of construction from its originally planned value of 300 mm.

The data acquired during the research provided a rare insight into the in-situ thermal response of a concrete ground floor slab and the underlying substrata. During the monitored period, the building was subject to both natural temperature variations and artificial heating provided by an internal central heating system. Edge effects at one corner of the building were monitored as well as temperature variations directly beneath the floor slab. Data have been recorded over an eighteen month period.

EXPERIMENTAL DESIGN

Prior to installation of instrumentation a thorough site investigation was undertaken. The results of the investigation provided a detailed description of the soil strata below the building. Subsequently, a comprehensive range of instrumentation was installed during the construction of the building. Seventeen heat flux sensors were installed at various locations, flush with the surface of the concrete floor slab, bedded on silicon mastic to ensure thermal contact. Thermocouples were suspended on nylon lines above the heat flux sensors to measure related air temperatures. Seven columns of thermistor probes were used to measure ground temperatures. Probes were secured to a uPVC framework and lowered into boreholes. The borehole sleeves were then extracted leaving the sensors in direct contact with the soil. The thermistor probe 'stacks' were constructed to depths of up to 4 m. Readings were available at 250 mm depth intervals below the ground surface. Five neutron probe access tubes were installed to depths of 4 m from which moisture content readings were taken at 100 mm depth intervals on a weekly basis.

Campbell Scientific CR7 data loggers were used to record electronic data from the instrumentation. The heat flux sensors, thermocouples and thermistor probes were interrogated every half hour. The loggers were connected to a Personal Computer which had been programmed to extract the data after each logging cycle. The data was stored directly on the computer's hard disk providing automated, non-volatile storage. A rigorous back-up regime was carried out to safeguard against data loss.

The data acquisition system described above generated 7392 readings per day. The large amount of data was processed using a series of purpose written dedicated macros running in a proprietary spreadsheet. The data acquisition exercise yielded a comprehensive high quality data base of information. Approximately 4.1 million readings were captured in digital form over the duration of the monitoring exercise.

In order to interpret the enormous amount of data a dynamic method of presentation (Windows based) was developed in-house[3]. The software included an animated graphical presentation system which was used to obtain a qualitative assessment of the entire data set. Viewing the result in this cinematographic form provided an extremely efficient method of data interrogation.

In the following numerical investigation, consideration is specifically given to the analysis of transient thermal behaviour in the vicinity of the Upper Ground Floor of the West Building. *Figure 1* illustrates the instrumentation layout in the region considered. HFS1 to HFS7 indicate the locations of Heat Flux Sensors mounted flush with the surface of the normal weight concrete floor slab. There are three columns of Temperature Sensors (thermistor probes); Stack 1, Stack 2 and Stack 3 comprising of 13, 12 and 14 sensors, respectively (TS1-TS14, TS15-TS27 and TS56-TS70). Air temperatures were measured using standard 'type T' thermocouples at seven locations within the building, indicated by TC1 to TC7 in *Figure 1*. Also shown in *Figure 1* is the location of a Neutron Probe access tube (NP1) allowing ground moisture content readings to be taken at 100 mm depth intervals.

TP1 indicates the location of a Thermal Conductivity Probe[4]. The Thermal Property Probe was used to obtain direct measurement of the thermal conductivity of the foundation soil.

THEORY AND NUMERICAL MODEL

The work reported is based on a two-dimensional heat conduction model. A numerical solution of the model had been previously developed to solve steady state, transient linear and transient non-linear problems[5]. The governing equation of the most general case, i.e. transient non-linear problems is:

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z}\right]=\phi\frac{\partial H}{\partial T}\cdot\frac{\partial T}{\partial t} \tag{1}$$

Where $K(T)$ is the thermal conductivity, H is the enthalpy, x and y are the Cartesian co-ordinates. Solution of (1) yields temperature variation as a function of time and space (i.e. $T=T(x, z, t)$).

The Galerkin Weighted Residual finite element method was used to achieve spatial discretisation of the domain. Eight node quadrilateral elements were employed in the model[6]. A finite difference algorithm was employed to accommodate the time varying nature of the problem. A detailed account of the theoretical model and its numerical solution is fully described by Lewis *et al.* (1995)[5] and therefore will not be repeated here.

Material properties

The set of material properties listed in *Table 1* have been used in the following numerical study. The material properties were obtained from the technical literature[2,7]. The thermal properties specified in *Table 1* represent the different materials encountered during the site investigation. However, a single value of thermal conductivity and heat capacity is used to describe each soil layer thus the analyses presented below are linear.

Application of numerical model

Calibration of the numerical model was sought in the first instance against a relatively simple one-dimensional case. The robustness of the model is assessed in four distinct one-dimensional

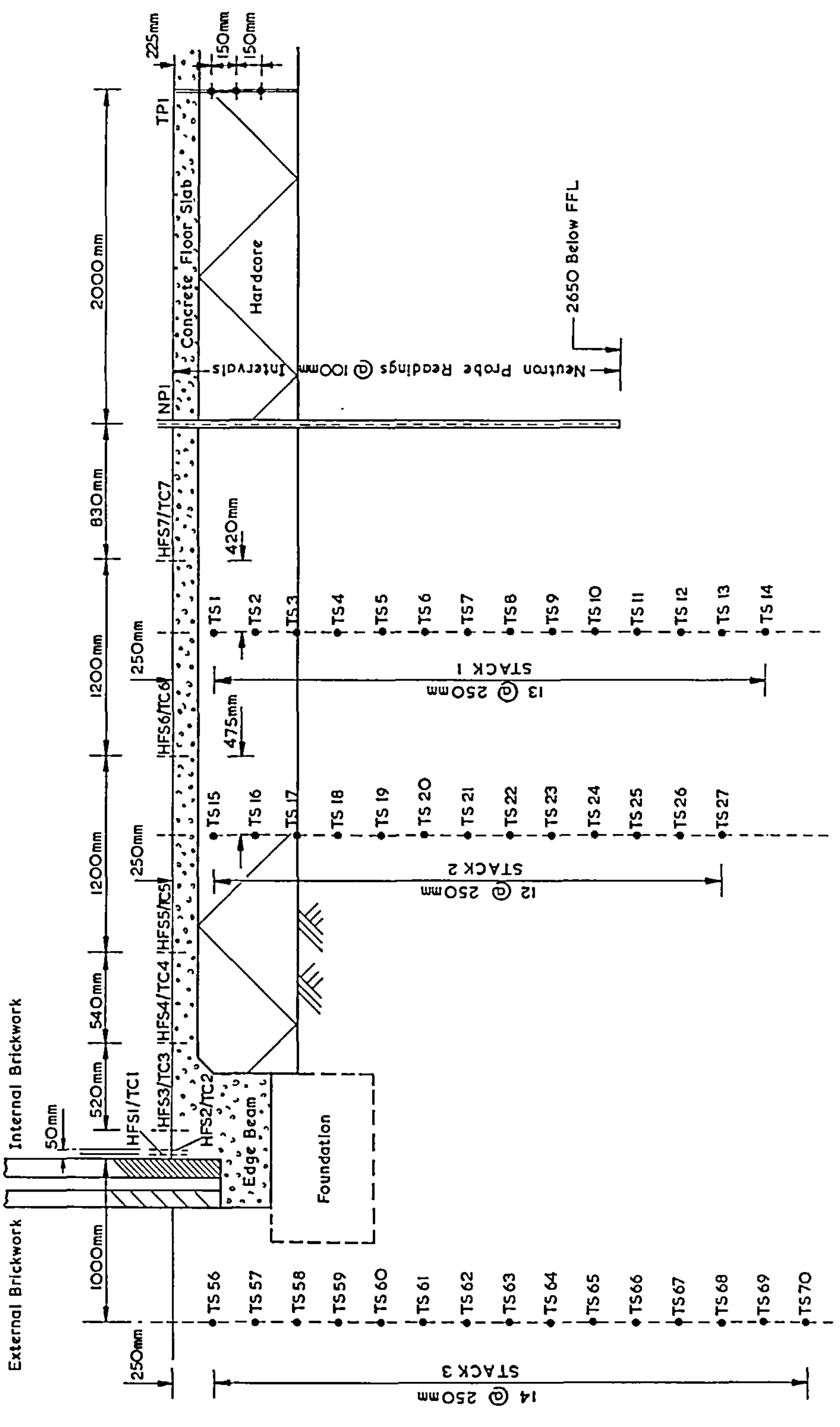

Figure 1 Experimental layout

Table 1 Thermal properties

Material	Thermal conductivity W/m K	Specific heat capacity J/Kg K	Density Kg/m^3
Concrete	1.37	880	2400
Hardcore	1.2	930	2000
Made ground	1.5	2000	1500
Sand and gravel	2.0	1350	1500

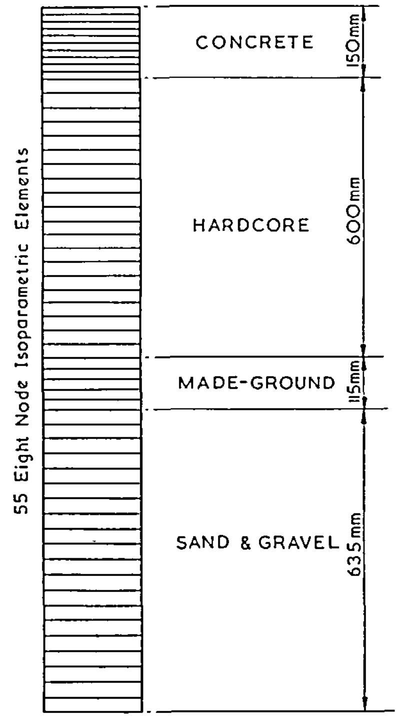

Figure 2 Finite element mesh

analyses. The precise form of the initial and boundary conditions adopted are described below for each simulation presented.

Interpretation of the data base revealed that underneath the building, remote from the outer wall, temperature variations were essentially one-dimensional. *Figure 1*, illustrates that relevant measured ground temperature variations can be obtained from temperature sensors located in Stack 1.

Finite element mesh

The finite element mesh used to represent the floor slab and underlying ground conditions in the vicinity of Stack 1 is shown in *Figure 2*. The mesh extends to a depth of 1500 mm below the surface of the ground floor slab. A total of 55 eight node quadrilateral elements have been used to achieve spatial discretisation. Smaller elements have been used near the surface where the boundary condition is applied. *Figure 2* also illustrates the variation with depth of the soil profile indicated by the borehole logs.

APPLICATIONS

Simulation 1

The first analysis considers a twenty four hour period, Day 364 of the data base (30/12/91). *Figure 3* shows the measured heat flux through the ground floor slab obtained from heat flux

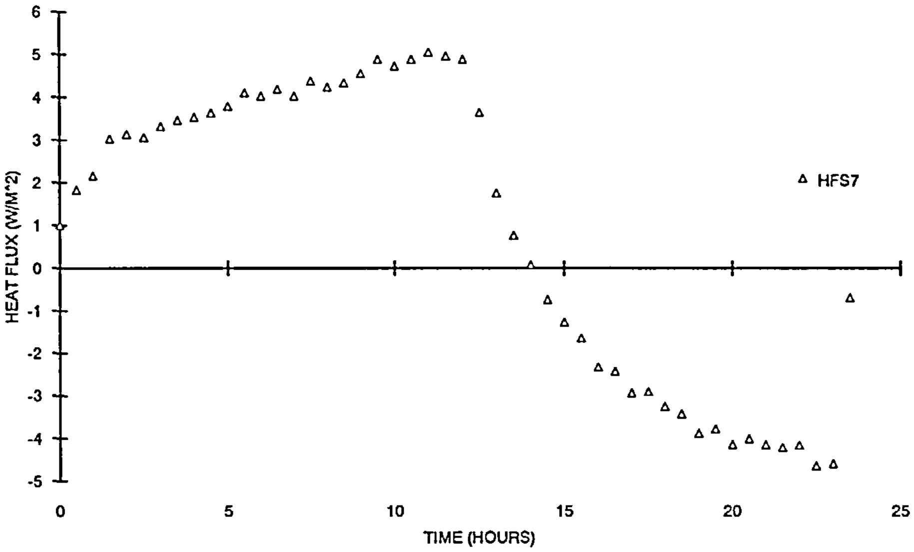

Figure 3 Flux boundary conditions—1 day period

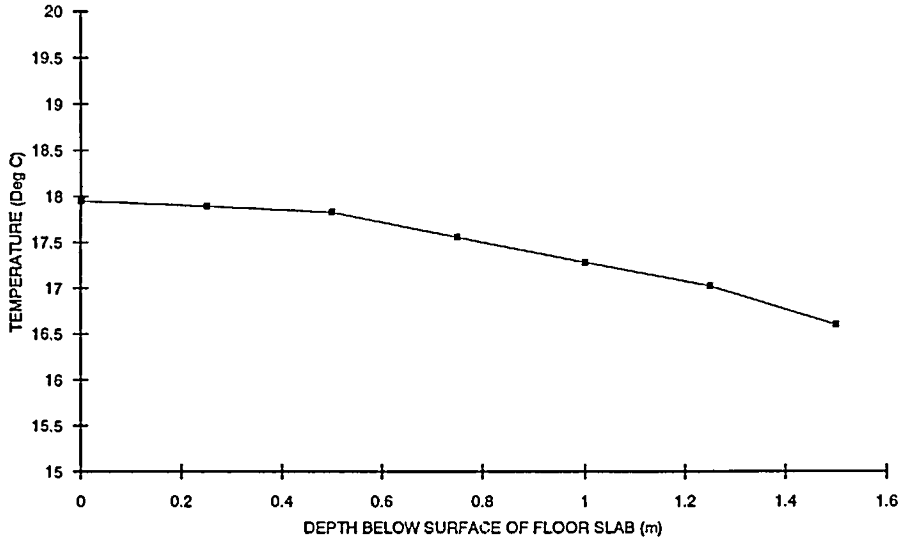

Figure 4 Initial temperature distribution—Simulation 1

sensor HFS7 (*Figure 1*). The figure illustrates an initial period of 12 hours during which heat is flowing out of the building into the foundation soils. During the latter 12 hours of the day a gradual reversal of heat flow occurs as thermal energy stored in the ground during the day provides a heat source for the building.

The data presented in *Figure 3* was used directly to define heat flux boundary conditions for the simulation. The boundary conditions were time varying, at intervals of 30 minutes, and applied to the surface nodes of the finite element mesh shown in *Figure 2*.

Initial conditions for the analysis were obtained directly from the measured temperature distribution at time zero of Day 364. *Figure 4* illustrates the measured values. The exact temperature value at the surface was not known. Therefore an approximate value has been

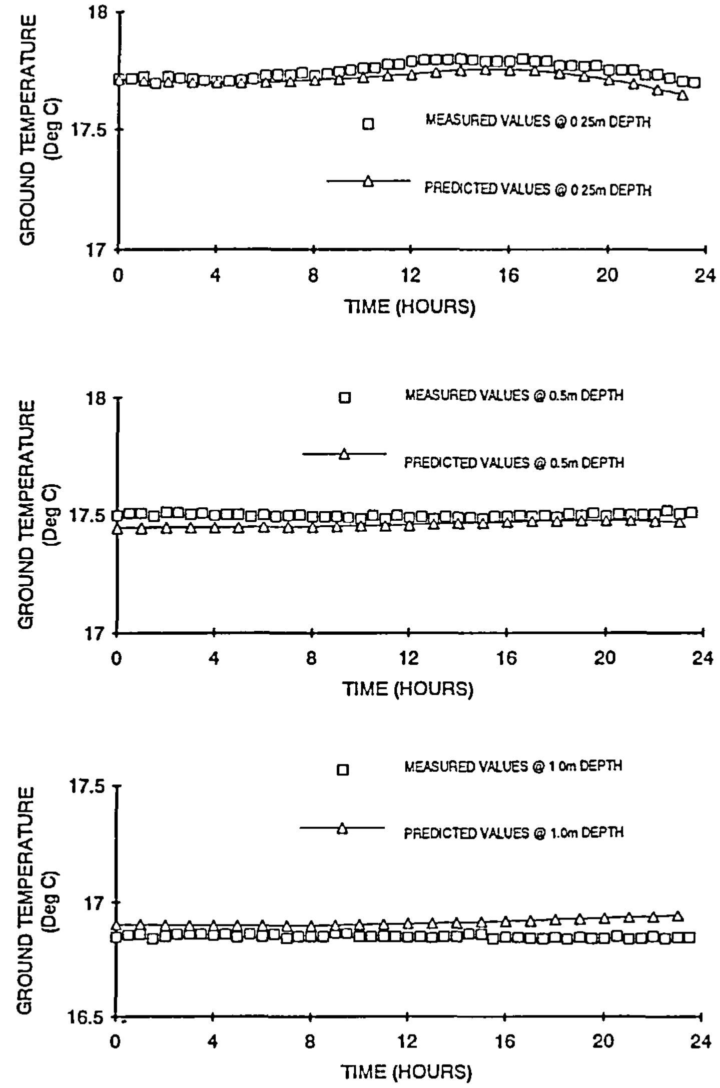

Figure 5 Variation of temperature vs time—Simulation 1

obtained by linear extrapolation of the measured values of 0.25 m and 0.5 m depth to the surface of the floor slab. The resulting temperature distribution varies from 18°C at the surface of the floow slab to approximately 16°C at a depth of 1.5 m. The distribution shown in *Figure 4* was used to define the initial temperature values at all nodes in the finite element mesh.

The results obtained from the analysis are presented in *Figure 5*. Variations below the 1.0 m depth were negligible during this period and were therefore excluded from consideration. Considering first, the results achieved at 0.25 m depth in comparison with the measured temperature variation. During the first 9 hours of the analysis the predicted temperatures are in very good agreement with the measured values. However, during the remaining 15 hours some disparity between predicted and measured behaviour is evident. However, given the small magnitude in temperature variation that actually occurs during the period analysed the results are in general viewed as encouraging.

The predicted temperature response at 0.5 m below the surface of the floor slab is in excellent agreement with the measured values, albeit for relatively little variation in temperature. At 1.0 m below the floor slab, however, the model predicted a slight decrease in temperature, whereas the measured data showed little change over the 24 hour period.

Simulation 2

The second simulation addresses a 5 day period, Day 355 (21/12/91) to Day 359 (25/12/91) in the data set. The measured temperature variations over this period are presented in *Figure 6*. Results are shown at 0.25 m, 0.5 m, and 1.0 m depth. Clearly, near the surface the measured temperature variation is significantly greater than that at depth. At 1.0 m depth the magnitude of temperature variation during the period is small, nevertheless a progressive reduction in temperature is evident.

Figure 7 presents the measured heat flux sensor data during the 5 day period. During the first half a day, heat is flowing from the building into the underlying ground. The following two days indicate a period where heat is returning from the ground to the building (a weekend period with no artificial heating of the building). The remaining two and a half days show a normal

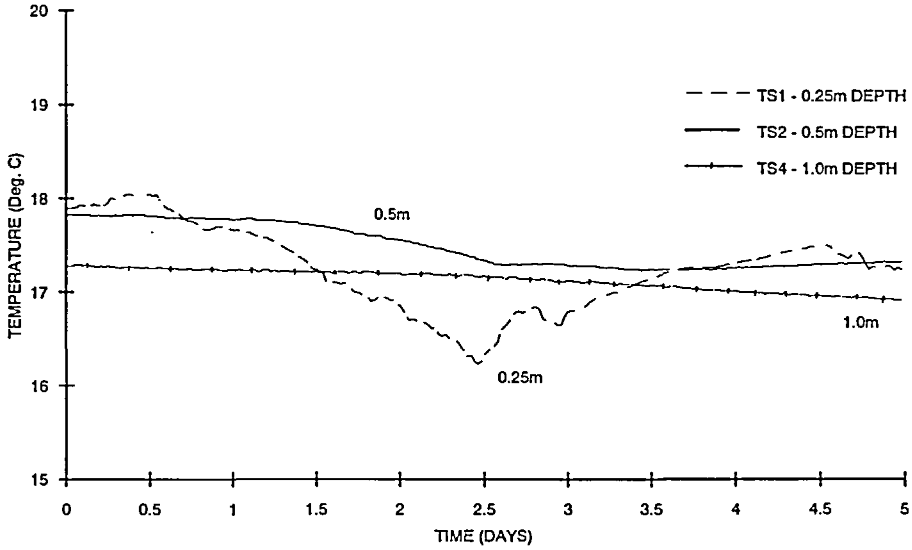

Figure 6 Measured ground temperature vs time—5 day period

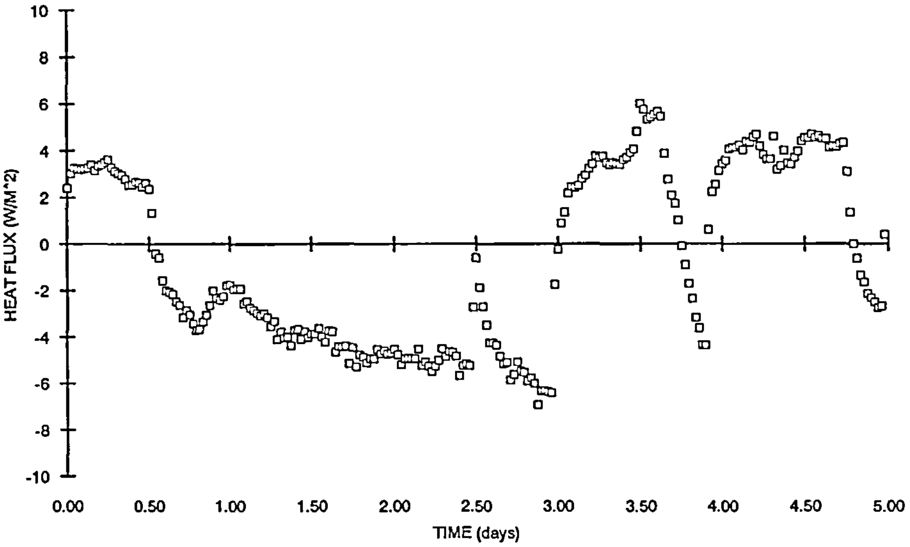

Figure 7 Flux boundary conditions—Simulation 2

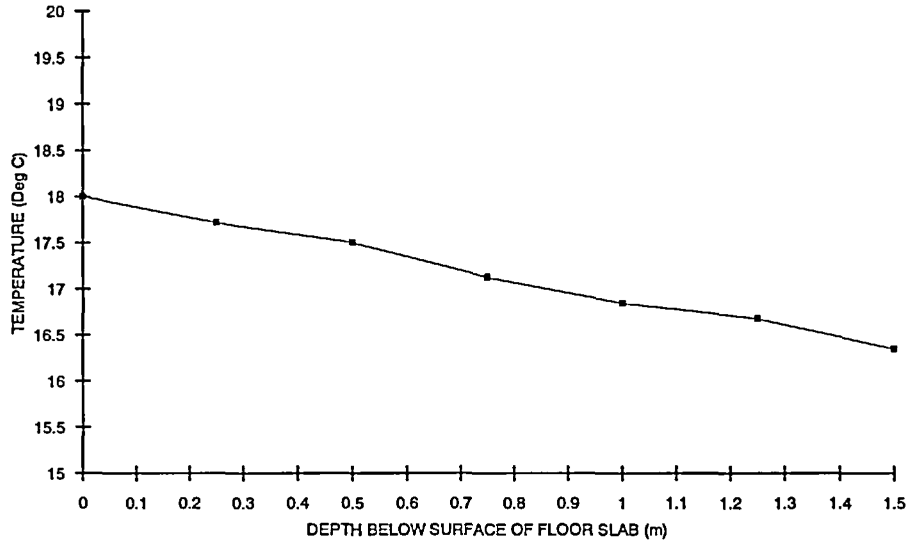

Figure 8 Initial temperature distribution—Simulation 2

daily variation. The heat flux values shown in *Figure 7* were used as time varying boundary conditions in the manner described above for Simulation 1.

The initial temperature distribution used in the simulation is presented in *Figure 8*. The values shown were obtained directly from the data set at the start of Day 355. Linear interpolation was once again used, in the same manner described above, to estimate the temperature at the surface of the floor slab.

The results of the analysis are presented in *Figure 9*, for depths of 0.25 m, 0.5 m and 1.0 m below the surface of the floor slab. The figure reveals that the model predicted a similar total

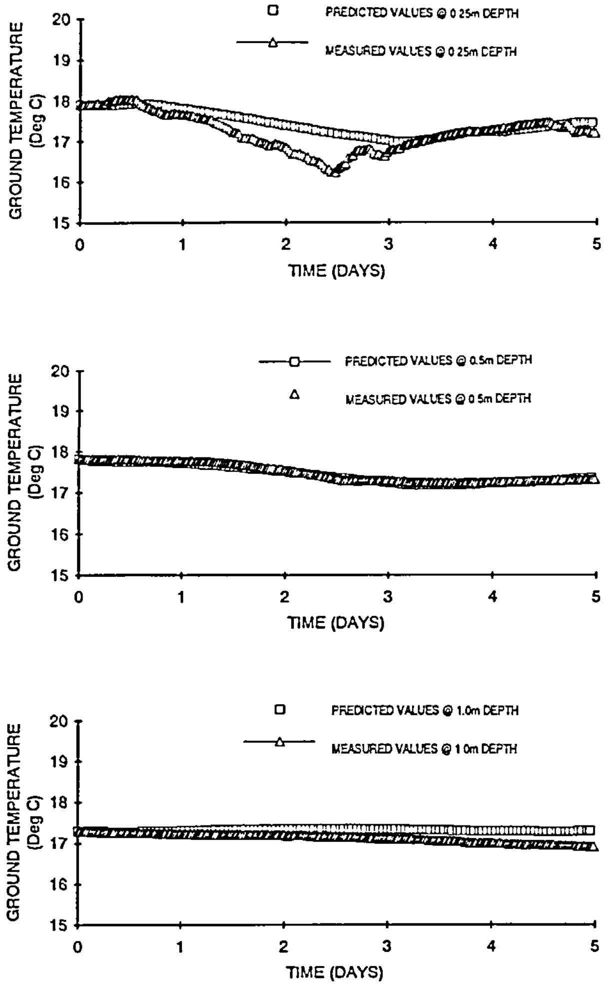

Figure 9 Variation of temperature vs time—Simulation 2

change in temperature at 0.25 m depth over the 5 day period to that masured in-situ. However, the predicted transient variation does not accurately match the measured behaviour. At approximately 2.5 days into the analysis the predicted temperature is 1°C greater than the measured value. The maximum variation in temperature at this depth during the entire period is of the order of 2°C. In contrast, *Figure 9* also illustrates that the analysis yielded results which are in excellent agreement with the measured temperature variation at 0.5 m depth. Reasonable correlation was achieved at 1.0 m depth.

Overall, the analysis has produced reasonable correlation with measured data. However, an accurate prediction of near surface transient behaviour was not achieved in this simulation.

Simulation 3

The third analysis provides an alternative simulation of the 5 day period modelled in Simulation 2 above. Initial conditions and material properties are identical to those described above.

The experimental data base also included air temperature variations for the 5 day period. Therefore, in this simulation, the use of air temperatures to prescribe boundary conditions is explored. The relevant air temperature data, measured at thermocouple TC7 (*Figure 2*), is presented in *Figure 10*. The data is consistent with the heat flux sensor data shown previously in *Figure 7*. For the first half a day the room temperature is slightly increasing. The following 2 days show a period of temperature reduction. As the heating is turned on and off again the air temperature rises and falls respectively during the remaining two and a half days. The maximum change in temperature in the room during the 5 day period is approximately 4°C.

The data shown in *Figure 10* was used to prescribe a set of time varying fixed temperature boundary conditions which were applied to the surface nodes of the finite element mesh. Once again the boundary condition data were specified at 30 minute intervals.

The results of the analysis are presented in *Figure 11* for depths of 0.25 m, 0.5 m and 1.0 m below the surface of the floor slab. Considering first the results achieved at 0.25 m depth, a good correlation between experimental and predicted results can be seen to have been achieved. The results are significantly different from those achieved in the previous simulation. In this case the model slightly over-predicts the magnitude of temperature variation. However, in general the match between measured and predicted results is now significantly improved at this depth.

The excellent correlation previously obtained at 0.5 m depth has been lost in this case. However, the results are still in reasonable agreement with the measured values. Excellent correlation was achieved at 1.0 m depth.

The direct use of air temperature values as fixed boundary conditions has yielded improved overall results in comparison with the previous analysis. This fact has important implications for future applications in the sense that air temperature is a much easier parameter to measure than heat flux.

Simulation 4

The model was next calibrated against measured seasonal trends. The particular period chosen for consideration began on Day 262 (19/9/91) and ended on Day 205 (23/7/92) spanning a total of 312 days. *Figure 12* illustrates the measured daily mean temperature response at depths of 0.25 m, 0.5 m 0.75 m and 1.0 m below the surface of the floor slab. The results clearly show that

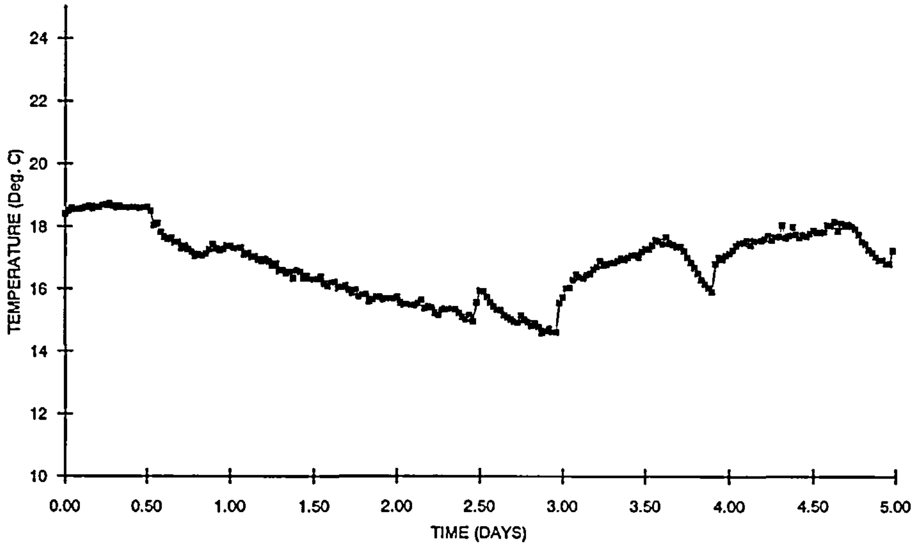

Figure 10 Measured air temperature vs time—5 day period

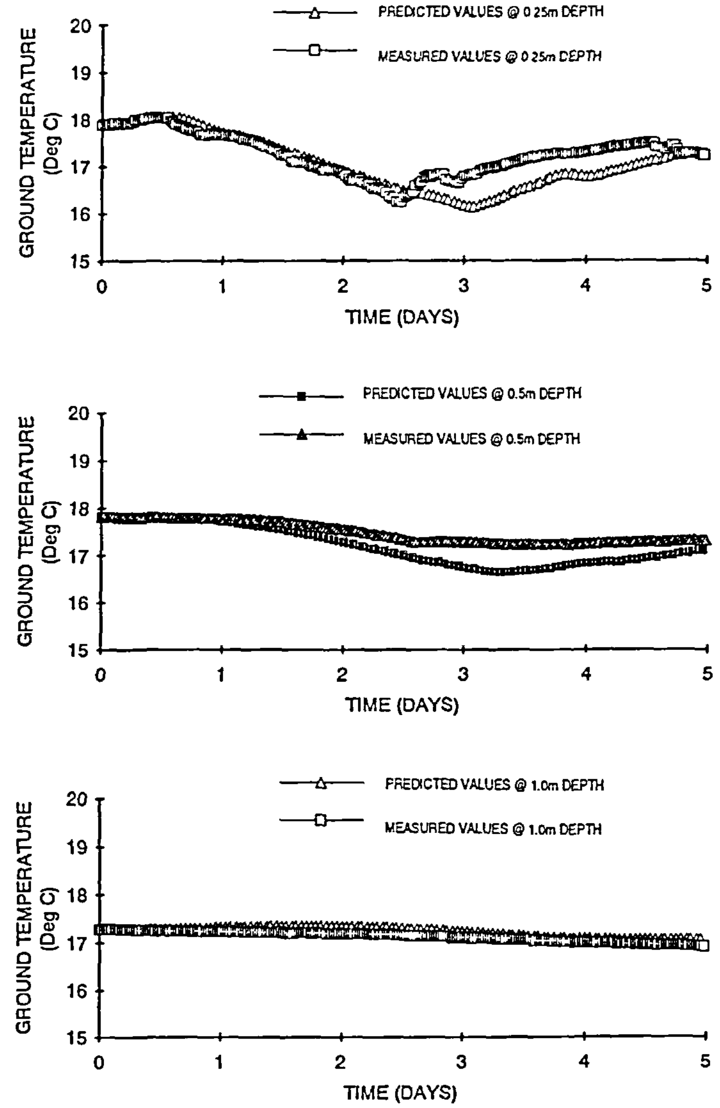

Figure 11 Variation of temperature vs time—Simulation 3

the near surface sensor has been subject to the greatest variation in temperatures, with less variation occurring at 1.0 m depth.

The measured air temperature variation over the period is shown in *Figure 13*. The data is presented in terms of daily mean temperatures and has been used to specify time varying fixed temperature boundary conditions applied to the surface of the finite element mesh.

The initial temperature distribution measured at the start of Day 262 is shown in *Figure 14*. The surface temperature was again extrapolated from the measured data. The resulting temperature distribution is approximately linear over the top 1.0 m of the ground profile. Below this depth a more rapid decrease in temperature was measured.

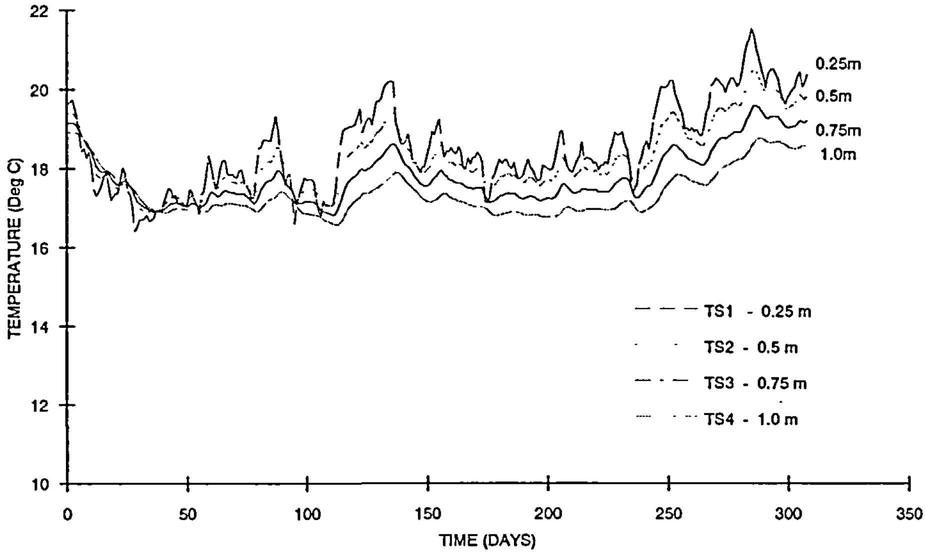

Figure 12 Measured ground temperature vs time—10 month period

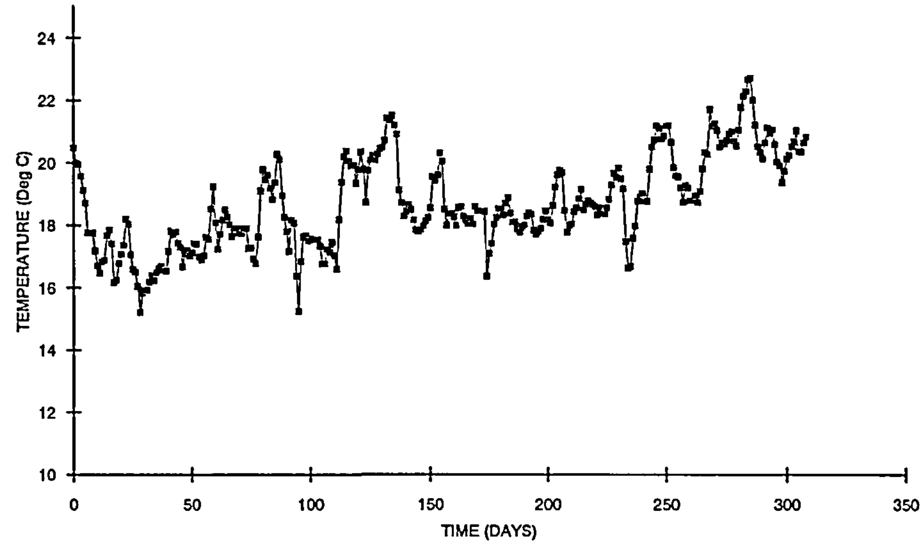

Figure 13 Measured mean daily air temperature variation—10 month period

The results of the analysis are presented in *Figure 15* for depths of 0.25 m, 0.5 m and 1.0 m. Excellent correlation was achieved at a depth of 0.25 m below the surface of the floor slab. At this depth, the predicted results are almost indistinguishable from the measured data. The results achieved at 0.5 m depth also show very good correlation with measured data. The predicted response at 1.0 m depth yielded relatively poor correlation. However, it should be noted that the disparity between predicted and measured results is at most 2°C.

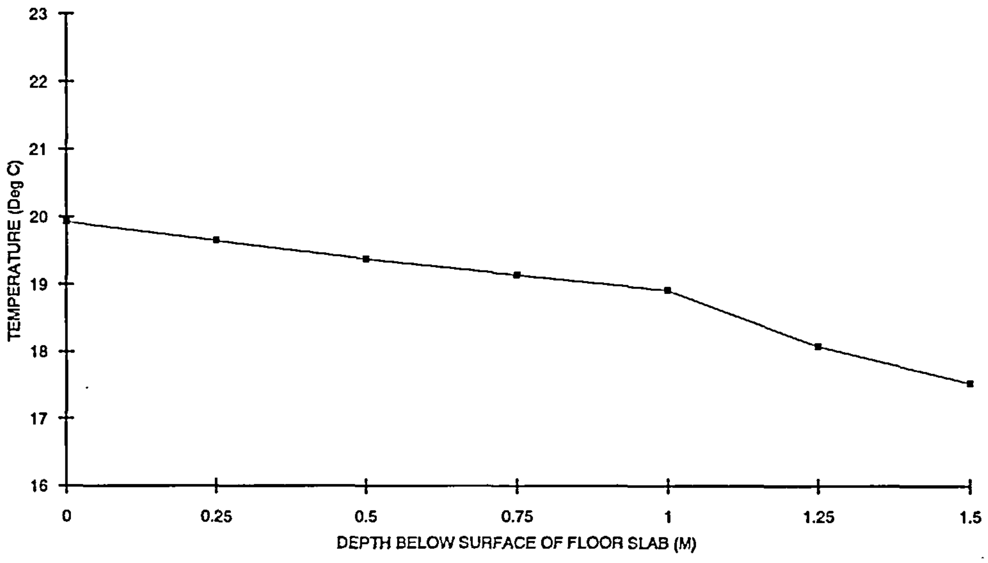

Figure 14 Initial temperature distribution—Simulation 4

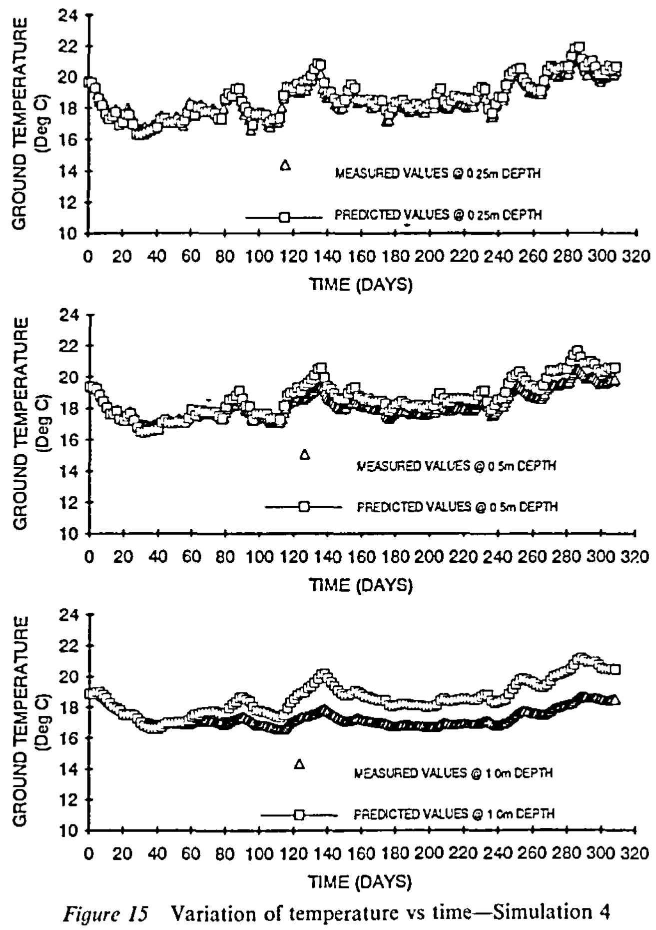

Figure 15 Variation of temperature vs time—Simulation 4

CONCLUSIONS

Results obtained from a comprehensive in-situ experiment to monitor thermal performance of a ground floor slab of a real building were presented. Details were provided of the wide range of instrumentation used.

The results of the experiment were used to calibrate a numerical heat transfer model. Material properties were obtained from the literature. Boundary and initial conditions were obtained directly from experimental data.

The model was applied to the simulation of four one-dimensional problems covering a number of different time periods to include both diurnal and seasonal behaviour. The model was shown to be capable of representing diurnal variations in temperatures both within the ground floor slab and in the underlying foundation strata. Good correlation was achieved between predicted and measured temperature variations.

The model was next applied to the simulation of a five day period. For this period, two alternative modelling approaches were explored. The first approach used measured heat flux data to define time varying flux boundary conditions. Results from this simulation yielded a poor correlation with measured data near the surface and good correlation at depth. The second simulation made use of measured air temperature variation to define time varying fixed boundary conditions. The results achieved from this approach showed considerable improvement in comparison to those achieved using flux boundary conditions.

The final simulation presented considered seasonal temperature variations. Air temperatures were once again used to define boundary conditions. The results achieved from this simulation were in good agreement with measured data.

Some of the results presented were not in very close agreement with the measured data. Such disparity between numerical and measured data is likely to be principally related to the fact that material properties have been assumed. Interpretation of borehole logs to describe the soil profile at the precise location of the instrumentation may also contribute to such disparity.

In summary, the numerical modelling approach identified was shown to be capable of representing real transient temperature variations underneath a building. The research presented provides an insight into the real thermal behaviour of a structure, and is therefore seen as a valuable aid to understanding the complex transient heat migration patterns that occur in practice.

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