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Evaluation of thermal imaging as a method of measuring moisture profiles over an interface between cement-lime mortar and brick.

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ABSTRACT

Moisture profiles reveal much about the moisture behavior of a material or combination of materials. Measured transient moisture profiles can also be used to verify and evaluate moisture diffusivities. One possible method of measuring these profiles is thermal imaging. This paper evaluates this technique applied to bricks with and without cement-lime mortar attached. The measured temperature profiles are transformed to moisture profiles through calibration curves obtained by measuring the temperature decrease on preconditioned specimens. The use of calibration curves avoids problems arising from possible difference in emittance between wet and dry surfaces.

1 INTRODUCTION

There are several methods of determining moisture profiles. The most accurate is probably the "slice-dry-weigh method," which measures moisture content directly. In this method, the specimen is rapidly sliced into discs that are weighed, dried, and weighed again. The water in the disc evaporates during the drying and the water content in mass by mass can be determined directly from the weight loss. This method is, however, quite time-consuming and can in some cases present practical difficulties. Besides, it might also be difficult to split the specimen into discs thin enough to evaluate a very steep moisture front.

Other methods of determining moisture content rely on measuring other physical attributes, such as electrical conductivity, electrical capacitance, gamma-ray attenuation, nuclear magnetic resonance, and the temperature loss when liquids evaporate. These and other methods are briefly outlined in Janz (1997). The method used in this paper is thermal imaging; i.e. measurement of the decrease in temperature when water evaporates.

Moisture diffusivity can be determined from moisture absorption profiles or redistribution profiles. Two of the most common methods of doing this are the Boltzmann transformation method and the profile method. These methods are described in de Freitas et al. (1995). Measurements of moisture distribution obtained through such techniques as thermal imaging can also be used to verify measured moisture diffusivities. Such verification is important in order to establish correlations between empirically measured distributions and existing models of transport properties so as to develop better models.

The combination of mortar and brick can be sensitive to frost attack. Although both the brick and the mortar may themselves be frost resistant, the combination can cause failure. In some cases a thick layer of mortar protects the brick, while a thin layer increases the risk of frost attack. The critical degree of saturation of the brick will, of course, not change in this combination. However, the quality of the mortar may change, because the brick sucks water from the fresh mortar. This effect is dependent on the thickness of the mortar, with a thin layer being proportionately more affected than a thick layer.

The main reason for the increase or decrease in frost resistance is the moisture levels reached in the brick. The mortar will always have some influence on these moisture levels. It may, for example, lower the moisture content in the brick by reducing moisture absorption during driving rain. However, it will also simultaneously lower the capacity of the brick to dry out, which may increase the moisture content in the brick.

The moisture levels reached in a multi-layer construction will depend on both the moisture diffusivity and the moisture storage capacity of all the construction materials. The moisture diffusivity determines the rate of moisture transport within a specific material, while the moisture storage capacity determines the moisture equilibrium at interfaces between materials and at the boundary to the surrounding environment. Current models for calculating moisture transport and transport properties in homogenous materials do not show satisfactory agreement with measured moisture distributions for many materials. The agreement is even worse for multi-layer constructions. There is clearly a need for methods of measuring actual moisture distribution. One such method is thermal imaging.

2 PRINCIPLE OF THERMAL IMAGING

Thermal imaging is a simple method of determining moisture distribution, or the distribution of any volatile fluid. This method makes use of a split surface of the specimen, and hence it is destructive, with one specimen used every time the moisture profile is measured.

Immediately before measuring, the specimen is split into two halves, parallel to the moisture flow direction. As the moisture in the specimen starts to evaporate from the split surface, the temperature of the surface drops. An infrared camera registers the temperature distribution over the split surface, and this distribution is used to construct a moisture profile.

It should be noted that thermal imaging measures the radiation from a surface, rather than the surface temperature. The camera computes the surface temperature from the measured radiation, and in order to do so the emittance of the surface must be known. The magnitude of the total radiation from a certain surface with a temperature equal to the temperature of the surrounding air is described by

$$q_{rad} = \varepsilon E_b + (1-\varepsilon) q_{in} \tag{1}$$

where

q_{rad} is the total radiation [W/m^2];
ε is the emittance [–];
E_b is the total emitted radiation from a black body [W/m^2];
q_{in} is the incident radiation in the object measured on [W/m^2].

The first term in Equation 1 describes the total emitted radiation from the surface while the second term describes the reflected radiation.

The total emitted radiation from a black body is given by Stefan-Boltzmann's equation:

$$E_b = \sigma T^4 \tag{2}$$

where σ is the Stefan-Boltzmann constant with a magnitude of 5.68 · 10^{-8} W/(m^{2}K^4) and T is the absolute temperature [K] of the surrounding air.

Liquid water will evaporate when a split surface of a specimen with raised moisture content is exposed to the surrounding air. This process requires a certain amount of heat, and hence the evaporation decreases the surface temperature. The magnitude of the heat of vaporization is dependent, among other things, on the moisture content, the rate of moisture transport to the surface, the rate of vapor transport from the surface, the specific heat of vaporization, and the temperature.

The decrease in the surface temperature of a wet surface results in the total radiation of the wet split surface being lower than the total radiation of a dry surface. The total radiation of a surface with a moisture content u (moisture content mass by mass) can be described by

$$q_{rad,u} = \varepsilon_u \sigma T_S^4 + (1-\varepsilon_u) q_{in} \tag{3}$$

where $q_{rad,u}$ is the total radiation from a surface with the moisture content u, ε_u is the emittance of a surface with a moisture content u, and T_S is the decreased surface temperature.

The decrease in radiation emitted from the surface is proportional to the evaporation, and consequently also to the moisture content. Thus the moisture content in the material can be described in terms of the difference between the radiation from a dry surface and a wet surface:

$$\Delta q_{rad} = \sigma \left(\varepsilon_0 T_0^4 - \varepsilon_u T_S^4 \right) + q_{in} \left(\varepsilon_u - \varepsilon_0 \right) \tag{4}$$

where ε_0 is the emittance of a dry surface and T_0 is the temperature of a dry surface.

The output from an infrared camera is the temperature. Thus, in order to measure the correct surface temperature, the emittance of the surface must be known and programmed into the camera. Since only one emittance at a time can be programmed into the camera, the surface temperature measured will be incorrect when ε_0 differs from ε_u.

This problem can, however, be avoided by using a method of calibration proposed by Janz (1997). In this method the temperatures of the split surface on which the profile is measured are calibrated against the temperatures of split surfaces of well-conditioned specimens. The calibration is performed on specimens of the specific material with different, known moisture contents. The measuring procedure and conditioning procedure must take place in a climate room with constant relative humidity and temperature, and the image must be taken at the same time after splitting the specimen. Both the calibration and the measurement of profiles must, of course, be performed with the same camera settings. Since the emittance at a specific moisture level is the same independent of whether the temperature is measured on a calibration specimen or on a specimen with a moisture distribution, the magnitude of the emittance is insignificant. A specific temperature decrease always implies a definite moisture level, even if the measured temperature is incorrect. While the conditioning procedure is time-consuming, the accuracy of the measured water content is high. This is the method used to evaluate the profiles presented in this paper.

Another method of evaluating moisture profiles without any calibration is given in Sosoro and Reinhardt (1995). They claim that the moisture profile in a specimen with a constant cross-section over depth can be calculated by:

$$\psi(x) = \frac{(T - T_S(x))^2}{\frac{S}{V_{fl}} \cdot \int_0^{\ell} (T - T_S(x))^2 \, dx} \tag{5}$$

where

ψ is the water content volume per volume [$\mathrm{m^3/m^3}$];
T is the temperature of the surrounding air [K];
T_S is the surface temperature [K];
x is the co-ordinate in the direction of water transport [m];
S is the surface area exposed to fluid [$\mathrm{m^2}$];
V_{fl} is the total absorbed test fluid [$\mathrm{m^3}$];
ℓ is the specimen length [m].

Measured profiles of different liquids and laboratory arrangements are described in Sosoro et al. (1995), Sosoro (1995), Sosoro (1998) and Johansson (1999).

2.1 Limitations

Since evaporation involves cooling of the evaporating surface, thermal imaging can never be used to detect moisture contents directly after a period of desorption. Some absorption time must always precede the imaging so that the specimen is at the same temperature as the climate room. Hence it follows that the moisture distribution cannot be studied immediately after a period of drying.

3 MATERIALS AND METHOD

3.1 Specimens

The test was performed on bricks with or without mortar attached. The attached mortar consisted of cement-lime mortar CL 50/50/650. The porosity, density, and sorption coefficient of both the brick and the mortar had been measured. The porosity and density were determined according to Archimedes' principle (weighing vacuum saturated specimens in air and water). The sorption coefficient was determined on specimens dried in, and in equilibrium with, normal room climate. The porosity, density, and sorption coefficient of the brick were 26%, 1978 kg/m^3 and 0.35 $kg/(m^2\ s^{½})$, respectively. For the cement-lime mortar the same properties were 30%, 1853 kg/m^3 and 0.091 $kg/(m^2\ s^{½})$, respectively.

The specimens were manufactured by sawing a brick in two, yielding pieces of approximately 250 x 120 x 30 mm^3. An edging was attached around the 120 x 30 mm^2 surface in which the cement-lime mortar was to be cast. The edgings were 2 and 10 mm in height, reflecting the desired thickness of the mortar. Some variation occurred, however, especially in the thin mortar layer.

Before the mortars were attached, the bricks were stored in water for a week. The purpose of this water saturation was to prevent the bricks from sucking water from the cement-lime mortar during the casting and curing, and so to obtain the same characteristics in the 2 mm mortar and the 10 mm mortar. This saturation procedure also avoided differences at varying depths of the 10 mm mortar. After casting the specimens were stored at room climate for at least 4 months so that all the mortar was carbonized when tested.

In total, 57 specimens were manufactured: 17 with a 2 mm thick mortar, 34 with a 10 mm thick mortar and 6 without any mortar. Of the 34 specimens with a 10 mm thick mortar, 19 were used in the calibration procedure. All the other specimens were used for measurements of the moisture distribution.

3.2 Camera

The camera used was AGEMA, Thermovision 900. The camera has, according to its manual, a sensitivity of 0.1°C at 30°C.

3.3 Calibration procedure

Measurement of the surface temperature of specimens with known and well-conditioned moisture contents produced calibration curves. These curves were used to determine moisture distributions from measured temperature profiles.

At the start of the calibration procedure, the mortar and brick were separated with a diamond saw, making it possible to condition the mortar and the brick separately. The conditioning process started with drying the specimens in an oven at a temperature of 60°C until no changes in weight were observed, whereafter they were vacuum-saturated with water. The vacuum saturated specimens were then dried to the desired moisture content.

To achieve homogenous moisture distribution, the specimens were wrapped in plastic film and stored for at least 2 months in a climate chamber. A water-filled container was placed in the chamber with the specimens in order to keep the relative humidity in the chamber as close to 100% as possible, so preventing moisture loss through the plastic during the storage period. During this period the moisture in each specimen was redistributed so that the specimens would have a uniform distribution when the surface temperature was measured. Two weeks before the temperature measurement, the climate chamber was placed in the climate room were the surface temperature was to be measured. Thus the specimen was at the same temperature as the climate room when measured.

The temperatures of the calibration specimens were measured using thermal imaging in a climate room with a temperature of 20.6 ± 0.1°C and 19 ± 1% relative humidity. The procedure for measuring the surface temperature was identical on all measuring occasions. The specimens were split with a sharp cutting edge and exposed to the climate in the climate room. A fan, mounted half a meter from the specimen, generated turbulent air flow with a velocity of approximately 0.7 m/s over the split surface. Thermal imaging of the split surface took place exactly one minute after the specimen was split. The specimen was during the imaging placed 1 m from the camera. After the thermal imaging, the exact moisture content mass by mass of the specimen was determined by weighing it, drying it at 105°C, and finally weighing the specimen again.

The calibration curves obtained for the brick and cement-lime mortar are shown in Figure 1 and Figure 2. Possible differences between individual specimens were avoided by using the relative moisture content and relative temperature rather than the actual moisture content and temperature. Hence the moisture content was represented as the relative moisture content u/u_{cap}, where u is the actual moisture content mass by mass and u_{cap} is the moisture content at capillary saturation for the specific specimen. The temperature is represented by $(T_0-T_S)/(T_0-T_{S,cap})$ where T_0 is the temperature of the dry surface of the specimen, T_S is the actual surface temperature, and $T_{S,cap}$ is the temperature of the capillary saturated surface of the specimen. On average T_0 and $T_{S,cap}$ were 20.60°C and 17.76°C for the brick and 21.70°C and 16.03°C for the cement-lime mortar. The standard deviation of T_0 and $T_{S,cap}$ were 0.15°C and 0.36°C for the brick and 0.13°C and 0.39°C for the cement-lime mortar.

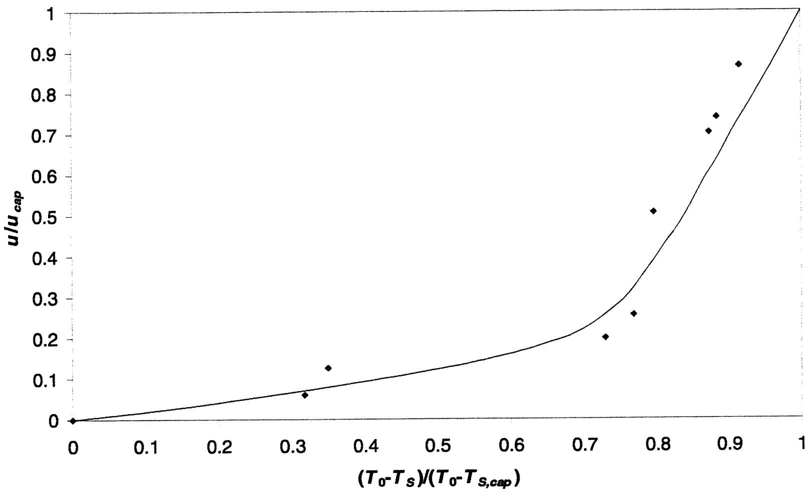

Figure 1 *Calibration curve of the brick. The relative decrease in surface temperature is plotted against the relative moisture content.*

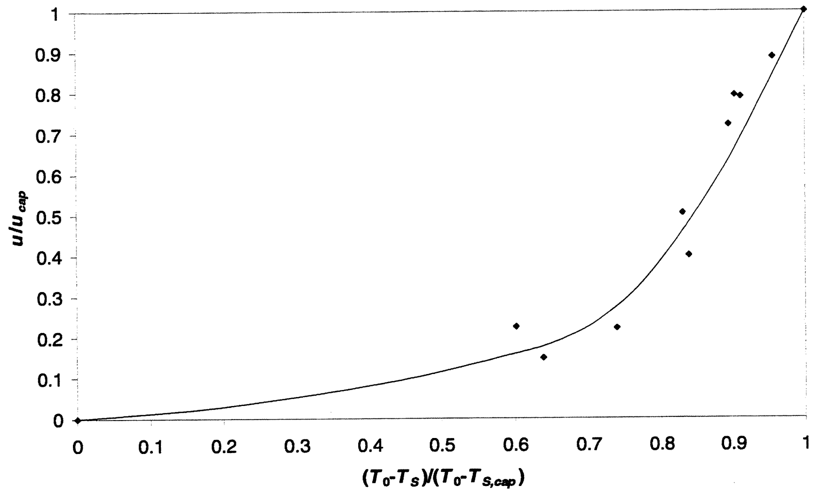

Figure 2 *Calibration curve of the cement-lime mortar. The relative decrease in surface temperature is plotted against the relative moisture content.*

3.4 Measurement of temperature profiles

The temperature profiles, and thus indirectly also the moisture profiles, were measured on dry specimens (dried at 60°C) subjected to different moisture loads. The dry specimens were wrapped in plastic film and stored for 2 weeks in the climate room where the surface profiles were to be measured so that the specimens were at the same temperature as the climate room. Conditions in the climate room were identical to those maintained when measuring the calibration curves, i.e. the temperature was 20.6 ± 0.1°C and the relative humidity was 19 ± 1%.

Before the temperature profiles were measured, the mortar-coated sides of the specimens were exposed to liquid water or the climate in the climate room for varying times. Moisture transport was prevented on all other sides of the specimens. Thus the moisture transport in the specimen during absorption and drying took place in only one direction. The water used for the absorption was acclimatized to the temperature of the climate room so that it was at the same temperature as the specimens.

Once a specimen had been subjected to the desired moisture load, it was split with a sharp cutting edge parallel to the direction of absorption and desorption. Thermal imaging of the split surface was conducted as described in section 3.2.

4 RESULTS AND DISCUSSION

The measured temperature profiles were compared to the calibration curves that had been obtained (see Figure 1 and Figure 2). The emitted radiation at a certain moisture level in the moisture distribution measurement was the same as the emitted radiation on the calibration specimen with the same moisture content. Any differences in emittance between a wet and dry surface were therefore insignificant in the tests performed here. Both the calibration curves obtained were very similar. If this is a coincidence or if there is any physical explanation for the similarity is not analyzed in this paper. If the similarity is a coincidence could however be checked by measuring calibration curves for more materials.

Figure 3 shows a typical measured temperature profile. The brick in question was exposed to water for 12 hours followed by 12 hours of desorption at 75% relative humidity, and finally by an additional 12 hours of absorption before the temperature profile was measured with thermal imaging. Figure 4 shows a moisture profile derived from the measured temperature profile. The derivation was performed using the calibration curves shown in Figure 1 (brick) and Figure 2 (cement-lime mortar).

As can be seen in Figure 3, the slope of the temperature profile is not perfectly sharp at the interface between mortar and brick. Consequently near the interface the moisture content is below capillary saturation in the cement-lime mortar and above capillary saturation in the brick (see Figure 4).

This phenomenon is a product of the limitations in the spatial resolution of the camera used. Figure 5 shows a temperature profile over an interface between cellular plastic and a steel plate. On this occasion, the cellular plastic had a temperature of 20.9°C and the steel a temperature of 16.6°C. There is thus a sharp temperature profile between the steel and cellular plastic, but the camera cannot register this sharp step. Therefore, the thermal imaging shows an inclined temperature profile. Thus, if using a camera and camera settings similar to the one used in this investigation, this method cannot register sharp temperature profiles, making it impossible to measure moisture levels close to the interface. From Figure 5 it appears that the spatial resolution of the camera and camera setting used in this investigation is approximately 11 mm. Moisture profiles with very large gradients will thus to some extent be incorrect.

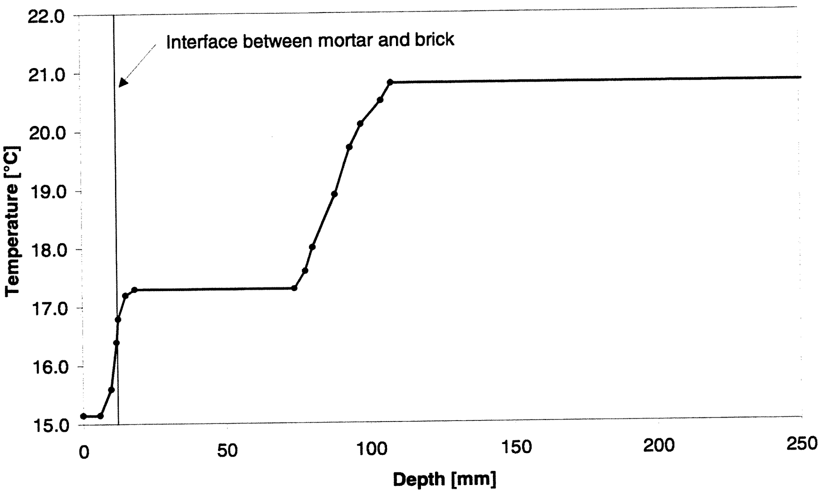

Figure 3 *Measured temperature profile on a brick with 12 mm mortar. The brick was exposed to water for 12 hours, followed by 12 hour desorption at 75% relative humidity, and finally an additional 12 hours absorption.*

The temperature profiles of specimens that were first exposed to water, followed by varying periods of redistribution, are shown in Figure 7 to Figure 9. During the redistribution period, the specimens were wrapped in plastic film so that no water could leave them. Figure 7 shows profiles measured on specimens without mortar, Figure 8 profiles measured on specimens with a thin layer of mortar, and Figure 9 profiles measured on specimens with a thick layer of mortar.

Unfortunately it was impossible to recalculate the temperature profiles to moisture profiles since the values of $T_{S,cap}$ and T_0 were unspecified for the specimens tested. At the measuring occasion the relatively great variation of $T_{S,cap}$ and T_0 was unknown and therefore not measured separately. During an absorption test these values appear directly from the temperature profile whereupon the moisture profiles can be calculated. In future studies the values of $T_{S,cap}$ and T_0 will be measured in separate tests for each specimen.

From the profiles it appears that during redistribution the water penetrates the specimen only to a certain level, where penetration more or less stops. The stop in moisture flow is probably due to the decreased moisture gradient resulting in a marked decrease in moisture diffusivity.

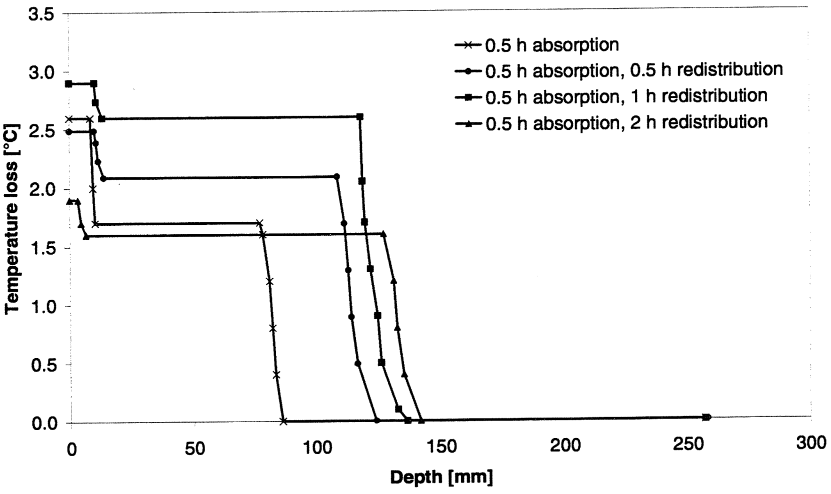

Figure 7 Temperature profiles measured on bricks without mortar.

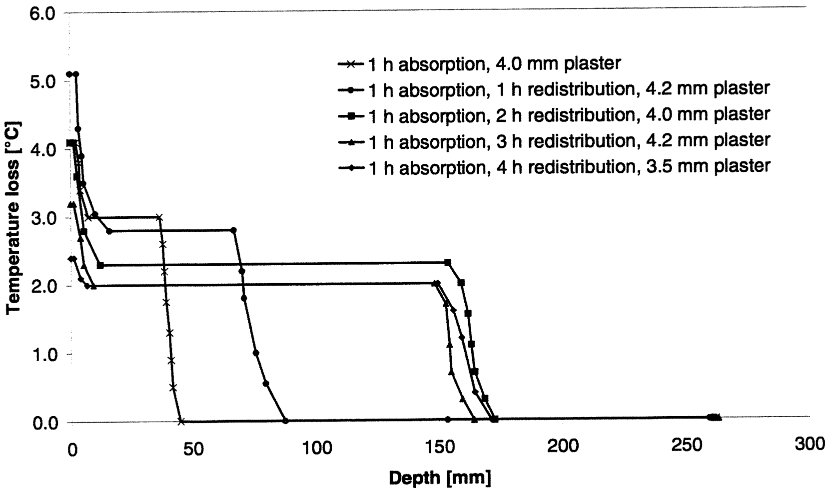

Figure 8 *Temperature profiles measured on bricks with a thin layer of mortar attached.*

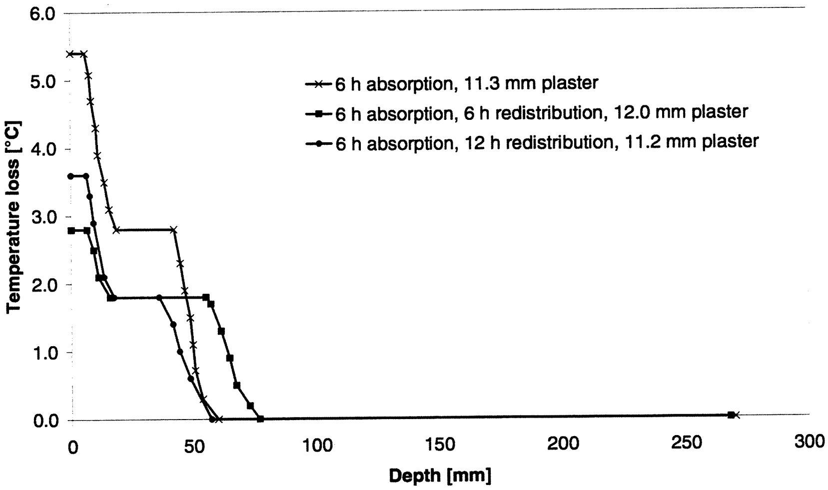

Figure 9 *Temperature profiles measured on bricks with a thick layer of mortar attached.*

5 CONCLUSIONS

Thermal imaging provides a quick and easy way of measuring penetration depth and the shape of the moisture profile. Compared to other methods of measuring transient moisture profiles, this method is relatively inexpensive and requires no major technical outlays other than for the camera. Moreover, thermal imaging eliminates the need for any special geometry in the specimens. The only requirement is that it must be possible to split the specimen parallel to the moisture flux.

Time-consuming calibration is needed if exact moisture levels are to be derived from the temperature profiles. In such cases a climate room is needed in addition to the camera.

The major weakness of thermal imaging is that it cannot be used directly after periods of desorption since evaporation cools the evaporating surface and disturbs the imaging. A period without desorption must always precede imaging to ensure that the specimen is at the same temperature as the surrounding air.

The partial resolution of the camera used in this study was rather low, making it impossible to evaluate the moisture content near the interface between mortar and brick.

6 ACKNOWLEDGMENT

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