INFLUENCE OF POROSITY ON THERMAL PROPERTIES OF CERAMIC FLOOR TILES

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ABSTRACT

In this work, the changes in the thermal behaviour of ceramic floor tiles caused by the porosity resulting from the introduction of five different weight fraction contents (ranging from 10 to 40 wt-%) of amorphous silica fibres (ASF) and by the application of five different compaction pressures (ranging from 10 to 30 MPa) were evaluated by chemical analysis, scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS) as well as by thermal (thermal conductivity and effusivity) and physical (porosity) measurements. The objective of this work was to understand the interaction of human bare feet in contact with porous ceramic floor tiles in order to design thermally comfortable high performance ceramic products. The results show that by increasing the porosity of the ceramic floor tiles the thermal conductivity and effusivity decrease so that the heat flow transducers used in this work can be considered an important tool for the evaluation of transient thermal systems.

1. INTRODUCTION

Ceramic floor tiles are widely used in buildings. They have aesthetical and technical functions. Among the technical functions floor thermal insulation it became very important in buildings with human occupation where thermal comfort is required.

The human body can be considered as a "thermal machine" which generates a heat amount between 100 and 1000 W according to the performed activity. As we have hot blood the heat generated by the human body must be dissipated to maintain the human body temperature constant (it is considered normal between 35 and 37°C). The thermal regulators mechanisms (constriction, sudation) are responsible for this task.

Many are the elements that contribute for the comfort sensation and they are characterized by the physiological and psychological response intensities of an individual to the environment around him[1]. The main environmental variables are: the air temperature, the relative moisture, the wind speed and the radiant temperature[2-3]. However, we can be subjected to some kind of localized discomfort like for example the feet contact when the floor is hot or cold. Research works related to the people's response with respect to the floor temperature revealed that when people have footwear the finished flooring material is not important; however, in places where people are barefoot this aspect becomes significant. The discomfort can be characterized by heated floor surfaces in external environments which are exposed to sun radiation (swimming pools areas) or by cold floor surfaces in internal environments (bed rooms, path rooms). The thermal sensation is related to the skin temperature, in this case with the feet surfaces attached or in contact with the flooring. The contact temperature can be correlated by a property named thermal effusivity. The lower the flooring thermal effusivity and the closer is the contact temperature to the human body, the temperature resulting provides the best comfort.

In this context, this work has as objective to develop a ceramic floor tile with low thermal effusivity maintaining all the properties and characteristics required for finished ceramic floor tile products.

The thermal effusivity is directly correlated to the thermal conductivity and the material density. Materials with low thermal conductivities and densities can be obtained by porous inclusion. It can be considered a general rule that thermal conductivity of porous materials decreases as the porosity increases[4]. Pores in ceramic materials are due particularly to the processing conditions usually employed. The presence of pores generally involves low mechanical strength. By combining appropriately the raw materials and processing techniques it is possible to obtain porous ceramics with high mechanical and chemical resistances as well as high refractoriness and high structural uniformity with favourable thermal properties for a given application. There are many methods to obtaining porous ceramics. One of the first developed methods, which is still at present widely used, consists of the incorporation of organic products to the ceramic body which are removed during the firing step leaving pores whose sizes are related to the organic particle sizes. Each method has its advantages and potential uses. Meanwhile, the processing control and consequently the final material properties are a general problem[5]. In this work, porous ceramic tiles were obtained by pressing an industrial atomized ceramic powder incorporated with different weight fractions (10, 20, 30 and 40%) of amorphous silica fibres. In the same way but without fibre incorporation, as an alternative to evaluating the influence of the compaction pressure, additional porous ceramic tiles were obtained by the application of different compaction pressures (10, 15, 20, 25 and 30 MPa). Raw materials and the obtained compacted samples were evaluated by chemical analysis, scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS) as well as by thermal (thermal conductivity and effusivity) and physical (porosity) measurements. The results show that by increasing the porosity of the ceramic floor tiles the thermal conductivity and effusivity decrease so that the heat flow transducers used can be considered an important tool for the evaluation of transient thermal systems.

2. THEORY

2.1. EFFUSIVITY

If two semi infinite solids (A and B), initially in the uniform temperatures T_A and T_B, are put in contact they will achieve the equilibrium. Disregarding the contact resistance it demonstrates that the interface temperature (T_{interf}) will be constant with the time and can be calculated according to equation 1:

$$T_{interf} = \frac{\varepsilon_A T_A + \varepsilon_B T_B}{\varepsilon_A + \varepsilon_B} \qquad (1)$$

where $\varepsilon_{A,B}$ is the thermal effusivity of the A and B bodies defined by equation 2:

$$\varepsilon = \sqrt{\lambda \rho c} \qquad (2)$$

where λ is the thermal conductivity (W/m.K), ρ is the density (kg/m^3) and c is specific heat (J/kg.K).

Thus, the effusivity is a pondering factor which determines if the interface temperature (T_S) will be close to T_A (if $\varepsilon_B > \varepsilon_A$) or to T_B (if $\varepsilon_B < \varepsilon_A$). The ceramic materials (porous or non-porous one) show specific heat values very close (about 1kJ/kg.K). Consequently, the effusivity depends on the thermal conductivity and material's density.

2.2. CORRELATION BETWEEN POROSITY AND THERMAL PROPERTIES OF POROUS CERAMICS

The theoretical model proposed by AIVAZOV and DOMASHNEV[6], correlates well the thermal conductivity of porous ceramics with the porosity according to equation 3:

$$\frac{\lambda}{\lambda_o} = \frac{1-P}{1-nP^2} \qquad (3)$$

where λ is the thermal conductivity of a porous ceramic body, λ_o is the thermal conductivity of a pore-free ceramic body, P is the volume fraction of porous, and n is a constant. SUGAWARA and YOSHIZAWA[7] measured the thermal conductivity of a ceramic tile at 70ºC. According to their measurements n corresponds to 3 and $\lambda_o = 1.65$ W/m.K.

Considering that there is no specific heat exchange with porous inclusions and that the air density can be disregarded in regard to the ceramic matrix density, equation 3 can be written in terms of effusivity (ε) according to equation (4):

$$\frac{\varepsilon}{\varepsilon_o} = \frac{1-P}{\sqrt{1-nP^2}} \quad (4)$$

where ε_o is the effusivity of the continuous phase.

3. MATERIALS AND METHODS

An industrial spray-dried ceramic body (5.9 % humidity) used in the production of single-fired unglazed tiles and natural amorphous silica fibres (ASF) were chosen. The ceramic body was prepared in an industrial plant by wet grinding in a discontinuous ball mill and by spray drying of the resulting deflocculated concentrated aqueous suspension. This represents the normal practice followed in ceramic factories for the preparation of ceramic bodies.

To characterize the ceramic body and the natural amorphous silica fibres (ASF), chemical and energy-dispersive spectrometry (EDS) analysis were performed.

With the aim of verifying the influence of the porosity on the thermal behaviour of ceramic floor tiles the spray-dried ceramic body was compacted at five different pressures ranging from 10 to 30 MPa (typical pressure values used in the tile manufacture) by means of an automatic hydraulic press.

With the same finality, four additional ceramic bodies containing atomized ceramic powders and natural amorphous silica fibres ranging from 10 to 50 wt% were wet homogenized in a ball mill so that the obtained mixtures, after desegregated and humidified ranging from 10 to 14 wt%, were compacted at 30 MPa.

For the measurements, compacted samples with nominal dimensions of 100 x 100 x 10 mm were used.

The compacted samples were then dried at 110°C for 2 h and subsequently fired in a fast-cycle laboratory roll furnace at 1170°C according to a single fast-firing cycle of about 55 min. Apparent (ρ_a) and theoretical (ρ_r) densities of fired samples were measured by the Archimedes principle with mercury immersion at 25°C and by using a helium pycnometer, respectively. In order to determine the porosity (*P*) of the fired samples, equation 5 was applied.

$$P = 1 - \frac{\rho_\alpha}{\rho_r} \quad (5)$$

The morphology and microstructure of the polished and freshly fractured surfaces of amorphous silica fibres and fired samples were studied through the scanning electron microscopy (SEM) technique.

Thermal conductivity was carried out according to ISO 8301[8]. Measurements were performed at 25°C so that the measurement uncertainty was estimated in about 3%.

Effusivity was calculated from the thermal conductivity and density measurements. The specific heat was obtained from the literature.

To evaluate the under surface temperature of a bare foot on a ceramic floor tile surface an apparatus as shown in Figure 1 was assembled. In this case, ceramic floor tile samples were fixed on the base by using a thin layer of a high thermal conductivity paste ($\lambda \approx 10$ W/mK).

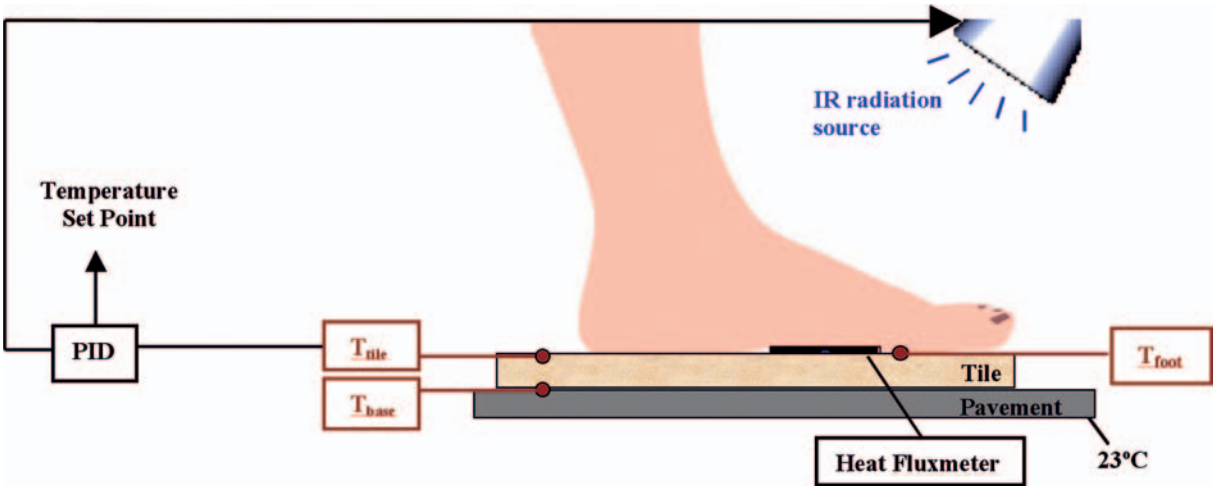

Figure 1. Schematic illustration of the experimental apparatus used in this work.

The base of the floor tile with 20 mm of thickness was kept at 23°C. The ceramic floor tile was initially subjected to an infrared radiation in order to maintain constant its surface temperature (T_{tile}). The temperature measurements were performed by using a T thermocouple (AWG 26) with a PID control system. The thermocouple (T_{foot}) was laminated so that its thickness was about 80 µm. For the heat flow measurements a "tangential gradient" transducer[9], with a thickness of about 300µm, was used. The foot-transducer contact was ensured by using the high thermal conductivity paste; therefore for the transducer-ceramic floor tile contact a 100 µm silicone rubber layer was used. By using this silicone rubber it looked to ensure a contact close to that between a foot and flooring. For tests the floor tile surfaces were heated up to a T temperature and then a foot of a person was positioned on the flooring surface so that each 1 s temperature and heat flow values were registered.

4. RESULTS AND DISCUSSION

Table 1 shows the chemical composition of the ceramic body used in this work. From the Table it can be seen that the constituent oxides are typical of ceramic bodies employed for the manufacture of ceramic floor tiles.

OXIDES	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	TiO_2	MgO	CaO
Wt. (%)	67.35	19.79	2.52	0.15	4.13	0.92	2.00	2.32

Table 1. Chemical composition of the ceramic body used in this work.

The morphology of the natural amorphous silica fibres used in this work is shown in the SEM micrographs of Figures 2 and 3 at low and high magnifications, respectively.

Figure 2. SEM micrograph related to amorphous silica fibres. Magnification: 75 X.

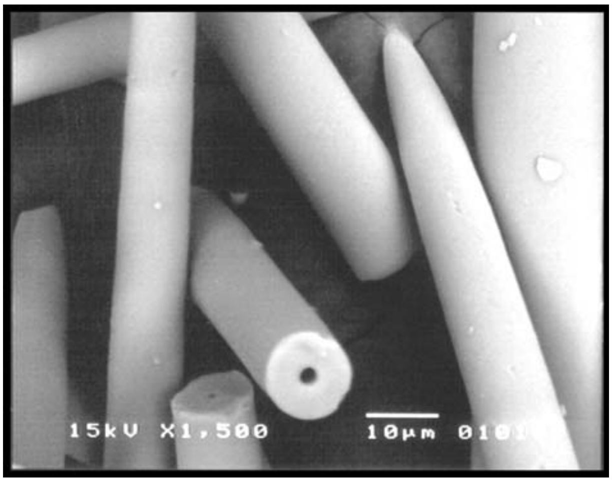

Figure 3. SEM micrograph related to amorphous silica fibres. Magnification: 1500 X

According to the SEM micrographs and the performed measurements the silica fibres are characterized by an acicular shape with a mean diameter of about 10 μm and lengths ranging from 200 to 600 μm. Moreover, the silica fibres are like pipes since they have a central hole with diameters lower than 1 μm. The silica fibres, according to[10-11], show a density of about 1.7 $g.cm^{-3}$ and colours ranging from white to light brown. In this work, over the porosity produced by the application of different compaction pressures, the silica fibres are the natural porous formers. These natural silica fibres are mineral bodies from geological deposits found in Brazil which are resulting from biogenetic precipitations accomplished by sweet water sponges. In Brazil the Indians already used mixtures of clay and natural silica fibres for the production of bricks[10]. The fibres found in nature are not pure since they have small quantities of alumina, iron and alkali metals, some organic matter and sand residues as well as clays. Consequently, for some engineering applications the silica fibres must be benefited to remove impurities. In fact, the fibre used in this work, according to EDS analysis is constituted just by silica.

SEM micrographs related to a ceramic sample with 10 wt-% amorphous silica fibres incorporation are shown in Figures 4 and 5 at low and high magnifications, respectively.

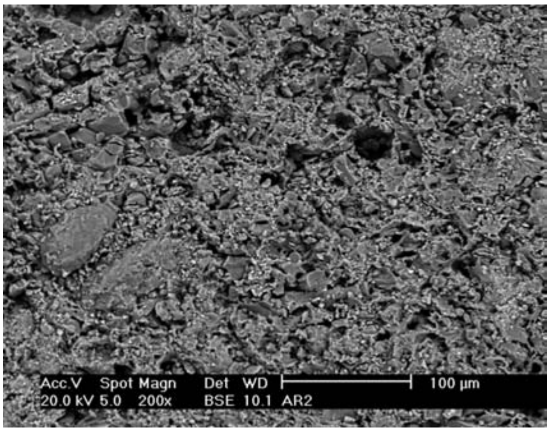

Figure 4. SEM micrograph related to a ceramic sample with 10 wt% amorphous silica fibres incorporated. Magnification: 200 X.

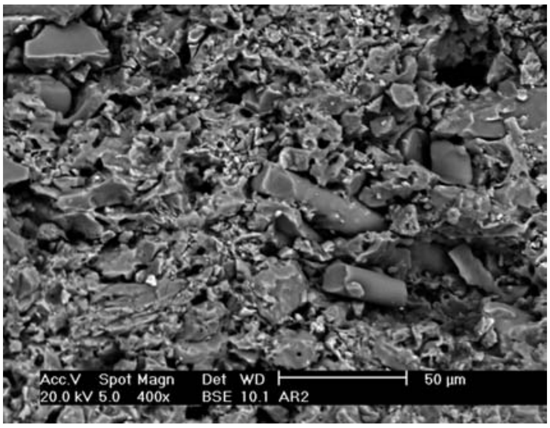

Figure 5. SEM micrograph related to a ceramic sample with 10 wt% amorphous silica fibres incorporated. Magnification: 400 X.

From carefully observation of the micrographs, in particular that one at higher magnification, it can be seen that over the normal porosity usually observed in typical ceramic floor tiles there is also porosity provided by the silica fibres holes. Moreover, is expected that the silica fibres, considering its intrinsic properties, actuate as a reinforcing second phase improving mechanical strength and dimensional stability.

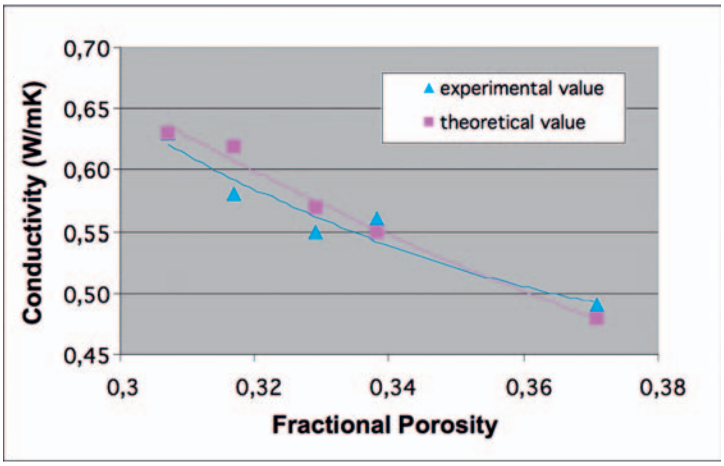

Figure 6. Measured and theoretical thermal conductivities as a function of porosity (compaction pressure ranging from 30 to 10 MPa) for samples without silica fibres.

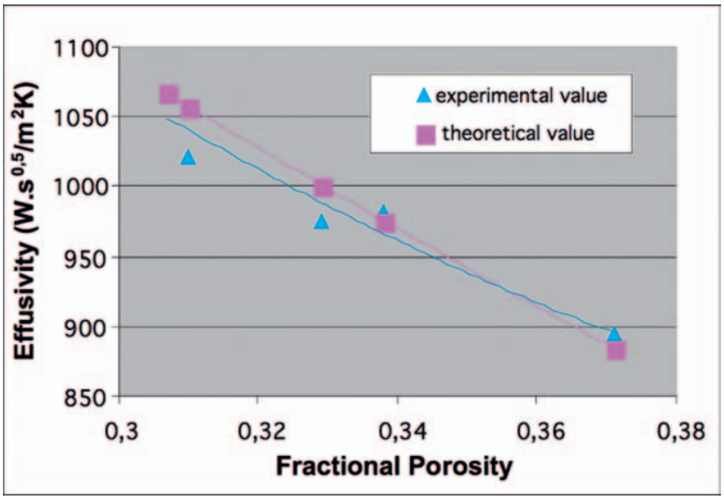

Figure 7. Measured and theoretical thermal effusivities as a function of porosity (compaction pressure ranging from 30 to 10 MPa) for samples without silica fibres.

Figures 6 and 7 show the porosity effect on the thermal conductivity and effusivity, respectively for ceramic bodies compacted at different pressures.

It can be seen from the figures that the thermal conductivity and effusivity are dependent on porosity, i.e. they decrease as the porosity increases by changing the compaction pressure from 30 to 10 MPa. Comparing the experimentally obtained results with the theoretical models proposed by AIVAZOV and DOMASHNEV[6] for thermal conductivity and SUGAWARA and YOSHIZAWA[7] for thermal effusivity, according to equation 3 and 4, it can verify a good correlation in the porosity interval studied for $n = 8$ and $\lambda_o = 1.6$ W/m.K.

Figures 8 and 9 show the porosity effect on the thermal conductivity and effusivity, respectively for ceramic bodies with silica fibres incorporation and compacted at 30 MPa. It can be seen from the figures that the thermal conductivity and effusivity are dependent on porosity, i.e. they decrease as the porosity increases by changing the silica fibre contents from 0 to 40 wt%. Since silica fibre content is not constant λ_o was pondered but maintaining n=14. Even so, the experimental results, in this case, are not well correlated with the theoretical models since they do not consider the ceramic materials as composites.

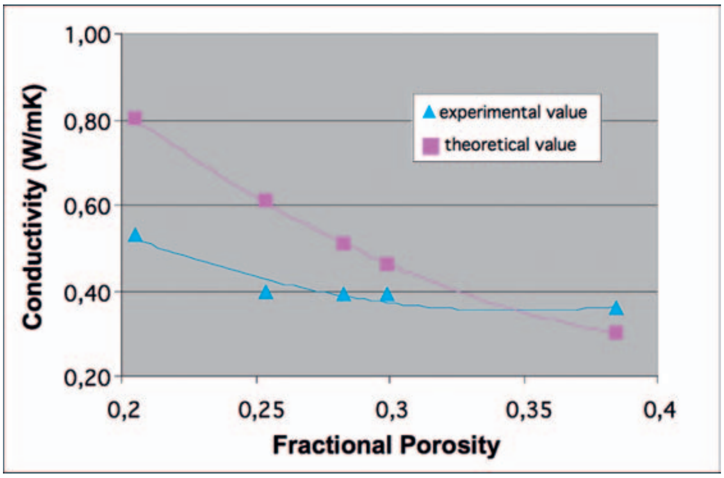

Figure 8. Measured and theoretical thermal conductivities as a function of porosity (silica fibre contents ranging from 0 to 40wt%) for samples compacted at 30 MPa.

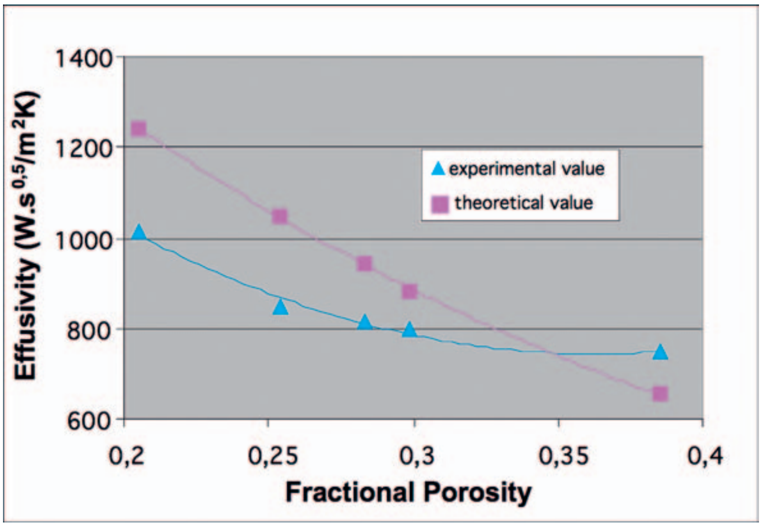

Figure 9. Measured and theoretical thermal effusivities as a function of porosity (silica fibre contents ranging from 0 to 40wt%) for samples compacted at 30 MPa.

According to the apparatus as shown in Figure 1, which allows to evaluated the discomfort level of a person walking with bare feet on a heated floor, two ceramic floor tiles both compacted at 30 MPa but without silica fibres incorporation (sample M) and with 40 wt-% of silica fibres incorporation (sample MS40) were tested at 60°C (surface temperature) during 15 minutes. Locating a person bare foot on the heated floor surface the temperature under the foot surface (T_{foot}) and heat flow were registered as shown in Figure 10. From the figure it can be seen that in the contact instant (time=0) the temperature under the foot surface was increased and then decreasing progressively due to the shadowing of the incident radiation. As expected the flooring assembled with ceramic floor tiles MS40 (40 wt-% silica fibres and with porosity=39%) achieved a temperature of about 4°C lower that one achieved by the ceramic floor tile M (without silica fibres and with porosity=21%). Even so, a small improvement in the comfort level by contact was obtained. Moreover, it can be observed from Figure 10 the measured heat flows during the foot-flooring contact. In the contact instant the heat flow achieves a maximum and then decreasing asymptotically during the test. As expected the heat exchanges between foot and flooring are lower for the flooring with higher porosity.

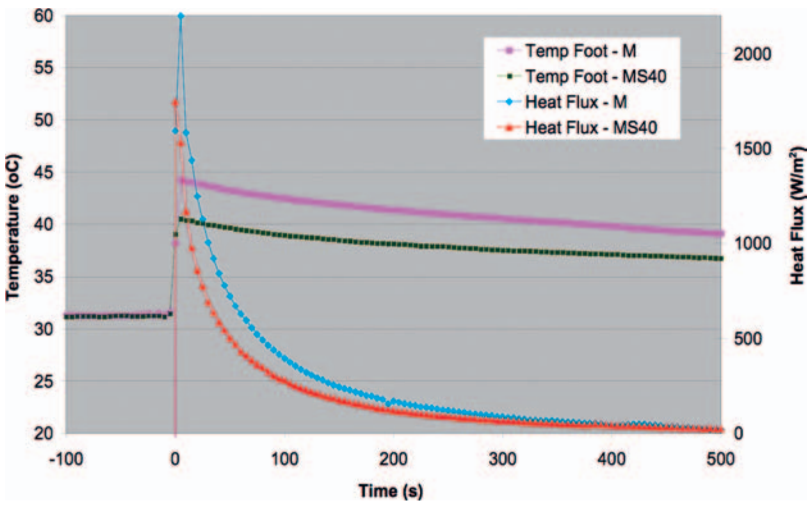

Figure 10. Relationship between temperature and time during barefoot-flooring contact.

Considering the foot and the flooring as semi-infinite solids, it can determine the interface temperature by equation 1. The foot can be considered as having thermal conductivity=0,37 W/mK, density=1000 Kg/m^3 and specific heat=1000 J/kgK so that the resulting thermal effusivity is 600 $Ws^{0,5}/m^2K$[12].

Table 2 shows a relationship between the measured temperature under the foot surface and the interface theoretical temperature.

CERAMIC TILE SAMPLE	T_{tile} (°C)	$T_{initial\ foot}$ (°C)	ε_{tile} ($Ws^{0,5}/m^2K$)	$T_{max\ foot}$ (°C)	T_{interf} (°C)
M (WITHOUT ASF)	60	31.5	1015	44.2	49.3
MS40 (40 wt-% ASF)	60	31.5	750	40.5	47.2

Table 2. Relationship between the measured temperatures under the foot surface and the interface theoretical temperature.

It can verify a significant difference between the experimental and theoretical values. Among the possible causes it can mention the uncertainty value of the foot thermal properties, the contact resistance foot-flooring and the semi infinite solid model.

5. CONCLUSIONS

By changing the compaction pressure and the amorphous silica fibres content it is possible to obtain porous ceramic floor tiles.

The thermal conductivity and effusivity are dependent on porosity, i.e. they decrease as the porosity increases by changing the compaction pressure from 30 to 10 MPa.

Comparing the experimentally obtained results with the theoretical models proposed by AIVAZOV and DOMASHNEV (1975) for thermal conductivity and SUGAWARA and YOSHIZAWA[7] for thermal effusivity, according to equations (3) and (4), good correlation ca be verified in the porosity interval studied for $n = 8$ and $\lambda_o = 1.6$ W/m.K.

The thermal conductivity and effusivity of ceramic bodies incorporated with amorphous silica fibres are also dependent on porosity but the experimental results, in this case, are not well correlated with the theoretical models since they does not consider the ceramic materials as composites.

The heat flow transducers used in this work can be considered an important tool for the evaluation of the thermal comfort in transient thermal systems.

6. ACKNOWLEDGEMENTS

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