FACTORS DETERMINING THE THERMAL SENSATION OF CERAMIC TILES

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ABSTRACT

The use of floors with a warm thermal sensation increases comfort and contributes to energy savings. Ceramic materials have a cooler feel than other materials, which is a disadvantage in some markets.

The thermal sensation depends on both physiological and physical aspects, so it is necessary to take both into account for its optimisation.

On the one hand, thermal sensation depends on the position and sensitivity of thermoreceptors located in the human skin. These receptors are not precise temperature sensors; however, they are very sensitive to changes in temperature and the comparison of signals between them. The thermal sensitivity of the skin depends on body part, age, gender, race, habits, etc., although cold sensation can be parameterised by considering the sensors at a depth of 0.5-1 mm and an excitation threshold of 20 °C.

On the other hand, when two materials are placed in contact, a non-stationary heat flow is produced across the interface from the hotter to the colder one. This flow depends on the thermal inertia of both materials and, more precisely, on their effusivities. The effusivity (ε) of a material, which depends on its thermal conductivity (k), its density (ρ) and its specific heat (c), determines the interface temperature.

In a real contact of two objects, the thermal contact resistance and, as a result, an effective effusivity must also be taken into account.

In the present work, the effect of surface roughness on the effective effusivity has been tested. The surface roughness of the tiles generates an air layer that limits heat transfer and significantly reduces effusivity. It has been found that the higher the roughness, the greater the reduction in effective effusivity.

1. INTRODUCTION

Ceramic tiles have exceptional mechanical and chemical resistance and can be easily decorated, making them the best choice for many applications. However, their thermal properties, related to comfort or energy efficiency, cannot be compared to other materials of organic nature.

The thermal sensation produced by touching an object with the skin is a complex perception that depends on the combined information sent to the brain by thermoreceptors located in the dermis [1]. These thermoreceptors are Krauss' corpuscles, Ruffini's endings and free nerve endings. Krauss corpuscles are primarily responsible for the sensation of cold, although their sensitivity above 20 °C is low. The thickness of the skin varies significantly from one part of the body to another and with numerous physiological factors (gender, race, age, ...). Krauss corpuscles are located immediately below the epidermis, so their approximate distance to the surface can be considered to be 0.5-1 mm.

When the skin is in contact with an object (ceramic tile) heat (q") is transferred across the interface by conduction (Figure 1).

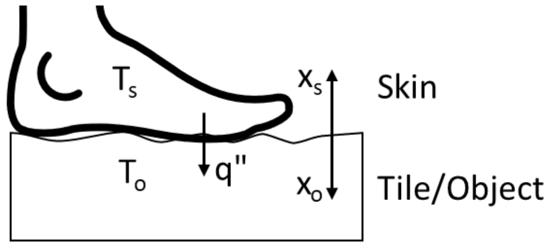

Figure 1. *Heat transfer process scheme between the sole and the tile.*

Assuming that both materials have semi-infinite dimensions [2], the equations governing the process are:

Skin: $\frac{d^2\,T_s}{dx_s^2} = \frac{1}{\alpha_s} \cdot \frac{dT_s}{dt} \quad where\!: T_s = T_{si} \;@\; t = 0;\; T_s = T_{si} \;@\; x_s = \infty$ (eq.1.a)

Object: $\frac{d^2\,T_o}{dx_o^2} = \frac{1}{\alpha_o} \cdot \frac{dT_o}{dt} \quad where\!: T_o = T_{oi} \;@\; t = 0;\; T_o = T_{oi} \;@\; x_o = \infty.$ (eq.1.b)

Where the thermal diffusivity is included (α) and the subscripts refer to the skin (s), the object (o) and the initial conditions (i).

According to the boundary conditions of the system, at the skin-object interface the heat flux (q") must be constant. This can be calculated from the quotient of the temperature difference of the two surfaces (T_{ss}-T_{os}) and the resistance to heat flow (R).

The surface temperature on the skin can be calculated by integration of the above equations, resulting in the following exponential equation:

$$T_{ss}(t) = \frac{A}{B} \cdot \{1 - \exp\,(\alpha_s B^2 t) \cdot erfc[B \cdot (\alpha_s t)^{0.5}]\} \quad \text{(eq.2)}$$

where: $A = -\frac{-(T_{si} - T_{oi})}{k_s R}$ y $B = \frac{1}{k_s R}\left[1 + \frac{(k_s \rho_s c_s)^{0.5}}{(k_o \rho_o c_o)^{0.5}}\right] = \frac{1}{k_s R}\left[1 + \frac{(\epsilon_s)^{0.5}}{(\epsilon_o)^{0.5}}\right]$

Where the properties of the two materials are used: thermal conductivity (k), density (ρ) and specific heat (c), and their effusivity (ε).

The temperature profile within the skin and the object (ceramic tile) can also be calculated from the integrated equations developed by Congyan [3].

Effusivity indicates the ability of a material to exchange thermal energy with its surroundings. It is not strictly a property of the material but appears as a parameter in the integration of the heat equations when two substances are brought into contact. Physically, it determines the temperature of the interface between the two materials when there is no contact resistance:

$$T = \frac{\epsilon_S T_S + \epsilon_O T_O}{\epsilon_S + \epsilon_O} \quad \text{(eq.3)}$$

According to this equation, the temperature at the interface will be closer to that of the material with the highest effusivity, so to improve the thermal sensation it is desirable that the tile should have the lowest possible effusivity.

Table 1 shows the main thermal properties of common materials [4]. Ceramic materials have a much lower effusivity than that of metals, but higher than that of wood and other organic compounds. Also included are the thermal properties of skin and a standard ceramic tile with which the thermal calculations have been made.

	Thermal Conductivity (W/m·K)	Thermal Diffusivity (mm^2/s)	Specific Heat Capacity (J/kg·K)	Thermal Effusivity ($W \cdot s^{0.5}/m^2 \cdot K$)
Air	0.025	19.4	1004	6
Water	0.607	0.145	4181	231
Hardwood	0.16	0.18	1255	380
Glass	1.046	0.54	837	1419
Porcelain	2.092	0.82	753	2314
Iron	72	20.4	448	15924
Skin	0.34	0.085	3340	1167
Ceramic Tile	1.046	0.48	837	1509

***Table 1**. Thermal properties*

The effusivity of air is very low, so the modification of this property in any material is based on the incorporation of air. The air can be located within the material, leading to porous materials, or at the surface, leading to rough materials.

The existence of pores in ceramic glazes is problematic [5] as it affects mechanical properties and appearance. Some researchers have achieved good results by generating them at high temperature [6] and anchoring the bubbles to prevent them from reaching the surface; however, their robustness under industrial firing conditions is not high enough, as it reduces the overall quality of the product.

The manufacture of rough materials with reduced effusivity has not been studied in the literature. However, there are references on how roughness affects heat transfer due to its influence on contact resistance. Chen [3] found a direct relationship between contact resistance (R) and root mean square roughness. Zhang et al [7] also experimentally showed the influence of mean arithmetic roughness on contact resistance, although they did not develop an empirical model for its estimation.

The aim of this work is to show the influence of the surface topography of ceramic tiles on their apparent effusivity and, as a result, on the thermal sensation transmitted when they are touched.

2. EXPERIMENTAL

2.1. MATERIALS

A set of 14 industrial ceramic tiles with a very wide range of characteristics were selected. Porcelain stoneware and porous earthenware substrates were used, as well as glossy, matt, crystalline and opaque glazes. Of this set of samples, the most relevant, due to the level of roughness and the procedure used to obtain them, are the following:

- Press relief (Sample 4)
- Glazing line relief (hydrophobing) (Sample 6)
- Matt glaze (Sample 3)
- Polished glaze (Sample 5)

2.2. TECHNICS

The surface topography of the samples was measured by means of an Olympus confocal microscope, using a 5x objective. In order to obtain a study surface representative of the surface roughness, the analysis area was enlarged using the stitching technique, allowing relatively large areas to be studied. All the roughness parameters used were calculated from the area data using the usual formulae.

Figure 2 shows the topographies of the four most relevant samples. The colour code, representative of the height, has been adapted to the topography of each sample.

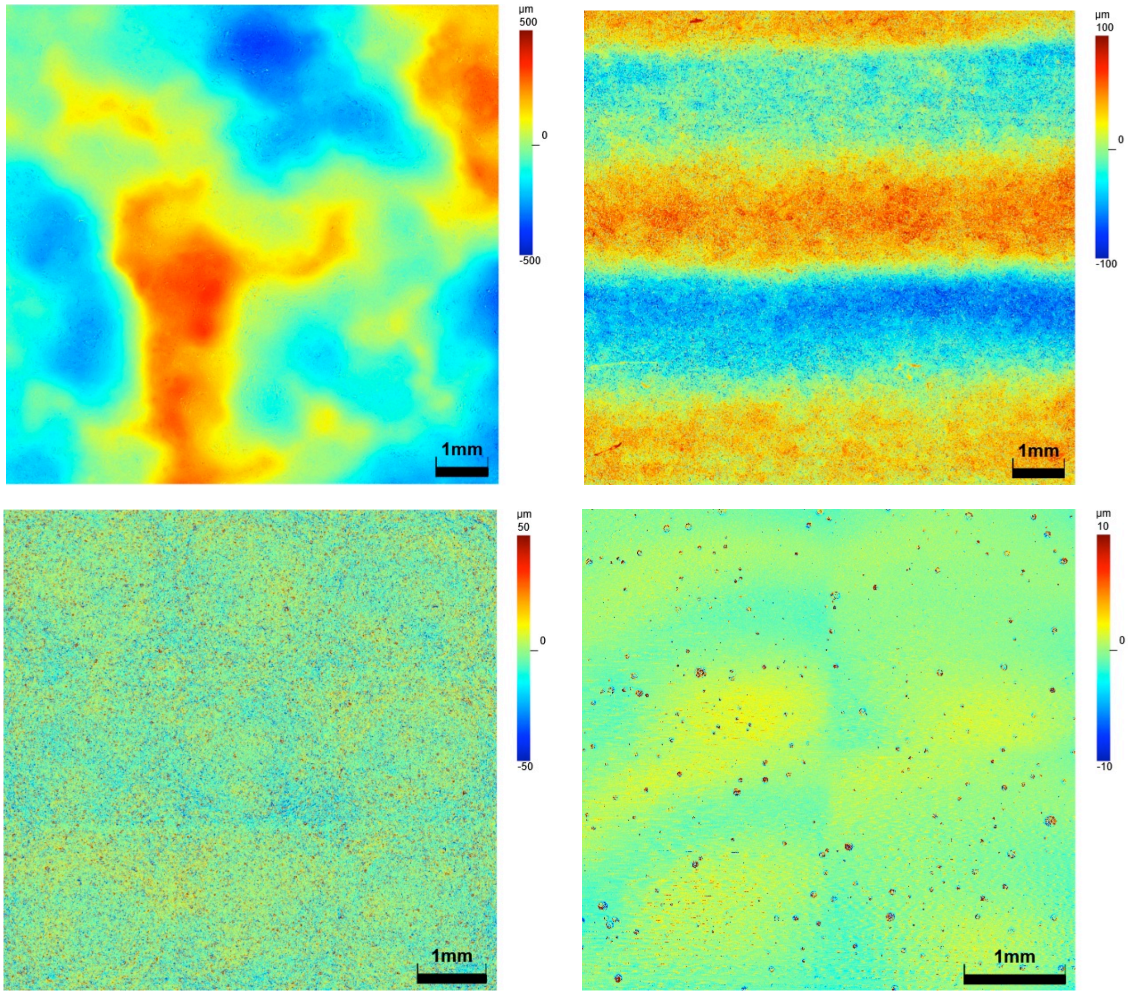

Figure 2. *Topographies of samples 4 (top left, press relief, ±500µm), 6 (top right, glaze line relief, ±100µm), 3 (bottom left, matt glaze, ±50µm) and 5 (bottom right, polished glaze, ±10µm).*

The average thickness of the air layer retained between the tile and the object in contact with its surface has been calculated from the material curve (Figure 3). This curve indicates the volume fraction of material between the highest peak and the deepest valley. The elimination of the volume fractions corresponding to the peaks and valleys makes it possible to analyse the main volume in which most of the roughness develops.

Different parameters can be obtained from the material curve, although the most useful one has been found to be the Core void volume (V_{vc}), as it reflects the average thickness of air at the surface retained as a result of the roughness.

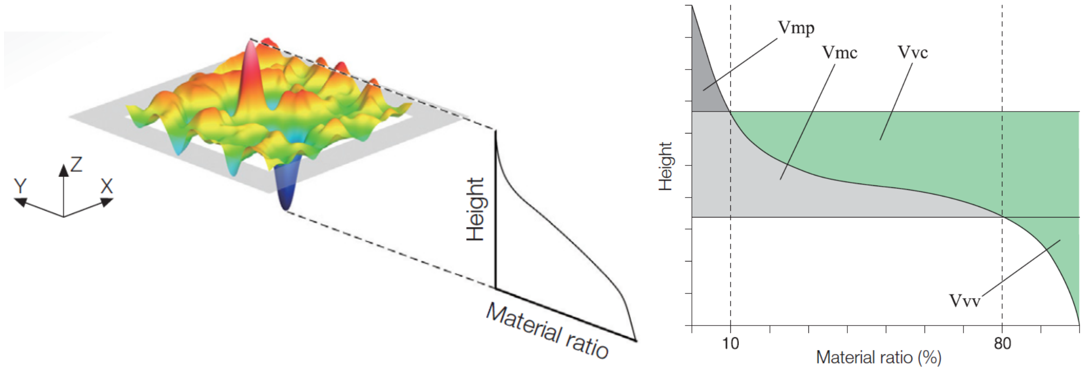

***Figure 3**. Calculation of the material curve from the topographic data (left). Calculation of the Core void volume (Vvc) from the material curve (right).*

The measurement of thermal effusivity was done by The Modified Transient Plane Source (MTPS) Method (ASTM D7984-16) [8][9]. It is an enhancement of the Transient Plane Source Method that requires only a single-sided interface with the sample during the measurement of thermal properties. In this method, a known heat flux is generated by a resistor and the temperature evolution of the material is measured. In other words, by using the boundary condition (known q"), the equation of one of the two materials is eliminated.

There are several devices on the market that use this technique [10][11]. In the present work, the C-Therm with the ESP measuring cell was used. The maximum effusivity measurement range of this device is 5-40000 $W \cdot s^{0.5}/m^2 \cdot K$.

The measurements of the thermal effusivity of the material were made using water as the contact material between the tile and the sensor membrane, so that the thermal contact resistance can be assumed to be negligible.

The apparent or effective effusivity measurements were made without using any contact material, so the material at the interface was air.

The effect of topography on the effusivity was evaluated from the difference and relative change between the material effusivity and the apparent effusivity.

3. RESULTS

The skin-tile interface temperature can be calculated by equation 3, valid for any time, provided that the thermal contact resistance is zero. Taking into account the effusivity data of the skin and of a standard ceramic tile (Table 1), that the temperature of the human sole is about 30 ºC and assuming that the ceramic tile is initially at about 10 ºC, the temperature of both surfaces would be 18.7 ºC. This result does not reflect the real behaviour of the system, as it does not take into account the contact thermal resistance, which is always present, nor the location of the cold thermoreceptors, located at a depth of 0.5-1 mm and with an approximate sensitivity threshold of 20 ºC.

When the contact thermal resistance at the interface is taken into account and the temperature profile inside the skin is calculated, the result changes considerably (Figure 4).

On the one hand, the temperatures of the two surfaces, corresponding to the skin and the tile, are time-dependent and are no longer equal. This temperature gap will be greater the higher the thermal contact resistance. On the other hand, the temperature in the inner layers of the skin (0.5-1 mm), where the sensors are located, is higher than at the surface due to the delay in the thermal response of the system. This delay is all the greater the higher the contact resistance, due to its influence on the heat flow.

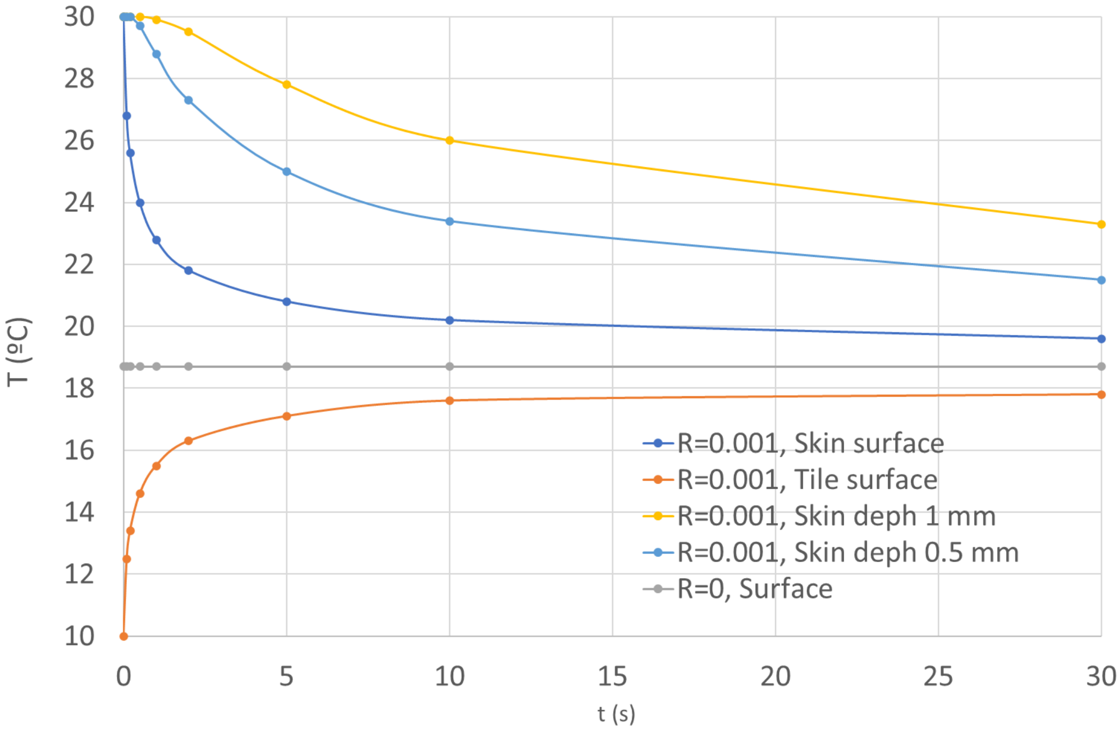

Figure 4. *Simulation of tile and skin thermal behaviour. R in m^2K/W units.*

Therefore, the study of the thermal behaviour of the system requires the consideration of the thermal contact resistance. However, this parameter is not easy to measure directly, as it would require a complicated experimental device [2], so in this work we have measured it indirectly.

Although there is always a contact resistance, the effusivity obtained using water at the interface has been considered to be representative of the material, regardless of its surface topography. This would be the circumstance that could occur in a bath with wet feet. The values obtained for the set of samples vary between 1280 and 1766 $W{\cdot}s^{0.5}/m^2{\cdot}K$ (Figure 5. left), in agreement with the existing data in the literature for ceramic materials. It is worth highlighting the behaviour of samples 1-3, which correspond to porous wall tiles, where the porosity of the substrate has reduced the experimental effusivity. If the interface temperature is calculated under these conditions (equation 3), temperatures below 20 ºC are always obtained, which would activate the Krauss corpuscles and lead to the sensation of cold (Figure 5. right).

When measuring effective effusivities, without contact material, lower apparent effusivities are always obtained. This difference is due to the influence of the contact resistance on the measurement of effective effusivity. This would be the case when walking barefoot on a dry surface. It is possible to estimate the effective surface temperature by using the effective effusivity in equation 3, as this implicitly includes the effect of contact resistance (Figure 5.b). Unsurprisingly, the contact temperature increases and, in some cases, exceeds 20 °C, so the possible cold sensation would be moderate.

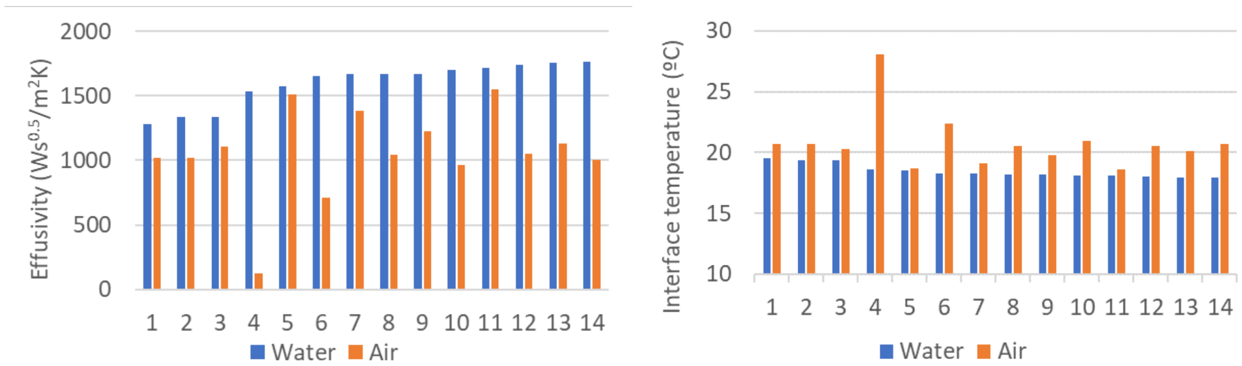

Figure 5. *Actual and effective effusivity of the sample set used (left). Contact temperatures (right).*

Although contact thermal resistance influences apparent effusivity, there are no studies that relate them, so it is not known what kind of dependence exists. Using the material effusivity and the average interface temperature that would be obtained with the apparent effusivity, the theoretical resistance required to obtain the same behaviour was calculated. The calculations were made with the integrated equations developed by Chen [3].

The contact thermal resistances obtained by this indirect procedure are 0.0006-0.046 m^2K/W, in line with values obtained by other researchers using direct methods (Figure 6). The resistances obtained are higher the larger the relative change in effusivity, varying according to a power law equation. For intermediate values the correlation is acceptable; however, extreme values deviate from this trend. As a result, it is feasible to estimate the thermal contact resistance from the effusivities obtained with and without a contact agent.

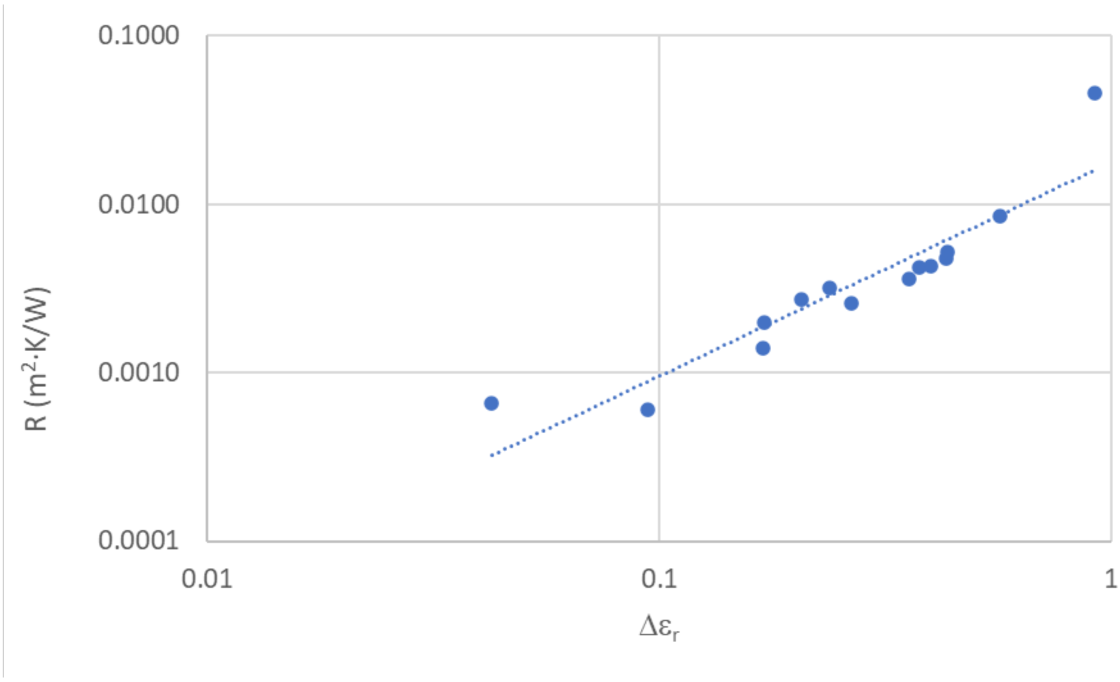

Figure 6. *Correlation between thermal contact resistance and relative effusivity variation ($R=0.0178 \cdot \Delta\varepsilon_r^{1.27}$, $r^2=0.8$)*

Other conditions kept constant, the thermal contact resistance is usually related to the average roughness by means of a linear equation with a positive slope, so that the higher the roughness, the higher the resistance. In the set of samples studied, the indicated trend was verified, although due to the wide range of roughness used, the correlation is low. The calculation of the average roughness does not distinguish between surfaces with many or few voids, so it can only be used when the morphology of the peaks/valleys is the same. In the set of samples studied, the surface morphologies have been very different so this parameter could not work.

It was found that, over the whole range studied, the parameter that best relates to the relative change in effusivity is the average thickness of air retained at the surface (Figure 7). This thickness is calculated from the material curves obtained from the topography of the samples. This correlation is valid for very smooth surfaces, such as polished (±10µm) or matt (±50µm) glazes, as well as for glaze line reliefs (±100µm) or press reliefs (±500µm).

Air has a very low effusivity, so the higher the retained air layer, the lower the effusivity. The first layers of air have a very important relative effect (20%), and can reach, with very pronounced roughness, reductions of 40% and 90%.

The calculation of average values of the thermal properties in this surface layer is highly dependent on the microstructure formed by the material and the air (parallel layers, pillars, ...), so its estimation has not been considered relevant from a practical approach.

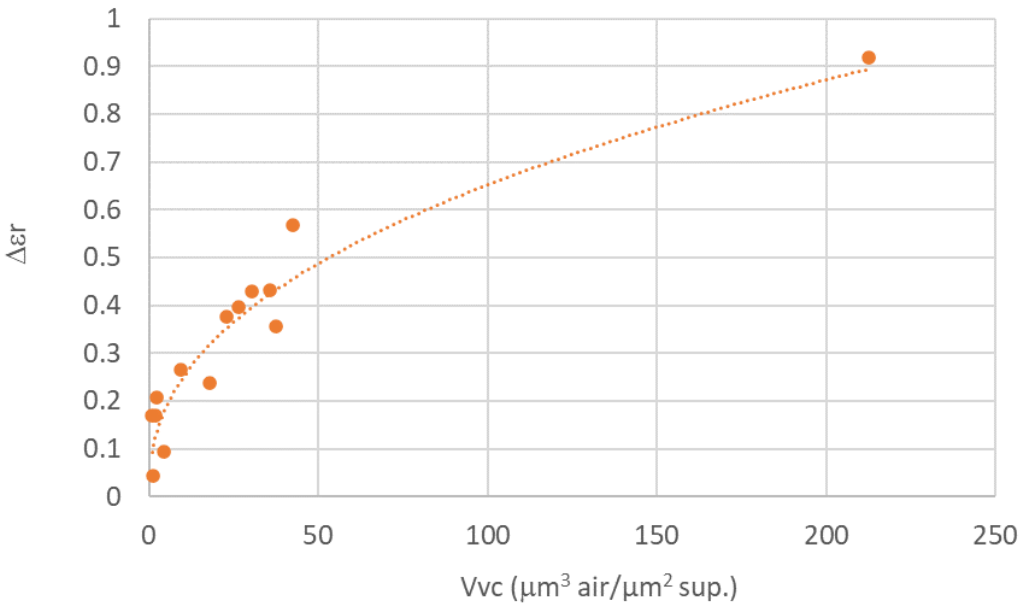

Figure 7. *Influence of the average thickness of trapped air on the relative change in effusivity ($\Delta\varepsilon_r = 0.0947 \cdot V_{vc}^{0.419}$, $r^2 = 0.92$)*

4. CONCLUSIONS

The thermal sensation we feel when we step on a ceramic tile depends mainly on its effusivity.

The effusivity of ceramic materials varies within narrow limits, so the main way to reduce its value is to incorporate air into the system. Air retention on the surface of dry tiles has been found to be a very effective mechanism for reducing the effective effusivity of ceramic tiles due to its direct effect on the contact thermal resistance.

Although there are techniques available to develop different levels of roughness (crystallisations, repellence or pressing) their optimisation requires the simultaneous consideration of other properties, such as slip resistance, wear or ease of cleaning in the intended use.

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