THEORETICAL ANALYSIS ON THE THERMAL STRESSES OF CERAMIC TILE COATING SYSTEMS
Thermal stresses on ceramic tile coating

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Abstract

The stresses on ceramic tile coating systems, subjected to temperature increase, were estimated by a 2-D finite element linear analysis. Physical and mechanical properties of the materials involved (ceramic tile, adhesive mortar, rendering mortar and grout) were determined experimentally and were used as model input. The numerical analysis has shown that peak stresses occur in the centre of the grout and decrease to nearly zero at the centre of the tile. The model is very sensitive to the tile Coefficient of Thermal Expansion and Young modulus and insensitive to the same parameters at the mortar layer.

Keywords: ceramic tile coating, finite element analysis, thermal stresses

1 Introduction

In spite of great development within the ceramic industry, problems related to ceramic tile detachment on buildings are very common at earlier ages or after a long period of adequate performance.

Since earlier ages, each layer of ceramic tile coating system (substrate, rendering, grout, adhesive mortar and ceramic tile) suffers differential volumetric changes due to factors inherent in the materials (drying shrinkage of mortar, moisture expansion of ceramic tile) or external factors (changes in temperature and/or humidity). Since free deformation of each layer is limited by the bond between them, stresses will likely occur.
Ceramic tiles are subject to temperature and humidity changes, especially on flat roofs and façades. The response of the materials to such variations appears in the form of differential volumetric changes between each layer of the system, causing stresses, which vary according to the magnitude of changes. As the properties of the materials are different, the stresses may be of important intensity. According to Billi et al. (1995), the coefficient of thermal expansion (CTE) of ceramic tiles varies from 6 to 7 x 10^-6/ºC. This value is two times lower than cement-based materials (CTE around 15 x 10^-6/ºC according to Illston, 1994) in the form of rendering, adhesive and grout mortars. This difference can result in serious problems, especially in places and regions where great and rapid temperature changes may occur. Large falls of temperature may also produce stresses high enough to detach ceramic tiles after a long period of adequate performance.

It is possible to estimate the stresses on the various layers of a ceramic tile coating system subjected to temperature changes, by numerical modeling of it (Bowman and Banks, 1995). It is also possible to ascertain the influence of materials properties on the stress development.

In this paper, a 2-D finite element, linear elastic analysis was developed with the purpose to estimate the stresses. Experimental tests were performed to obtain data for the model, such as temperature variation through the system layers and physical and mechanical properties of the materials. Values obtained by other researchers were applied when there was no possibility to perform tests.

2 Experimental procedure

2.1 Materials characterization

Ceramic tile, adhesive mortar, rendering mortar and grout were studied to obtain values for model input. The ceramic tile used is called gres, obtained from powder pressing and two burning times, resulting in a high-performance material. Three adhesive mortars with different proportions of the polymer, methyl-hydroxyethyl-cellulose (MHEC), were studied. Table 1 shows the proportion mix of these mortars.

<table>
<thead>
<tr>
<th>Table 1: Proportion of materials in adhesive mortars (weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>RM*</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
</tbody>
</table>

* RM = reference mortar (without polymer)
** the weight of MHEC was not considered

Rendering mortar consisted of a mix of Portland cement, medium sand and hydrated lime, in proportions of 1:1:6 by volume (cement:lime:sand) and water/cement ratio of 1.76 (Mohamad, 1998). Grout mortar, used to fill the joints between each
ceramic tile, contained Portland cement, fine sand, and MHEC polymer. The proportions used were 1:3:0.002 (by weight).

The coefficients of thermal expansion (CTE) of the materials described above were determined, using Netzsch Model 202 and Shimadzu Model 50H Thermomechanicals Analysers (TMA). Young's modulus and Poisson's ratio of the materials were also determined. The mortars were tested in compression according to NBR 8522/84 (Brazilian Standard for Young's modulus determination). The specimens of ceramic tile were cut in dimensions of 35 x 35 x 8 mm, and were also tested in compression. Table 2 shows the CTE, Young's modulus and Poisson's ratio obtained for each material.

Table 2: Average Coefficient of Thermal Expansion, Young's modulus and Poisson's ratio for mortars and ceramic tile

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE (°C⁻¹)</th>
<th>Young's modulus (MPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic tile</td>
<td>4.6 x 10⁻⁶</td>
<td>38779</td>
<td>0.10*</td>
</tr>
<tr>
<td>Grout mortar</td>
<td>10.0 x 10⁻⁶</td>
<td>12265</td>
<td>0.18</td>
</tr>
<tr>
<td>Adhesive mortar RM</td>
<td>22790</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Adhesive mortar M1</td>
<td>10.0 x 10⁻⁶</td>
<td>20739</td>
<td>0.18</td>
</tr>
<tr>
<td>Adhesive mortar M2</td>
<td>10745</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Rendering mortar</td>
<td>9.6 x 10⁻⁶</td>
<td>5918**</td>
<td>0.17**</td>
</tr>
<tr>
<td>Substrate</td>
<td>6.5 x 10⁻⁶</td>
<td>20000</td>
<td>0.07</td>
</tr>
<tr>
<td>Mortar</td>
<td>9.6 x 10⁻⁶</td>
<td>8000</td>
<td>0.17</td>
</tr>
</tbody>
</table>

* estimated

** after Mohamad, 1998

2.2 Temperature profile

In order to estimate the temperature variation in ceramic tile coating systems, a laboratory test was performed on a small system specimen, as shown in Figure 1. The ceramic tile glazing was heated from 23°C (ambient temperature) to 70°C by contact with a copper plate attached to a coil with flowing hot water. Thermocouples installed at layer interfaces monitored the varying temperature profile in the system for 4 hours.

![Fig. 1: Laboratory specimen and thermocouple positions.](image-url)
Figure 2 shows the evolving thermal profile for the first 1.5 hours. These values were also used as input to the model.

![Temperature profile graph](image)

**Fig. 2: Temperature profile in specimen**

3 Finite element model

3.1 Stresses due to thermal variation

To predict the thermal stresses on the rendering/adhesive mortar/ceramic tile interfaces, a 2-D finite element analysis was performed adopting a four-node plane element. The rectangular element shape suits the regular pattern of the tiling system. The model was considered isotropic and under plain strain.

The tiling system was modeled as a five-layer system (tile / adhesive / rendering / substrate / rendering) deforming linearly under a thermal loading. A full adhesive coverage was assumed. A panel, composed by 13 ceramic tiles (200-mm square) laid side by side on a ceramic block substrate, was analyzed. Taking advantage of the symmetry in the width direction, only half of the system was analyzed, with appropriate symmetry-boundary conditions. The boundary conditions adopted for this study were that the system was laterally fixed. The geometry used by the model is shown in Figure 3.

![Finite element model diagram](image)

Legend:
- a, c - rendering
- b - clay block
- d - adhesive mortar
- e - ceramic tile
- f - grout mortar
The tile surface was heated at 70 °C. After approximately six minutes of heating, there was a temperature profile through the system from 68 °C, on the tile surface, to 23 °C (the initial temperature) at the outer layer. As can be seen in Figure 2, this is the highest thermal gradient observed. Since it leads to the most critical situation, regarding stresses, the temperature profile (figure 2) obtained on this time was chosen to model the system. A linear temperature profile within each layer and a steady state were assumed.

To verify the model reliability, it was first considered homogeneous and isotropic. The tile mechanical properties presented on Table 2 were used to run this model. Since the system was free to expand in the y direction, the application of the thermal load did not produce stress in this direction. Therefore, a bi-axial state of stress was established, due to the boundary and the plain strain conditions. These stresses were expected to be equal and constant along an isothermal line. The stresses were compared to that obtained analytically by using the following equation (Timoshenko and Goodier, 1970):

$$
\sigma_x = \sigma_z = \frac{E\alpha \Delta T}{(1-\nu)}
$$

Where: - $\sigma_x$ and $\sigma_z$ are normal tensile stresses in the x and z direction respectively;
- E is Young’s modulus;
- $\alpha$ is the Coefficient of Thermal Expansion;
- $\Delta T$ is the temperature differential;
- $\nu$ is Poisson's Ratio.

The heterogeneous system was then run to generate numerically the shear and tensile stresses. The material properties adopted to run the model are those from Table 2.

The shear and normal stresses ($S_y$) on the tile/adhesive mortar and adhesive mortar/rendering interfaces can be seen in Figure 4 and Figure 5. As can be seen, the stresses are nearly zero in the center of the tile and increase near the tile/grout interface. Close to the tile/grout interface, a region of concentrated stresses appears, whose signature depends very much on the material properties. At the tile/grout junction there is a change in the sign of the stresses which may be credited to the difference in the coefficient of thermal expansion of the materials. Young's modulus of the grout was three times smaller than that of the tile, allowing better deformation capacity for the grout. This movement differential may be considered as the main reason for the observed stress concentration. On the other hand, the adhesive is not thick enough to dissipate the stresses discontinuity observed at the tile/adhesive interface and, due to this factor, a discontinuity was also observed along the adhesive/rendering interface. Tensile stresses (negative sign) may cause the detachment
of the tile.

Fig. 4: Shear and normal stresses between centers of adjacent tiles, at the tile/adhesive mortar interface

Fig. 5: Stresses of adhesive mortar/rendering interface

3.2 Sensitivity analysis

The sensitivity of the tiling coating system to the variation of Young's modulus and Thermal Expansion Coefficient of the tile and adhesive was investigated by calculating shear and normal (Sy) stresses. The variables were changed one at a time, according to the values shown in Table 3. In order to perform this analysis, only the interfaces of the tile located at the center of the system were analyzed. Three different values for the Young's modulus were chosen for the tile. The lowest and the highest values correspond to the lowest and highest adhesive stiffnesses found in the literature (Fiorito, 1994). The intermediate value was obtained from experimental testing. For the adhesive, four values were chosen: the lowest was obtained in the literature (Fiorito, 1994); the other three were taken from test results and correspond respectively to adhesives with highest, lowest and no polymers added to its formulae. Two different values of the thermal expansion coefficient were selected for the tile and adhesive mortar. Except for the lower value for the mortar adhesive, which was taken from the experimental programme, the other coefficients represent lower and upper limits from the literature (Fiorito, 1994; Billi et al., 1995; Illston, 1994).
Table 3: Mechanical properties of materials used in the sensitivity analysis

<table>
<thead>
<tr>
<th></th>
<th>Tile</th>
<th>Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (MPa)</td>
<td>30000</td>
<td>1050</td>
</tr>
<tr>
<td></td>
<td>38779</td>
<td>20739</td>
</tr>
<tr>
<td></td>
<td>70000</td>
<td>22790</td>
</tr>
<tr>
<td>α (°C⁻¹)</td>
<td>4.6E-6</td>
<td>1.0E-5</td>
</tr>
<tr>
<td></td>
<td>7.0E-6</td>
<td>1.5E-5</td>
</tr>
</tbody>
</table>

3.2.1 Effect of Young’s modulus on the stresses

Figure 6 shows the influence of the tile stiffness on the development of stresses with temperature change. As can be observed, highest tensile stresses are likely to occur, in both the tile/adhesive and adhesive/rendering interfaces, by increasing the tile modulus. It was found that peak stresses rose by more than 100% by changing E by 79%. Shear stresses seem to be even more sensitive to the E variation (Figure 7). By changing E by 30%, peak stress increased by about 108%.

Fig. 6: Influence of the tile modulus on normal stresses (Sy).

Fig. 7: Influence of the tile modulus on shear stresses.
Regarding the influence of Young's modulus of the adhesive mortar, it could be noticed that the highest tensile stresses were obtained, in the tile/adhesive interface, for the most flexible adhesive (Figure 8 a). On the other hand, this value is responsible for the lowest stress profile in the adhesive/rendering interface (Figure 8 b). It is worth noticing that it was necessary to have a very huge change (about 900 %) in the E value to promote sensitive variations in the stress values. It might indicate that Young’s modulus of the adhesive mortar is not important to the development of stresses.

![Figure 8: Influence of adhesive mortar modulus on normal stresses (Sy)](image)

(a) Tile/Adhesive Interface  
(b) Adhesive Mortar/Rendering Interface

Fig. 8: Influence of adhesive mortar modulus on normal stresses (Sy)

Regarding shear stresses, it can be seen that the most flexible adhesive mortar does not produce high stress levels in the stress profile (Figure 9). Only with a very high increase in Young's modulus was it possible to obtain considerable variations in the critical stress values.

![Figure 9: Variation of shear stress with the adhesive mortar modulus](image)

Fig. 9: Variation of shear stress with the adhesive mortar modulus

3.2.2 Effect of Coefficient of Thermal Expansion on stresses

The sensitivity of the model to the Coefficient of Thermal Expansion of the tile was also tested. It can be seen in Figure 10a that, at the tile/adhesive interface, the Sy maximum tensile stress is slightly lower for the higher coefficient. For compressive
stresses, a higher variation is observed and, in this case, the higher coefficient produces a lower peak stress at the connection point with the grout. In the adhesive/rendering interface, the Sy stresses, compressive and tensile, increase with the Thermal Expansion Coefficient, as can be seen in Figure 10b. At the grout connection point, tensile stress is obtained. For both interfaces the higher the Coefficient of Thermal Expansion the higher the shear stresses (Figures 11 and 12).

![Graph of Tile/Adhesive Mortar Interface](image-a)
![Graph of Adhesive Mortar/Rendering Interface](image-b)

**Fig. 10:** Influence of tile Coefficient of Thermal Expansion on tensile stresses

![Graph of Shear Stress at Tile/Adhesive Mortar Interface](image-c)

**Fig. 11:** Influence of tile CTE on shear stresses at Tile/Adhesive Mortar Interface

![Graph of Shear Stress at Adhesive Mortar/Rendering Interface](image-d)

**Fig. 12:** Influence of tile CTE Expansion on shear stresses at Adhesive Mortar/Rendering Interface
4 Conclusions

The model used to establish the stresses on a wall coated with ceramic tile has proved to be adequate. In all cases, stresses, shear and normal ($S_y$) are nearly zero in the center of the tiles, increasing near the tile / grout junction. This behavior might be attributed to differential movement of the materials due to their different mechanical properties.

The sensitivity analysis has shown that the ceramic tile coating system is more sensitive to the tile than to the adhesive mortar mechanical properties. Highest tensile and shear stresses were observed for stiffer tiles on both the tile / adhesive mortar and adhesive mortar / rendering interfaces.

The effect of the tile Coefficient of Thermal Expansion has proved to be smaller. Higher values of CTE produced lower peak stress at the connection point with the grout. With respect to the CTE of the adhesive mortar, the system is not as sensitive.

5 References


