MOISTURE EXPANSION

Very porous ceramics (high water absorption capacity, $E>10\%$) usually have abundant capillaries and large pores, the former favouring water circulation in the ceramic and the latter favouring contact of the water with the ceramic. As a result, such materials usually increase in volume considerably when they are in contact with water. In contrast, impervious or non-absorbing ceramics, such as porcelain or stoneware tile, usually have low coefficients of moisture expansion.

In the case of ceramic tiles, moisture expansion mainly affects tile length and width dimensions, just as linear thermal expansion, which is why it is evaluated as expansion by unit length (mm/m). When the manufacturer supplies the coefficient of moisture expansion as a percentage, multiplication of this value by 10 gives the value in mm/m.

It is vital to know this coefficient in order to calculate tile-to-tile joint width and, in particular, the width of the movement joints, as well as the maximum distance between the movement joints.

It is also convenient to know this coefficient in glazed ceramic tile with high porosity in order to foresee the potential risk of delayed crazing in humid or wet environments, after the tile has been installed.

The coefficient of moisture expansion in ISO 10545-10

Standard ISO 10545-10 sets out the test method for the determination of accelerated moisture expansion by immersion of a refired tile in boiling water, and measurement of tile relative change in length.

Moisture expansion, expressed in millimetres per metre, is calculated from the formula:

$$\frac{\Delta L}{L} \times 1000$$

where

- $\Delta L$: is the difference between the average values, before and after boiling (in mm)
- $L$: initial average length of the test piece (in mm)

Moisture expansion, expressed as a percentage, is calculated from the following formula:

$$\frac{\Delta L}{L} \times 100$$

Annex A (informative) of ISO 10545-10 states that “most GL and UGL tiles have negligible moisture expansion ‘that does not contribute to tiling problems when tiles are correctly fixed’.”
The Annex states further: ‘However, with unsatisfactory fixing practices and in certain climatic conditions, natural moisture expansion may **aggravate problems**, especially when tiles are directly fixed to inadequately aged concrete substances. In these cases, a maximum limit of 0.06% [equivalent to 0.6 mm/m] moisture expansion is recommended when the test is used.’

On the other hand, European standard **EN 14411** does not address the problem either. For the different product groups it only indicates that there is a ‘test method available’, leaving it up to the manufacturer whether or not to indicate this parameter in the trade documents, while referring the reader to a remark similar to that in the foregoing paragraph in **Annex P** (informative) on the test methods.

Of course, neither the problems, nor the term ‘inadequately aged concrete substances’, nor the phrase ‘in certain climatic conditions’, are defined. Hollow recommendations are involved, which in no way help the specifications writer or the professional tile fixer.

But is the moisture expansion that ceramic tiles undergo really ‘negligible’ from a tile installation standpoint. Let us examine an example in relation to a good natural porcelain tile.

**Example:** B1a ceramic tiles with E<0.1%, UGL, and \( \alpha_t = 6.5 \cdot 10^{-6} \) K\(^{-1}\), and moisture expansion of 0.1 mm/m. We shall assume a 10-metre-long floor, and maximum thermal variation of 40ºC at the ceramic surface.

- Increase in length caused by temperature variation:
  \[ \Delta L = \alpha_t L_0 \Delta T = 6.5 \cdot 10^{-6} \cdot 10,000 \cdot 40 = 260 \cdot 10^{-2} = 2.6 \text{ mm} \]

- Increase in length caused by moisture expansion:
  \[ \Delta L = \alpha_e L_0 = 0.1 \text{ mm/m} \cdot 10 \text{ m} = 1 \text{ mm} \]

It may be observed that even in such a favourable example as porcelain tile, moisture expansion constitutes just under one third of the total increase in length of the 10-metre-long ceramic flooring.

If, instead of installing a floor with porcelain tile, this had been done with terracotta or fired clay tiles (CIII), with a moisture expansion of 0.5 mm/m, moisture expansion would have been 5 mm, namely twice that of the expansion of thermal origin! In any event, the sum of both expansions (3.6 mm for the porcelain tile and 7.6 mm for the terracotta tile) can constitute a formidable pressure on the abutting construction elements if there are no intermediate and perimeter movement joints to absorb that pressure. If those joints are not present, in view of the low deformability of grouting materials, the flooring will arch or crack.

The phenomenon of moisture expansion is not simple to explain. On the one hand, adsorption (absorption of a gas by a solid) occurs of the water vapour by the ceramic body, which expands (increases in volume) as water penetrates into the ceramic structure. The more porous the ceramic body, the greater the resulting expansion, especially in unglazed tile (UGL). When the ceramic body dries, it loses this water and tile volume returns to its original size.
However, the foregoing process is complemented by another that consists of the hydration (capture of water molecules) of the amorphous compounds in the ceramic body which contains silica and silicates. This second process, called chemisorption, does not cease when the tile dries but continues in time in a practically indefinite way. As a result, when a ceramic tile dries it may shrink or continue expanding, depending on whether physical adsorption of the water vapour or chemisorption predominates. The phenomenon of delayed crazing has much to do with the process of chemisorption of water vapour by free silica and silicates in the ceramic body.

Trade catalogues and technical information provided by the manufacturer usually indicate the coefficient of moisture expansion in millimetres per metre (mm/m), which allows direct calculation of the increase in length of a wall tiling or flooring by multiplying that coefficient by the length of the stretch of tiling, expressed in metres.

If the manufacturer expresses the coefficient as a percentage, multiplication of that coefficient by 10 will convert it into millimetres per metre. For example, a coefficient of moisture expansion of 0.05% is equivalent to 0.5 mm/m.

Highly vitrified products, especially pressed products (B1a or B1b), usually have low coefficients of expansion (0.1–0.2 mm/m). Very porous products, formed by extrusion or other methods, usually have high coefficients of moisture expansion, above 0.5 mm/m.

The coefficient of moisture expansion is fundamental for the design of movement joints, and its contribution is ten times larger than that of the coefficient of linear thermal expansion.

The tile fixer and dimensional changes in ceramic tile

With a view to designing and installing a ceramic tiling, the tile fixer needs to:

- Know the coefficients of linear thermal expansion and moisture expansion of the ceramic tile to be installed.
- Anticipate the maximum temperature oscillation at the tiling surface. In this sense, it is useful to know that installed dark tile may reach temperatures above 50 ºC under direct exposure to sunlight, and temperatures of 30-50 ºC in the shade.
- Consider tile-to-tile joint width as a prolongation of the ceramic tile in regard to expansion and shrinkage, because the poor deformability of these joints will hardly help absorb any movements. In addition, it may be noted that cement mortars have a coefficient of linear thermal expansion of \((10-12) \times 10^{-6} \text{ ºC}^{-1}\).
- Measure the net space that the ceramic tiling will occupy in both directions and between any abutting construction elements. The measurements should be expressed in millimetres.
- Calculate, from the corresponding formulas, the increase in length of the ceramic tiling in the most unfavourable conditions, summing the results of...
linear thermal expansion and moisture expansion. For each direction, this then yields:

\[ \Delta L_{\text{TOTAL}} = \Delta L_T + \Delta L_E = \alpha_l \cdot L_0 \cdot \Delta T + \frac{\alpha_E \cdot L_0}{1000} \]  
(result in mm)

where:
- \( \Delta L_T \): increase in length caused by linear thermal expansion (in mm)
- \( \Delta L_E \): increase in length caused by moisture expansion (in mm)
- \( \alpha_l \): coefficient of linear thermal expansion (in \( ^\circ \text{C}^{-1} \))
- \( L_0 \): net length (or width) of the ceramic tiling (in mm)
- \( \Delta T \): maximum foreseen variation in temperature (in \( ^\circ \text{C} \))
- \( \alpha_E \): coefficient of moisture expansion (in mm/m)(*)

(*) if \( \alpha_E \) is given as a percentage, multiplying this by 10 converts it into mm/m

- Add a 10% safety margin to the total lengthening \( \Delta L_{\text{TOTAL}} \)
- Decide on the type of filler or mastic to be used in the movement joints, choosing between two extreme alternatives:
  - Fillers with high abrasion resistance and chemical resistance (for example, polyurethane/bitumen), but a low movement accommodation factor (MAF), about 10%.
  - Fillers with low chemical resistance and mechanical strength, but a high movement accommodation factor (MAF), about 25%.
- Calculate the number of movement joints in each direction, two of these being perimeter joints and the rest intermediate joints, assuming in addition that the width of these joints is equal to that of the tile-to-tile joints.
- Finally, design the layout of the tiles and the joints.

This entire process is illustrated in the detailed solution of a hypothetical case example, with two variants, which describes all the steps to be followed (see Hypothetical case example).

Although the foregoing recommendations and the content of the hypothetical case example correspond to the section on the design and setting out of the movement joints, it has been considered useful to anticipate that information in view of the close connection between the movement joints and the parameters linear thermal expansion and moisture expansion.

Without going into detailed calculations like those in the hypothetical case example, the tile fixer can use the information in the following charts as a guide or approximation to the sizing of the movement joints.
Physico-chemical characteristics

Moisture expansion

<table>
<thead>
<tr>
<th>Contributing factor</th>
<th>Coefficient</th>
<th>Approximate dimensional variation (in mm) (per linear metre and 10 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture variations</td>
<td>$\alpha_E$ (0.1–0.6 mm/m)</td>
<td>0.1–0.6</td>
</tr>
<tr>
<td>Temperature variation (every 10 °C)</td>
<td>$\alpha_l$ [(4.5–7) x 10(^{-6}) °C(^{-1})]</td>
<td>0.045–0.07 (^{(1)})</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td>0.145–0.67</td>
</tr>
<tr>
<td>Safety margin (10%)</td>
<td></td>
<td>0.015–0.067</td>
</tr>
<tr>
<td>TOTAL (For every 10°C temperature variation)</td>
<td></td>
<td>0.16–0.74 (^{(2)})</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Even for variations in steps of 10 °C, linear thermal expansion produces dimensional variations of **hundredths of a millimetre**, whereas moisture expansion produces variations of **tenths of a millimetre** (i.e. 10 times more!) for 1 linear metre of wall or floor tiling, depending on the type of ceramic tile ($\alpha_E$).

\(^{(2)}\) Since the contribution of moisture expansion is 10 times that of thermal expansion, the correction factor for temperature will just affect the second decimal (hundredths of a millimetre).

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**MOVEMENT ABSORPTION ACCORDING TO TYPE OF JOINT (per linear metre)**

<table>
<thead>
<tr>
<th>Temperature variation $\Delta T$ °C</th>
<th>Total dimensional variation $\Delta L$ (in mm/m)</th>
<th><strong>MINIMUM DISTANCE BETWEEN MOVEMENT JOINTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum (^{(1)})</td>
<td>Maximum (^{(2)})</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>0.16</td>
<td>0.74</td>
</tr>
<tr>
<td>20</td>
<td>0.21</td>
<td>0.81</td>
</tr>
<tr>
<td>30</td>
<td>0.26</td>
<td>0.89</td>
</tr>
<tr>
<td>40</td>
<td>0.31</td>
<td>0.97</td>
</tr>
<tr>
<td>50</td>
<td>0.36</td>
<td>1.05</td>
</tr>
<tr>
<td>60</td>
<td>0.41</td>
<td>1.12</td>
</tr>
<tr>
<td>70</td>
<td>0.46</td>
<td>1.2</td>
</tr>
<tr>
<td>80</td>
<td>0.51</td>
<td>1.28</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Total dimensional variation as a function of temperature for tiles with a minimum coefficient of moisture expansion ($\alpha_E$ , 0.1 mm/m), such as the case of porcelain tile (BIa).

\(^{(2)}\) Total dimensional variation as a function of temperature for tiles with a maximum coefficient of moisture expansion ($\alpha_E$ , 0.6 mm/m) according to EN 14411, such as the case of BII, AIII, or CIII tiles.
Scientific-technical aspects

Porous ceramics undergo an expansion process when they are left for varying periods of time in contact with ambient humidity or moisture, an expansion that occurs through two simultaneously occurring mechanisms.

On the one hand, water is physically adsorbed and the piece expands when it become wet owing to the increase in volume occupied by the water, subsequently shrinking to its original size when it dries, i.e. reversible dimensional changes are involved.

The other mechanism, of a chemical nature (chemisorption), takes place by hydration of constituents such as amorphous aluminosilicates, glasses, and amorphous silica, which gives rise to a volumetric expansion that occurs during both wetting and drying, with the ensuing irreversible dimensional change in the tile. In addition, if the tiles are heated to accelerate the drying, the rate of expansion increases. Thus, though the pieces always expand by the action of moisture, when they dry they may either shrink or continue to expand, depending on whether physical moisture adsorption or chemisorption predominates.

Water adsorption on the phases (which may be amorphous, crystalline, or glassy) in the fired product will depend on the surface characteristics of the phases present and of how the energy of those surfaces evolves when that phenomenon occurs.

Amorphous materials generally have a large specific surface area and high surface energy, which therefore lead to very pronounced surface relaxation effects. In the case of silica or silicates, the break-up of Si-O-Si bonds to form Si++Si-O allows chemisorption of water with saturation of the free valencies, first giving rise to Si-OH+Si-OH and then to Si-O-H3O+Si-O-H3O. This initial chemisorption is followed by adsorption of additional quantities of water by means of Van der Waals forces, which contribute further to decreasing the surface energy of the solid.

Crystalline materials have much a smaller specific surface area than amorphous materials and, therefore, contain a smaller number of unsaturated valencies. The freshly fractured surfaces of a quartz crystal will have approximately the same surface energy as those of amorphous silica, but the specific surface area of the fractured crystals is much smaller. This means that crystalline materials may be expected to play an insignificant role in moisture expansion.

Glasses, in their initial unaltered state, have a small specific surface area and their surface energy is often also very low due to the compensation produced by diffusion towards the surface of network-modifying ions. However, when a glass is subjected to the action of water, an exchange occurs between the alkaline ions in the glass and the hydrogen ions in the water, with the ensuing formation of a glass surface layer with a structure resembling that of amorphous silica. In addition, this leaching process has the secondary effect of opening pores that were previously closed, thus increasing the accessible area for water adsorption and, hence, further encouraging moisture expansion.
When moisture expansion is plotted versus treatment time in an autoclave, curves are obtained that are characterised by a fast initial rise, a transition area, and a final area, with a much smaller slope, in which growth is almost linear.

The rapid expansion that occurs during the first contact period with water or water vapour is due to saturation of the exposed surfaces. Since amorphous materials are involved, which present the greatest available surface for exchange, it is reasonable to expect that these will be mainly responsible for the initial expansion.

In the last region of the curve, it may be observed that expansion does not tend to a maximum value, but instead continues to grow in a slow and steady way. The only constituent undergoing important changes in the ceramics during the humidity treatment is the glass and, as a result, it appears reasonable to assume that this is responsible for the linear behaviour observed at the end.

Tests conducted at different firing temperatures have shown that as temperature rises beyond 1000°C, moisture expansion increases when the amorphous constituents increase, maximising at about 1050°C, at which the expansion is greatest and fastest, after which expansion decreases at higher temperatures.

The evolution of moisture expansion with firing temperature depends on the composition of the body, on tile forming, and on the firing cycle used, which is why different results may be expected, all of which can be predicted from the phase diagrams.

When the firing cycle is prolonged, at a constant temperature, moisture expansion diminishes, demonstrating that when the crystallinity of the system increases, moisture expansion decreases. That is why using ever shorter firing cycles raises the risk of greater moisture expansion, making it necessary to use formulations that give rise to smaller quantities of amorphous and glassy phases and less reactive phases.
State of the art

Since, in practice, the moisture expansion of a porous material reaches its limit value after long periods of time, taking even 10 years under normal temperature and relative humidity conditions, it is necessary to accelerate the phenomenon artificially using boiling water or water vapour under pressure.

A number of studies are reported in the specialised literature, in which it has been attempted to relate the results of ceramic tile moisture expansion obtained by direct measurement in environmental conditions to those obtained under accelerated treatment conditions in the laboratory.

The following table compares the conditions of the moisture expansion tests in different regulations, and shows the equivalent exposure time at 100°C with saturated vapour, and at 23°C with 50% relative humidity.

<table>
<thead>
<tr>
<th>TEST METHOD</th>
<th>CONDITIONS</th>
<th>EQUIVALENT EXPOSURE TIME AT 100°C WITH SATURATED VAPOUR (HOURS)</th>
<th>NATURAL AGING TIME EQUIVALENT EXPOSURE TIME AT 23°C WITH 50% RELATIVE HUMIDITY (YEARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 1281</td>
<td>100 psi, 2h (7.03 kg/cm²)</td>
<td>69.8</td>
<td>105</td>
</tr>
<tr>
<td>EN 105</td>
<td>0.5 MPa, 1h (5.1 kg/cm²)</td>
<td>19.0</td>
<td>28.5</td>
</tr>
<tr>
<td>ASTM C 2424</td>
<td>1st Cycle - 50 psi, 1h (3.5 kg/cm²)</td>
<td>10.5</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>2nd Cycle - 100 psi, 1h (7.03 kg/cm²)</td>
<td>45.4</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>3rd Cycle - 150 psi, 1h (10.5 kg/cm²)</td>
<td>120.5</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>4th Cycle - 200 psi, 1h (14.1 kg/cm²)</td>
<td>250.7</td>
<td>376</td>
</tr>
<tr>
<td></td>
<td>5th Cycle - 250 psi, 1h (17.6 kg/cm²)</td>
<td>451.0</td>
<td>677</td>
</tr>
<tr>
<td>ASTM C 370</td>
<td>150 psi, 5h (10.5 kg/cm²)</td>
<td>375.2</td>
<td>563</td>
</tr>
<tr>
<td>British Ceram. Society</td>
<td>50 psi, 7h (3.5 kg/cm²)</td>
<td>73.6</td>
<td>110</td>
</tr>
</tbody>
</table>

With respect to delayed crazing also see the section ‘Cracks in glazed tiles’.

For further discussion, see the paper ‘The need for establishing a moisture expansion convention for the analysis of tiling system failures’ by Richard Bowman [Qualicer'92 Proceedings]