Failures of floor structures made from concrete and fired clay units

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Abstract
Floor structures made from fired clay units have been applied for almost one hundred years in Central Europe. The assembling technology changed several times during the 20th century and, in recent years, ceilings have been made of two kinds of material – not only ceramic material but also concrete cast on the upper surface of fired clay units. Many failures of these structures have occurred recently. These failures are related to some types of ceramic-concrete structures. The lower part of the ceiling collapses within a few years after the casting of the concrete. In laboratory conditions, a number of long-term experiments simulating the real floor structure have been carried out, together with an investigation of the material properties. Our investigation then focused on long-term measurements of the shrinkage of the concrete and mainly on observing the irreversible moisture expansion of fired clay. Long-term monitoring of a full-scale model of the floor structure loaded only by self-weight and by volume changes was carried out. The experimental investigation and theoretical analysis proved that the failures are due to the volume changes. If the concrete is jointed together with the ceramic material and if volume changes take place, a failure occurs.

Keywords: ceramic, failures, fired clay units, moisture expansion, volume changes

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1.0 Introduction

In recent years, failures of floor structures with ceramic units (trading name: HURDIS) have aroused attention in the Czech Republic. In most cases, these incidents occur some time after completion of the construction, usually within a period of between half a year and six years. It turns out that architects, designers and structural engineers have quite unsatisfactory general knowledge about the basic mechanical and physical-chemical properties of ceramic building materials. Experts report that failures of ceramic floor structures occurred already in 1970s and 1980s in France, Italy and Germany. The combined effect of time dependent volume changes in concrete or mortar and a ceramic body was indicated as the cause of these incidents. Volume changes, i.e., shrinkage of concrete, moisture expansion of ceramic material and temperature expansion are important characteristics of building materials. Their magnitude may significantly influence the static reliability and durability of building structures.

2.0 Description of the floor structure and causes of the failures

More than 100,000 floor structures with HURDIS clay units have been erected in the Czech Republic in the last twelve years. The dimensions of HURDIS clay units are 1200/250/80 mm. The units are directly supported in the floor structures either by steel beams or by special footing clay units placed on the steel beams. The axial distance of the steel beams is 1300 mm. A scheme of the floor structure is plotted in Figure 1.

The cross section of a HURDIS clay unit is a multi-box with three holes. The units and footing units are always laid on the mortar layer. A concrete layer is cast on the upper surface of the clay units. The thickness of the concrete layer on the units is between 10 and 60 mm, and the thermal and acoustic insulation is placed on the top of it [1, 2, 3].

More than 100 failures of floor structures have been registered in the Czech Republic in recent times. The failures of floor structures made of fired clay units have revealed a common feature - the clay units have failed in the same characteristic way. The failure curves pass through the webs of the HURDIS plates and the entire bottom parts of the plates below suddenly collapse after a short cracking noise is heard. No distinct visual or acoustic warning precedes the failure. Such a
failure is dangerous to life and causes considerable material damage. The ceiling with a failed floor structure is shown in Figure 2.

Figure 2: Collapsed ceiling

Both experimental and numerical analysis proved that the main reasons are volume changes in two well bonded materials – concrete and fired clay. The changes – shrinkage of concrete, moisture expansion of fired clay and thermal expansion – cause a state of stress, and this leads to initiation of cracks in the ceramic material. While the rheological properties of concrete and cement compounds are generally well described in expert studies and consequently in the related standards, there is a lack of experimental and theoretical knowledge about volume changes in fired clay.

3.0 Moisture expansion

3.1 Moisture expansion of fired clay

More severe cases include failures of masonry due to prolonged moisture expansion of fired clay bricks. These symptoms of ageing of fired clay were described in the 1950s. These failures are manifested by marked cracks on the masonry surface. Vertical cracks occur in the corners, while horizontal cracks occur beneath concrete floors and around foundation structures. Based on experiments, it is recommended to provide dilation joints [4, 5].

Irreversible moisture expansion is a symptom of ageing invoked by the physical and chemical processes of fired clay material. The value of the reversible moisture expansion amounts to a fraction of the irreversible moisture expansion.

Firing clay mixtures produces relatively homogeneous bodies, usually with a complicated mineralogical composition and a high proportion of non-crystalline, insufficiently stable phases and with a relatively high degree of open porosity. Such bodies possess a variably high tendency to bond certain amounts of water in their porous structures. This moisture is of a hygroscopic nature, originating either from condensed vapour, especially due to fluctuating temperatures, or
from diffusion through the material. The moisture content varies with the size of the body and the properties of the environment, changing with temperature and ambient humidity. Prolonged contact of such moisture, especially with the porous phases of the body, results in the creation of bonds between the body and water that are of a different nature than physical bonds. These bonds are the chemisorptive, which are considerably stronger than common sorption, i.e., physical bonds. It can also be assumed that chemical bonds recur partially, i.e., hydroxide bonds. This process is irreversible and is substantially accelerated by increased temperatures and the pressure of water vapour [4, 5, 6].

The rehydration of dehydrated clay mineral is only partial under normal atmospheric conditions. It is relatively fast in the initial stages and slows with time. Nevertheless, this process has a very long duration. This spontaneous process of rehydration of the clay mineral is accompanied by a spontaneous increase in the volume of the body, proportional to the degree of rehydration. The limit value of moisture expansion and its course in time depend on the composition of the raw material and the technology of firing (temperature and duration). The irreversible moisture expansions of clay minerals can reach more than 5 mm/m [7].

3.2 Determination of irreversible moisture expansion - experimental methods

There are several experimental methods for determining the irreversible moisture expansion of fired clay material. They are mostly based on the production of extreme conditions in order to induce the moisture expansion limit of the fired clay. The basic principle is that the process of rehydration of fired porous materials of natural clays can be significantly accelerated by placing them in an environment with an increased temperature and vapour saturated atmosphere. These methods are used to determine the conventional value of the moisture expansion of fired clay materials. First, the specimens are refired (more than 600°C) in order to remove chemisorbed water from the material. Then one of the following procedures is applied:

- Boiling in steam for 5 hours in an autoclave (1MPa, 180°C) [8],
- Boiling in water for 24 hours (atmospheric pressure, 100°C) [9],
- Boiling in steam for about 4 hours (atmospheric pressure, 100°C) [10].

Another way is to estimate the moisture expansion by thermal dilation analysis. This method can be used in order to determine the value of the moisture expansion by controlled heating of a sample to 650°C and by continuous dilatometric measurement. Accurate measurements of the original specimen, the annealing specimen after cooling and the specimen after autoclave treatment can be used in order to determine the current degree of moisture expansion, as well as the extreme value of moisture expansion.

Basic chemical and physical properties of fired clay extracted from failed structures are presented in Table 1 and Table 2. Values of irreversible moisture expansion of the material, estimated by two different methods (boiling in autoclave and 24 hours boiling in water 100 °C), are shown in Table 3.

Table 1: Chemical composition

<table>
<thead>
<tr>
<th>Sample</th>
<th>Component content (weight ratio in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>1996</td>
<td>61.43</td>
</tr>
</tbody>
</table>
Table 2: Properties of fired clay

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moisture absorption (%)</th>
<th>Bulk density (g.cm⁻³)</th>
<th>Apparent density (g.cm⁻³)</th>
<th>Open porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>21.4 ± 0.5</td>
<td>1.679 ± 0.01</td>
<td>2.623 ± 0.007</td>
<td>36.0 ± 0.6</td>
</tr>
<tr>
<td>2001</td>
<td>20.6 ± 0.4</td>
<td>1.699 ± 0.01</td>
<td>2.626 ± 0.01</td>
<td>35.1 ± 0.5</td>
</tr>
</tbody>
</table>

Table 3: Irreversible moisture expansion

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test in an autoclave Test in an autoclave Boiling - 24 hours, 100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (mm/m) w (%) A (mm/m) w (%) A (mm/m) w (%)</td>
</tr>
<tr>
<td>1996</td>
<td>0.90 ± 0.02 9.7 ± 0.6 0.80 ± 0.03 0.3 ± 0.1 0.40 ± 0.05 14.5 ± 0.5</td>
</tr>
<tr>
<td>2001</td>
<td>1.05 ± 0.02 19.1 ± 0.6 1.03 ± 0.02 0.4 ± 0.1 0.32 ± 0.01 16.3 ± 0.5</td>
</tr>
</tbody>
</table>

Note: A is moisture expansion, and w is the actual moisture of the specimen.

3.3 Long-term measurements of moisture expansion

Samples of a ceramic material extracted from a failed structure were prepared for testing by refiring at a temperature of 600 °C. The growth of relative deformations in the course of 995 days in an environment with stable conditions due to irreversible moisture expansion, measured in four samples with a length of 200 mm, is shown in Fig. 3. A series of regression relations was derived for expressing the relative deformations by moisture expansion. In this case, the following formula was used:

\[ A = 20.81 \cdot t^{0.39} \text{ [\mu m/m]} \]  

(1)

where \( A \) is irreversible moisture expansion and \( t \) is age (in days) of specimen after the firing. This theoretical relationship is plotted in Fig. 4. The moisture expansion value that occurred previously can be used for estimating the age of a ceramic body in archaeology. M.A. Wilson [11] uses a similar expression with a coefficient equal to 9.87 and an exponent equal to 0.24 in order to estimate the age of historic bricks.

![Figure 3: Long-term measurements of irreversible moisture expansion on 4 specimens](image)
4.0 Failure of HURDIS fired clay units in laboratory conditions and in the conditions of a real structure

In laboratory conditions, we determined the deformation of the model of a floor structure formed by three HURDIS fired clay units assembled into footings in the mortar bed on hot-rolled I-beams. This experimental model was loaded only by self-weight and, of course, by volume changes (shrinkage of concrete and expansion of the ceramic material). The scheme of the test arrangement is presented in Fig. 5.

![Figure 5: Scheme of the experimental model](image_url)
A 20 mm thick concrete layer was cast on the upper surface of the units. The shrinkage of concrete was measured by dilatometer on specimens with dimensions 40/40/160 mm. In the midspan, two potentiometric transducers were placed – the first on the central unit (W1) and the second on the side unit (W2). For a period of two years, two transducers recorded the vertical displacements. During this time, the deflections reached a value of 1.8 mm or 0.8 mm (Fig. 6) and shrinkage of concrete reached 1.63 mm/m. Two months after the concrete had been cast, hairline cracks were found in the units on the bottom face of the model. The change of the crack width, monitored for 630 days, indicated that the growth was approximately 1.0 up to 1.5 µm within 24 hours (Fig. 7). The temperature in laboratory conditions varied in the range 17 – 23 °C.

The long term growth of the crack width was monitored in an analogous manner in the conditions of a real floor structure during four summer months. In this structure, a 30 mm concrete layer was laid on the ceramic units; cracks were determined on the plastered bottom face of the floor structure after 4 years after construction. The failure of the integrity of the ceramic body was
confirmed by a detailed investigation. The crack width increased approximately 60 µm within four months (Fig. 8).

![Figure 8: Growth of the crack width in a real structure in time](image)

**5.0 Numerical analysis**

First, a simple numerical model was used to analyse the stress state of one simple supported unit on which the concrete was cast. The ideal elastic material model was considered. The time-dependent deformation characteristics of concrete and the effect of creeping were neglected. The material contact (concrete-ceramic) was considered to be fixed. The state of stress was determined by means of a planar model (plane stress) that investigated the stress in the longitudinal section of the unit. In this case, the greatest values of the main tensile stress are in the region of the unit head; the stress direction is parallel to the surface. Tests of material properties later showed that just the effect of concrete shrinkage is sufficient to exceed the tensile strength of the ceramic material in many cases. Figure 9 illustrates the isolines of the main tensile stress. The model predicted approximately 1.0 mm deflection of the simple supported unit and loaded only by the concrete shrinkage and self weight (the deflection before initiation of crack). This corresponds to the values found experimentally.

![Figure 9: Results of the plane stress analysis of the clay unit – isolines of the main tensile stress](image)
In addition, we used a 3D model utilizing 2D elements in order to analyse part of the floor structure. We introduce the assumption that the clay units are supported like pined beam (hinges on the bottom surface at the unit head). In this case, a horizontal displacement may not be possible. Such a model (which is also linear) was used for estimating the deformations of the experimental model of the floor structure, which was placed in laboratory conditions and monitored over a long period of time. The results are presented in Figure 11.

![Figure 11: Results of the 3D model (a – isolines of vertical displacements of upper surface of clay units, b – isolines of main tensile stress in the webs of clay units)](image)

The question is how to use numerical methods during the analysis of existing structures, because the magnitude of the dominant action in an existing structure, i.e., the concrete shrinkage, cannot be determined reliably.

### 6.0 Conclusion

The experimental methods and the numerical analysis proved that the reason for the defects of floor structures made from fired clay units is the joint action of the subsequent stress and forces in the body of the unit induced by:

- shrinkage of the layer of fresh concrete,
- irreversible moisture expansion of the fired clay,
- effects of thermal expansion in the floor structure.

Irreversible moisture expansion is a non-negligible property of a ceramic body, if the structural arrangement of the building element limits the free course of the volume changes. It is the manifestation of aging caused by physical-chemical reactions of moisture with the porous brick body.

More than 100,000 floor structures of this type have been assembled. Approximately 15 failures per year have been registered in the Czech Republic since 1990s, and this tendency will probably continue. The type of failure is dangerous to life and causes considerable material damage. It should therefore receive careful attention.

The occurrence of a strong bond between fired clay and concrete should be prevented in order to avoid the collapse in future construction. A separation between the clay units and the concrete...
should be obligatory. In such a way, the effect of the volume changes in the floor structures is adequately reduced.

In case of existing structures, crack developments in clay units should be regularly monitored, e.g., through visual inspections of holes of HURDIS clay units by endoscope. Rehabilitation procedures for both partly and totally damaged floor structures have been elaborated. The most important aspect is the installation of the bottom plate, which prevents the collapse of the damaged parts of the clay floor units.

7.0 Acknowledgement

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8.0 References