Tomography investigations of an ancient building material from the Mỹ Sơn Sanctuary (Vietnam)

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Aims

Ancient Mỹ Sơn Sanctuary is located in central Vietnam. It was a capital of Champa Kingdom from 4th to 13th centuries CE. Initially, the temple complex consists of 71 buildings. Nowadays the 50 temples are destroyed to varying degrees (fig. 1). In 1999 Mỹ Sơn Sanctuary was included in the World Heritage List of UNESCO as a number 949 (http://whc.unesco.org/en/list/949). Several efforts to reconstruct the temple complex were taken (Kwiatkowski, 1985, 1990; Champa…, 2009). However the reconstruction of this complex was not completed. An aim of this paper is the study of structural features of the ancient bricks and sculptural elements by using the x-ray micro-CT and synchrotron tomography. It is very important for the recommendations of possible conservation techniques. Previously the tomography was not used for Mỹ Sơn Sanctuary investigations.
**Method**

There are several groups of the temples and towers of different building time: from A to H. Ancient bricks and sculptural elements of a building from G group are studied (fig. 2).

The objects were investigated by using x-ray micro-CT Skyscan 1172. Microtomography parameters: current was 100 mA, voltage was 103-104 kV, filter was Al (1 mm), pixel size was from 5 to 34.1 μm, rotation - 180°, steps of rotation 0.4 – 0.7°, random movement – 10, frame averaging – 8. TView, NRecon, 3DCreator, CTAn programs were used. Synchrotron tomography was carried out in National Research Centre "Kurchatov Institute" by using "Kurchatov synchrotron radiation source" (KSRS), at the station "LIGA". Filtered synchrotron radiation with a spectrum maximum about 60 keV (Cu filter 1.5 mm) was used. A frame exposure time was 50 ms; resolution – 250 μm; step of rotation – 0.5°. A vertical scanning step of 2 mm was applied. The scanning electron microscopes CamScan-4, Jeol JSM-6390LA with energy-dispersive microanalysis system OXFORD, Jasco FT/IR-4100 spectrometer, digital stereo microscope Leica M165 C were used as additional equipment. X-ray diffraction study was conducted at the KSRS station "Structural Materials Science" in the Debye-Scherrer geometry (transmission mode) using a two-dimensional detector Fujifilm Imaging Plate.

**Results**

Some internal structures in all building materials were found. Cracks are usually extended to a depth of 13 mm. They are present mainly in the outer layer (fig. 3). Three layers in the bricks are viewed. The layer thicknesses: the first outer layer – 8-13 mm, the second thin layer – 2-5 mm, the third inner layer – about 25 mm. A difference in the layer structure was not identified by using micro-CT. Unevenly distributed small cavities and large caverns are well visible. All voids in the bricks can be divided into two groups: cavities from 50×130 μm to 530×600 μm, and pores with diameter of less than 50 μm.
The grains of minerals of a different contrast in the specimens are viewed. The minerals kaolinite, metakaolinite, quartz, illite, common potash feldspars (microcline, orthoclase), albite, muscovite, montmorillonite and iron hydroxides were identified by using FT-IR spectroscopy and x-ray diffraction. Fired clay and the quartz are the bulk of the studied objects. The light gray grains probably are feldspars and micas. The white bright inclusions are probably the high contrast minerals (fig. 4-6). They might be iron compounds. A presence of titanium was found in bricks in addition to iron (tabl. 1). Its compounds can make the high ct contrast with other minerals.

Table 1. An average elemental composition of brick matter

<table>
<thead>
<tr>
<th>Chemical elements</th>
<th>Content, weight %</th>
<th>Matters</th>
<th>Content, weight %</th>
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<tr>
<td>C</td>
<td>14.94</td>
<td>C</td>
<td>14.94</td>
</tr>
<tr>
<td>O</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>4.11</td>
<td>Al₂O₃</td>
<td>7.76</td>
</tr>
<tr>
<td>Chemical elements</td>
<td>Content, weight %</td>
<td>Matters</td>
<td>Content, weight %</td>
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<tr>
<td>-------------------</td>
<td>------------------</td>
<td>---------</td>
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<td>Si</td>
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</tr>
<tr>
<td>Fe</td>
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<td>FeO</td>
<td>2.71</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 4: 3D-model of a brick fragment with mineral inclusions. Green – micas and feldspars, red – heavy minerals (with a high content of Fe, possibly, Ti). A function “transparency” is used. Width of the brick fragment – 15 mm.
Figure 5: 3D-model of a brick fragment with heavy minerals (red). A function “transparency” is used. Width of the brick fragment – 15 mm.

Figure 6: 3D-model of a brick fragment (see fig. 5) with microstructure elements. Blue – heavy minerals inclusions, light brown – the cavities. A function “transparency” is used.
Besides the above mentioned inclusions some oval contrast formations were found (fig. 7). The sizes of these formations are in the range from 500 to 690 μm. Their surface layer is well contrast. As compared with an internal content this layer has high density and is a covering of the formation. A friable matter is inside of the oval formation. It very differs in density from the surface layer. Perhaps, in the formation there are the minute cavities. These formations most likely consist of iron compounds.

Non charred remains of plant tissues and their imprints were found under the outer layer at a depth of 2-3 mm (fig. 8, 9). The single cells are viewed in the plant tissue. Also structural elements of plant tissues are identified by using SEM (fig. 9). The traces of the ribs are visible on the stem imprints surface (fig. 10, on the left). Most likely these stems have had to herbaceous plants from family Gramineae. The presence of non charred plant tissues under the surface is indicative of a low fired temperature of the bricks.

Probably the narrow cavities that are seen in the synchrotron tomography slices of the bricks are formed as a result of plant fragments destruction (fig. 11). Unusual cavities in micro-CT slices are viewed too. They are the semilunar in cross-sections cavities (fig. 10, on the right). It is assumed that they were also formed after plant fragments destruction.
Figure 8: Sand grains and plant remains (arrows) in the bricks. On the right picture can be seen preserved plant cells.

Figure 9: Elements of the plant tissues in the bricks. SEM was used.
Figure 10: The imprint of the rib plant stem (on the left). Semilunar cavities in the brick (on the right).

Figure 11: Narrow cavities in the bricks

It was possible to identify small differences in the density of the sculptural decoration element layers (fig. 12). A dense matter is observed in an outer layer. A thickness of the dense layer is 140-200 μm.
Conclusion
Thus, tomography technique is first time used to study of the Mý Sơn Sanctuary building material. Structural features of building material of temple from Mý Sơn group G are identified. The distribution of the cracks, cavities, caverns, pores, mineral grains, dense areas is very important for the conservation measures. In the production of bricks not only sand was used, but also plant fragments (straw) were mixed with clay. The presence of non charred plant tissues near the brick surface is an evidence of low fired temperature. Elemental and mineral compounds previously published by Italian researchers (Binda et al., 2006) are confirmed. Tomography techniques are perspective for further study of these archaeological objects and for a selection of conservation methods.

References:
5. “My Son Sanctuary” http://whc.unesco.org/en/list/949