SUMMARY

The article shows the investigations that led to the cause of decay of the alabaster sarcophagus and new methods for the restoration of the resin impregnated piece of art. The main reason was thermal decomposition of the gypsum and rapid rehydration accompanied by mismatching properties of the resin. The restoration used different formulas of cold-hardening PMMA resins combined with fillers and special coatings for 5 different steps of structural strengthening, adhesion, gluing of cracks, reshaping and retouching. The restoration has been successfully completed by a team of restorers.

ZUSAMMENFASSUNG

RESUME

Suite à une restauration problématique, le sarcophage en albâtre du duc Melchior von Hatzfeld avait de sévères dégradations, dont les causes furent déterminées. Les causes principales étaient la décomposition thermique du plâtre, les tensions mécaniques dues à une réhydratation rapide, ainsi que les propriétés physiques mal adaptées de la résine utilisée. Nous avons développé une nouvelle méthode de restauration basée sur un traitement en cinq phases avec des résines PMMA durcissant à froid. Le traitement avait pour buts: le renforcement de la structure, le colmatage des fissures et le remodelage des ornements. La restauration a été accomplie avec succès par une équipe de restaurateurs, le sarcophage est à nouveau exposé.

KEYWORDS: Restoration, alabaster, sarcophagus, conservation

1. INTRODUCTION

The sarcophagus of the late Duke Melchior von Hatzfeld was created in 1659 by the famous stonemason Archilles Kern from Forchtenberg (Unterfranken). In the year 1657 Melchior von Hatzfeld had been the liberator of Krakau against the Swedish army sent by the German Emperor. The sarcophagus was finely carved out of a famous alabaster coming close by Forchtenberg. It shows the Duke in a suit of armour on the cover plate and scenes of his battles on the sides. Because of his legacy Archilles Kern created two tombs with very similar sarcophagus one in Prausnitz (Silesia) and one in Laudenbach (Hohenlohe) in a little chapel in the mountains, called Bergkirche (fig. 1).
Figure 1: The Hatzfeld Sarcophagus after the successful restoration and reconstruction in the Bergkirche chapel in Laudenbach (picture by Georg Schmid, restorer).
Figure 2: Severe decay forms like warping, cracks and lamellar disintegration after the false restoration on one of the plates showing scenes from a battle (picture by Georg Schmid, restorer).
2. THE CAUSES OF DESTRUCTION

In 1982–1984 the object, which had been restored several times, underwent further restoration, this time by full impregnation with acrylic resin after preliminary tests on a sample slab had proved successful (Fig. 1 and 2).

After thorough preliminary treatment (sealing of cracks, coatings, etc.), the process comprised the following stages: drying at up to 100°C for several days, vacuum treatment at up to 0.2 Torr/0.9 bar, flooding with PMMA monomer solution at up to 20 bar to saturate the object, followed by hardening at a raised temperature, i.e. at up to 80°C.

Immediately after treatment the sarcophagus showed good superficial strengthening but damage ranging from warping to cracking was found as early as September 1984 after the object had been mounted on an aerated-concrete core and replaced in the Bergkirche church. By May 1985, the damage was more apparent. Numerous cracks had appeared and a large proportion of the joints had opened.

In October 1986 the State Office for the Preservation of Historic Monuments in Stuttgart (LDA B.-W.) called in to ascertain the causes of the damage and to try to repair it. Numerous scientific and technical tests were performed on the object to discover the cause of damage. Our main findings were as follows (Grassegger, 1987):

- As a result of drying and the process of impregnation with acrylic resin, the alabaster itself had partially dehydrated into semi-hydrate and anhydrite. This was proven in numerous surface and deep-section samples by means of phase analysis by x-ray diffraction. The degradation behaviour of gypsum had been underestimated because the literature often states that “plaster burning” starts at temperatures from 120°C. (In fact, water desorps in 2 steps and this process starts from as low as 40°C.)

- Due to its heterogeneous structure, the object was very unevenly impregnated, which gave rise to stresses. However, $^1$H NMR ($^1$H [hydrogen] nuclear magnetic resonance spectroscopy) measurements showed that the sarcophagus itself had been impregnated through to the centre. The PMMA (polymethyl methacrylate synthetic resin) content in the drilling core taken from the dog was approx. 13% PMMA by weight on the surface, falling to
approx. 5% PMMA in the centre (results gained by Günther Krause, Ref. 35 FMPA).

- Examination of the alabaster under a scanning electron microscope revealed clear coating of synthetic resin on the gypsum crystals and only very small vacuoles and air bubbles within the resin (Figs. 3 and 4).

- Selective moistening of samples proved the existence of residual swelling stresses in the impregnated material, leading to further warping and crack formation. In this material, water absorption was still approx. 0.5% by weight, whereas in a pure PMMA sample it should be 0%.

- The thermal expansion $\alpha_T$ of the resin treated material fluctuated markedly and unsystematically between 1.7 and $3.1 \times 10^{-5}$ m/mK and was non-linear. Its break point likewise fluctuated widely between + 20°C and + 80°C. The PMMA itself was $7.3 \times 10^{-5}$ m/mK up to a break point of + 25°C. Above that, it was $10.5 \times 10^{-5}$ m/mK up to 60°C. This indicates that expansion is heterogeneous and that the expansion properties of the alabaster and the PMMA overlap in different ways. This leads to stresses when the material is subjected thermal strain.

- According to the $\alpha_T$ tests and determination of the glass transition point by differential thermoanalysis (DTA), the PMMA’s glass transition point was approx. 60°C.

- A deep-section drilling core with an apparently even density showed very large variations in permeability to steam. On the surface was a dense zone with a coefficient of resistance to steam diffusion of $\mu = 1,200$, while deeper down the values fluctuated between $\mu = 380 –2,100$.

After damage had occurred, due to the contact with atmospheric humidity and in particular to the high moisture level when the sarcophagus was mounted on an aerated concrete pedestal in the very damp church, rehydration to gypsum was very rapid and was accompanied by stresses in line with the heterogeneity of material as described above. This led to severe deformation and in some areas to cracks and to disintegration of the structure in the form of expansions or swelling of the stone texture (see fig. 2).

Hence from the scientific and technical point of view there was a most unfortunate combination of harmful factors that could neither have been expected nor foreseen.
Restoration of the sarcophagus of Duke Melchior von Hatzfeld

Fig. 3: Stalk-like gypsum structure of very fine-grained alabaster formation impregnated and coated with PMMA. The large bubbles (vacuoles, below) are occasional places where air was trapped. Sample taken from the dog sculpture at a depth of approx. 10 cm (SEM picture).

Fig. 4: Coarse gypsum crystal (left) with synthetic resin coatings. The ring-shaped objects are cavities in the crystal which are lined with a film of resin. The flaky body on the right is probably a newly developed anhydrite with a porous structure. Sample taken from a depth of approx. 10 cm (SEM picture).
3. DEVELOPMENT OF RESTORATION METHODS

Several avenues had to be explored before a successful, practicable method was found. The conservation testing process lasted from 1986 until into 1998.

Experiments aimed at removing the resin by means various solvents were unsuccessful. Either hardly anything dissolved, or the process of dissolving caused severe swelling of the entire structure, so this approach was rejected. It also proved impossible to destroy the resin physically.

Subsequently, in the years up to 1996 various cold-hardening PMMA-based artificial resins were tested. PMMA products made by a company in Frankfurt proved to be the best base and had been tried out several times previously. The products in question were 3 types of synthetic resin, as follows:

1) Finish X30 (or X40) PMMA resin, which hardens physically and is dissolved in Xylene. This was used in different concentrations as:
   - A stabiliser and strengthener in the form of impregnation
   - As a preliminary treatment on powdery decay areas.

2) A PMMA-based synthetic resin adhesive that constitutes a reactive MMA resin that interlaces into a PMMA resin when mixed with hardeners and catalysts. It was used as:
   - A binder for a mortar with adhesive properties and for new shaping
   - A binder for materials for injecting into cracks (strongly adherent)
   - An adhesive

3) Motema-WPC, a water-soluble acrylic suspension that can also be diluted with water. This was used as:
   - A base for retouching paint, for which it was blended with pigments.
   - A binder for shaping and repair mortars

A team of restorers headed by Georg Schmid (of Messrs. Aedis, Stuttgart-Möglingen) devised the recipes for the various materials based on the above resins, optimised their properties for the purposes of application, and coordinated colours. Our job was by conducting stress tests to identify the versions that were the best technically, and the most stable (cf Table 1).
Table 1: Composition of the restoration materials employed
(Restoration expert Georg Schmid and team, Möglingen).

<table>
<thead>
<tr>
<th>Application</th>
<th>Description/Recipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive mortar, fine formula for repair and shaping</td>
<td>FM1= Acrylic resin suspension (Motema WPC) binder blended with Lenzin (natural gypsum) filler to a stiff, doughy consistency.</td>
</tr>
<tr>
<td>Injection mortar for adhesive and bridging of the cracks</td>
<td>I2= 1 part*) resin (Motema injection PMMA 220) + 1% by weight (in relation to the resin) peroxide catalyst plus 2 parts glass pellets &lt;50µ.</td>
</tr>
<tr>
<td>Structural strengthening of the damaged alabaster regions and pre-treatment of sides of cracks</td>
<td>Impregnation with 5% PMMA solution Finish X40 (further diluted with Xylol to 5% resin content, results cf. Table 2).</td>
</tr>
<tr>
<td>Intermediate treatment (intermediate varnish)</td>
<td>Impregnation with Finish X40, diluted to 5% resin content with ethyl acetate (to prevent previously applied coatings from dissolution.)</td>
</tr>
<tr>
<td>Final treatment, retouching paint.</td>
<td>R1 = Retouching of repair mortars (pigments and Motema-WPC binder, i. e. water polymer coating, Pigments: Mixol: ground, natural standard pigment mixtures).</td>
</tr>
</tbody>
</table>

*) = parts by weight

Preliminary testing of the resins to establish their suitability

The synthetic resins were investigated in several tests to establish their suitability and durability. This included artificial ageing simulations, tests to establish their penetration into the alabaster – which in cracks included measuring adhesion and determining their strengthening effect. All this was done using various recipes. Here we show, by way of example, only the increase in resistance to pressure, and adhesion (Tables 2 and 3).

Strengthening the alabaster

Strengthening was required because some of the alabaster had become powdery in defective parts and on the surface. Powdery layers along the sides of some cracks also needed to be stabilised before sealing. The gypsum was fully impregnated, to saturation point in the case of samples 1 to 6, with solvents and with Finish X 40 methacrylate solution to strengthen the structure. For comparison, untreated, freshly quarried alabaster material (samples A–C) was measured at the same time (Table 1).
Table 2: Pressure resistance in various strengthened gypsum samples (block, dimensions approx. 5x5x2.5 cm, test following standard DIN EN 1926, test vertical to height).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Treatment of sample</th>
<th>Bulk density [kg/dm³]</th>
<th>Breaking load [N]</th>
<th>Compressive strength [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>strengthened</td>
<td>2.26</td>
<td>23480.00</td>
<td>17.78</td>
</tr>
<tr>
<td>2</td>
<td>strengthened</td>
<td>2.22</td>
<td>40750.00</td>
<td>30.57</td>
</tr>
<tr>
<td>3</td>
<td>strengthened</td>
<td>2.20</td>
<td>34910.00</td>
<td>25.25</td>
</tr>
<tr>
<td>4</td>
<td>strengthened</td>
<td>2.22</td>
<td>59850.00</td>
<td>46.61</td>
</tr>
<tr>
<td>5</td>
<td>strengthened</td>
<td>2.21</td>
<td>25630.00</td>
<td>19.18</td>
</tr>
<tr>
<td>6</td>
<td>strengthened</td>
<td>2.20</td>
<td>60050.00</td>
<td>44.96</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>2.22</strong></td>
<td><strong>40778.33</strong></td>
<td><strong>30.72</strong></td>
</tr>
<tr>
<td>A</td>
<td>gypsum, freshly quarried</td>
<td>2.16</td>
<td>29870.00</td>
<td>19.41</td>
</tr>
<tr>
<td>B</td>
<td>gypsum, freshly quarried</td>
<td>2.24</td>
<td>28560.00</td>
<td>20.41</td>
</tr>
<tr>
<td>C</td>
<td>gypsum, freshly quarried</td>
<td>2.21</td>
<td>21120.00</td>
<td>17.88</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>2.21</strong></td>
<td><strong>26516.67</strong></td>
<td><strong>19.23</strong></td>
</tr>
</tbody>
</table>

Based on these findings, the result of strengthening could be rated very good. There was a substantial increase in resistance to pressure, from 19 to 30 N/mm² on average, equivalent to a rise of c. 50%. An even greater improvement in strength was to be expected in the case of disintegrating gypsoms like those in the sarcophagus, since a larger quantity of saturating material could be absorbed and residual strength had dropped to almost zero because of the destruction process.
Figure 5: Before the restoration, small putto statue with most severe damage as warping, cracks and almost complete disintegration (picture by Georg Schmid).

Figure 6: The same statue after restoration and treatment with 4 steps according to the methods proposed (picture by Georg Schmid).
Sealing the cracks in the alabaster

Numerous cracks in the alabaster and the open joints between the sections had to be tied positively without visible changes. For this, original alabaster material was glued together with various mixtures based on Motema 220 (Table 3).

Table 3: Tensile strength of gluing of two pieces of gypsum with various adhesives based on Motema 220 (measured in accordance with the DIN EN 12 372 standard).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Breaking load, total (N)</th>
<th>Tensile strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1-1 gluing with filled resin*)</td>
<td>1531</td>
<td>0.61</td>
</tr>
<tr>
<td>K1-2 gluing with filled resin</td>
<td>1542</td>
<td>0.61</td>
</tr>
<tr>
<td>K1-3 gluing with filled resin</td>
<td>2044</td>
<td>0.82</td>
</tr>
<tr>
<td>K1-4 gluing with filled resin (premature failure due to crack in gypsum)</td>
<td>144</td>
<td>0.06</td>
</tr>
<tr>
<td>K2 PMMA resin + 1% hardener, unfilled</td>
<td>2049</td>
<td>0.82</td>
</tr>
<tr>
<td>K3 PMMA resin + 1% hardener, unfilled</td>
<td>822</td>
<td>0.33</td>
</tr>
<tr>
<td>Average</td>
<td>1355</td>
<td>0.54</td>
</tr>
</tbody>
</table>

*) comparable to Recipe I2 with the addition of 1% Aerosil (precipitated silicic acid) as a filler.

The findings showed that all tensile tests on glued samples (both filled and unfilled adhesives) have a high level of tensile strength, higher than that of the stone itself. This is shown by the path of the fracture in the stone itself, i.e. a so-called cohesion fracture occurs in the stone.

UV resistance and ageing tests on the finished mixtures

For the sake of certainty, to check the durability of the finished mixtures they were tested for UV resistance. The plan was to expose all recipes that might be considered for use (20 in all) so as to rule out future changes.

A climate simulator of the global UV testing type, model UV 200 RB/20 DU, system Weiss, construction type BAM, was used. In this case, only UV radiation in long-term climatic conditions corresponding to the room climate was used. UV exposure took place in 2 cycles for a total of 300 hours. The samples were inserted vertically and half of each was covered with opaque foil (cf Figs. 4 and 5).

UV radiation was by means of fluorescent lamps that approximate the short-wave part of sunlight. In particular, radiation simulates the high-energy
UV-A and UV-B rays ($\lambda = 300–420$ nm) that could trigger photo-oxidation. The combination of fluorescent lamps employed corresponded to the spectral distribution as per Method B of DIN 53 384 E.

**Results of UV ageing**

No kind of UV ageing or other damage was found to result from storage in the room climate conditions and UV radiation. In this respect, the restoration materials must be described as durable and stable.

**CONCLUDING REMARKS**

These extensive tests created excellent conditions for the tomb’s lasting restoration. Skilful implementation by the team of restorers led by Mr. Georg Schmid/Stuttgart Möglingen reinstated the tomb to its former beauty (see Fig. 1 and 5).

By way of additional protection, the grave chapel containing the sarcophagus is to be air-conditioned with the aim of avoiding alternating strains in future. For the reasons stated at the beginning, a constant climate of approx. 10°C and a maximum of 50% relative humidity is to be aimed for.

**ACKNOWLEDGEMENT**

Thanks to the whole group of people who participated for the long period of investigations and trials until the sarcophagus could be restored, especially to Mr. Otto Wölbert and Mr. Meckes from the LDA who were the driving force of the project and never gave up.

The whole history of the piece of art and its restoration will be published in the upcoming issue of the “Nachrichtenblatt der Denkmalpflege in Baden-Württemberg”, 4/2002 by a team of authors Otto Wölbert (restoration history), Georg Schmid (restoration), Judith Breuer (art history), Robert Vix (Architecture) and Gabriele Grassegger (technical investigations).

**REFERENCES/INTERNAL REPORTS (SELECTION)**
