INVESTIGATIONS ON MASONRY OF THE BLUE TOWER IN BAD WIMPFEN

BESTANDSUNTERSUCHUNGEN AM MAUERWERK DES BLAUEN TURMS IN BAD WIMPFEN

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SUMMARY

At the Blue Tower in Bad Wimpfen, investigations on the historic masonry were carried out to set up a restoration concept. This paper presents the results of compressive strength tests on the natural stone and the historic mortar of the masonry as well as mineralogical investigations on salt efflorescences at natural stones and masonry mortar in the façade with x-ray diffraction (XRD) and thin section.

ZUSAMMENFASSUNG

Am Blauen Turm in Bad Wimpfen wurden für die Erstellung eines Sanierungskonzeptes umfangreiche Untersuchungen des historischen Mauerwerks durchgeführt. In diesem Beitrag werden die Ergebnisse der Druckfestigkeitsuntersuchungen am Naturstein und historischen Mörtel des Mauerwerks sowie die mineralogischen Untersuchungen mittels Röntgenbeugungs- und Dünnschliffanalyse an Salzausblühungen der Fassade, den Natursteinen und dem Mauermörtel dargestellt.

KEYWORDS: Masonry, natural stone, mortar, compressive strength, XRD, thin section analysis

1. MOTIVATION

The Blue Tower in Bad Wimpfen is part of a Staufer imperial palatinate and was built about 800 years ago. In the course of time, the appearance of the tower changed several times. This was usually due to heavy fire events. The tower is built with local limestone of Middle Triassic age. The limestone is part of the

Germanic Trias and the Muschelkalk consists of a sequence of limestone (grey coloured) and dolomitic beds (brown coloured when deteriorated).

After the event of fire in 1848 a first extensive documented renovation took place in the years 1851/1852. After this renovation, static problems occurred which necessitated further safety and renovation measures. The opening of several cracks in the masonry made of local limestone required the installation of four tie bolts at the end of the 19th century. In 1903 further vertical cracks occurred in the masonry and in 1907 four additional ring beams were installed. In 1972 the masonry of the tower was again in very bad condition and the first pre-stressed anchors and grout injections were performed by Pieper. A last major fire in 1984 again destroyed the pyramidal tower roof. During the reconstruction of the tower roof, progressive cracking, mortar damage and efflorescence were surveyed in a first scientific program by the TH Karlsruhe (SFB 315 „Erhalten historisch bedeutsamer Bauwerke“) in 1985.

In 2012, the consulting engineers Barthel & Maus Beratende Ingenieure GmbH were commissioned to document the ongoing damage, to determine the cause of the damage and to set up a restoration concept.

In 2013, the MPA University Stuttgart was involved in this project and commissioned with the necessary investigations to determine the status of the tower and to assist in the preparation of a restoration concept.

2. INVESTIGATION PROGRAM

First, the condition of the tower was visually inspected and subsequently drilling points for material samples for further investigations of the used natural stone and the existing masonry mortar were defined. The basis for the definition of the drilling points were the ground radar measurements made by GGU. The compressive strength of the natural stone and the masonry mortar was to be tested on the sample material taken from the cores. Furthermore, the mortar samples and the natural stones were examined by X-ray diffractometry and thin section analysis with respect to their mineralogical composition.

In the visual assessment of the façade surfaces, additional scratch samples of salt efflorescences were taken at eye-catching spots for examination by X-ray diffractometry.

3. TEST RESULTS

3.1 COMPRESSIVE STRENGTH OF NATURAL STONE

From the larger cores cylinders of triassic limestone, called “Muschelkalk-stein”, pieces were drilled at right angles to the core axis (loading direction in

Table 1: Results of the compressive strength tests on the natural stones of the drilling cores based on DIN EN 1926 [1]

Side	Core	Sam-ple	Cylin-der No.	Depth in core [cm]	Ø [mm]	Height [mm]	Bulk density [kg/m³]	Compres-sive strength [MPa]
East	1	1	1	10-20	50,9	54,7	2720	230
			2		50,9	53,6	2715	214
		2	1	40-50	50,9	54,3	2711	242
			2		50,9	53,4	2720	200
		3	1	120-130	50,9	51,7	2660	154
West	7	3	1	70-80	50,9	53,7	2714	198
	14	1	1	100-110	50,9	53,3	2717	250
			2		50,9	52,9	2715	258
	15	1	1	30-40	50,9	53,5	2681	166
			2		50,9	53,3	2675	167
		2	1	80-90	34,9	41,2	2375	136
			2		34,9	40,0	2386	109
South	4	1	1	10-20	50,9	53,8	2708	196
			2		50,9	54,4	2703	196
		2	1	50-60	50,9	53,9	2706	217
		3	1	80-90	50,9	54,8	2433	65
			2		50,9	55,5	2366	57
	5	3	1	130-140	50,9	54,5	2683	159
						Mean:	**2633**	**179**
						Standard deviation:	**135**	**58**
						Variation coefficient [%]:	**5,1**	**32,7**

the tower) to determine the compressive strength in accordance with DIN EN 1926 [1]with a diameter of approx. 50 mm or 35 mm. The cylinders then were cut to a height of approx. 50 mm or 35 mm and the loading surfaces of the cylinders were ground. On average, a compressive strength of 179 MPa was determined (values of 57-258 MPa). The average bulk density was 2633 kg/m³ (values from 2366 to 2720 kg/m³).

The individual results of the compressive strength tests are summarized in Table 1.

Correlation of the compressive strength values of the limestones with the depth of extraction is not possible. There is also no obvious correlation between exposition and compressive strength of the natural stones.

The Muschelkalk evidently show many cracks and natural beds. The compressive strength tests were carried out on largely undisturbed samples and thus represent the upper limit of the expected compressive strength for these natural stones.

Overall, the scatter of individual values in the compressive strength tests of the natural stones is high. The statistical evaluation of the data showed a 5% quantile (at a confidence level of 95%) for the compressive strength of 58 MPa.

The statistical evaluation was carried out in accordance with DIN EN 1926 [1], assuming a logarithmic normal distribution and a k-factor of 2.453 for quantile calculation for a random sample of 18 (confidence level 95%) according to DIN EN ISO 16269-6 [2].

3.2 COMPRESSIVE STRENGTH OF HISTORIC MORTAR

From the constituents of the drilling cores, pieces of the historic mortar were selected, at which a determination of the compressive strength was still possible. Microscopic investigations demonstrated lime lumps, a characteristic feature of many historic and mostly non-hydraulic mortars. These lumps of lime which result naturally during the slaking process of burnt lime with wet sand reduce the mortar's water requirements and increase its autogenous healing properties. The mortar pieces were equalized with gypsum and the joint compressive strength was determined on the basis of DIN 18555-9, method III [3].

On average, a compressive strength of the historic mortar of 5.5 N/mm² was determined (values of 2.3 - 14.1 N/mm²). The scatter of the results was very high.

The results of the determination of the compressive strength on the historical mortar are summarized in Table 2.

The statistical evaluation of the compressive strength of the historic mortar was carried out analogously to section 3.1 assuming a logarithmic normal distribution.

The evaluation of the data showed a 5% quantile (at a confidence level of 95%) for the compressive strength of the mortar of 1.5 N/mm².

Table 2: Results of the compressive strength test on the historic mortar from the drilling cores based on DIN 18555-9, method III [3]

<table>
<tr><th>Side</th><th>Core</th><th>Sam-ple</th><th>Speci-men No.</th><th>Depth in core [cm]</th><th>Ø [mm]</th><th>Height [mm]</th><th>Breaking load [kN]</th><th>Compressive strength [N/mm²]</th></tr>
<tr><td rowspan="3">South</td><td rowspan="3">5</td><td rowspan="3">1</td><td>1</td><td rowspan="3">7-20</td><td>20</td><td>21,0</td><td>1,802</td><td>5,74</td></tr>
<tr><td>2</td><td>20</td><td>32,0</td><td>1,012</td><td>3,22</td></tr>
<tr><td>3</td><td>20</td><td>27,0</td><td>1,408</td><td>4,48</td></tr>
<tr><td rowspan="11">West</td><td rowspan="7">7</td><td rowspan="2">1</td><td>1</td><td rowspan="2">20-30</td><td>20</td><td>31,0</td><td>2,539</td><td>8,08</td></tr>
<tr><td>2</td><td>20</td><td>27,0</td><td>2,583</td><td>8,22</td></tr>
<tr><td>2</td><td>1</td><td>50-60</td><td>80</td><td>88,2</td><td>18,86</td><td>3,75</td></tr>
<tr><td rowspan="3">4</td><td>1</td><td rowspan="3">100-110</td><td>20</td><td>33,0</td><td>1,053</td><td>3,35</td></tr>
<tr><td>2</td><td>20</td><td>23,0</td><td>0,730</td><td>2,32</td></tr>
<tr><td>3</td><td>20</td><td>28,5</td><td>2,453</td><td>7,81</td></tr>
<tr><td>5</td><td>1</td><td>130-140</td><td>20</td><td>45,0</td><td>2,329</td><td>7,41</td></tr>
<tr><td rowspan="2">9</td><td rowspan="2">1</td><td>1</td><td rowspan="2">100-110</td><td>20</td><td>21,0</td><td>1,631</td><td>5,19</td></tr>
<tr><td>2</td><td>20</td><td>29,0</td><td>1,609</td><td>5,12</td></tr>
<tr><td rowspan="2">13</td><td rowspan="2">1</td><td>1</td><td rowspan="2">30-40</td><td>20</td><td>36,0</td><td>1,273</td><td>4,05</td></tr>
<tr><td>2</td><td>20</td><td>42,0</td><td>0,844</td><td>2,69</td></tr>
<tr><td rowspan="3">North</td><td rowspan="2">11</td><td rowspan="2">2</td><td>1</td><td rowspan="2">40-50</td><td>20</td><td>25,0</td><td>0,914</td><td>2,91</td></tr>
<tr><td>2</td><td>20</td><td>27,0</td><td>4,441</td><td>14,14</td></tr>
<tr><td>12</td><td>1</td><td>1</td><td>10-20</td><td>20</td><td>25,0</td><td>1,799</td><td>5,73</td></tr>
<tr><td colspan="8">Mean:</td><td>5,5</td></tr>
<tr><td colspan="8">Standard deviation:</td><td>2,86</td></tr>
<tr><td colspan="8">Variation coefficient [%]:</td><td>51,5</td></tr>
</table>

A k-factor of 2.524 was used for the quantile calculation for a random sample of 17 (confidence level 95%) according to DIN EN ISO 16269-6 [2].

In the test of the compressive strength of the historical mortar, in some cases quite high compressive strength values have been determined. It should be noted that in the mortar samples some aggregates with a large diameter in relation to the sample thickness were present and this can lead to a falsification of the results. In addition, these are mortar samples that have survived the wet drilling process to the extent that it was still possible to test the compressive strength. So the samples tested here are basically the best quality historic mortar that still exists in the masonry.

As the tests sometimes resulted in unusually high compressive strengths for the historic mortar (eg. due to large aggregates in the mortar sample in relation to the sample height), the results were again checked for plausibility and it was decided to neglect all results above 6 N/mm² and to statistically evaluate the residual data again. This resulted in an average value of 4.1 N/mm² for the remaining 12 measured values. The value for the 5% quantile (at a confidence level of 95%) for mortar compressive strength increased to 1.74 N/mm² due to less scatter (k-factor of 2.737 for quantile calculation for a random sample of 12 (confidence level 95%) according to DIN EN ISO 16269-6 [2]).

With regard to the mortar compressive strength, no significant correlation between compressive strength and the orientation of the tower or the depth of the examined samples could be determined.

3.3 RESULTS OF X-RAY DIFFRACTOMETRY

Scratch samples of salt efflorescence on the surface of limestone/dolomitic limestone and sandstone as well as the sieved binder fraction (< 0.063 mm) of the historic mortar were analysed for their phase composition by X-ray diffraction. The mineralogical phase analysis of the salt efflorescence samples revealed some recurring salts in the efflorescence (see Table 3 and Fig. 1). The majority of salt efflorescences occurred at the stone and torkret mortar surface close to the historic lavatory bay at the southern facade.

During the restoration in 1971/72, done by Pieper, older historic joint mortars were replaced deeply by sprayed mortar with Portland cement in the binder. This sprayable mortar is well-known as Torkret mortar.

Table 3: Evaluation of the scratch samples of salt efflorescence of the stone surfaces and mortar surfaces

Sample	Salt
P 6	Gypsum, syngenite
P 11	Potassium nitrate, syngenite, potassium-sodium sulphate
P 12	Potassium nitrate, potassium-sodium sulphate, darapskite
P 13	Potassium nitrate, potassium-sodium sulphate, urea
P 15	Potassium nitrate, potassium-sodium sulphate, urea
P 16	Potassium nitrate, potassium-sodium sulphate, urea
P 20	Potassium nitrate, gypsum
P 52	Potassium nitrate, aphthitalite, darapskite, gypsum, syngenite
P 53	Potassium nitrate, aphthitalite, darapskite
P 58	Potassium nitrate, aphthitalite, darapskite, gypsum, syngenite
BK 3	Calcite, portlandite

A typical diffraction pattern with identified salt phases is shown in Fig. 1.

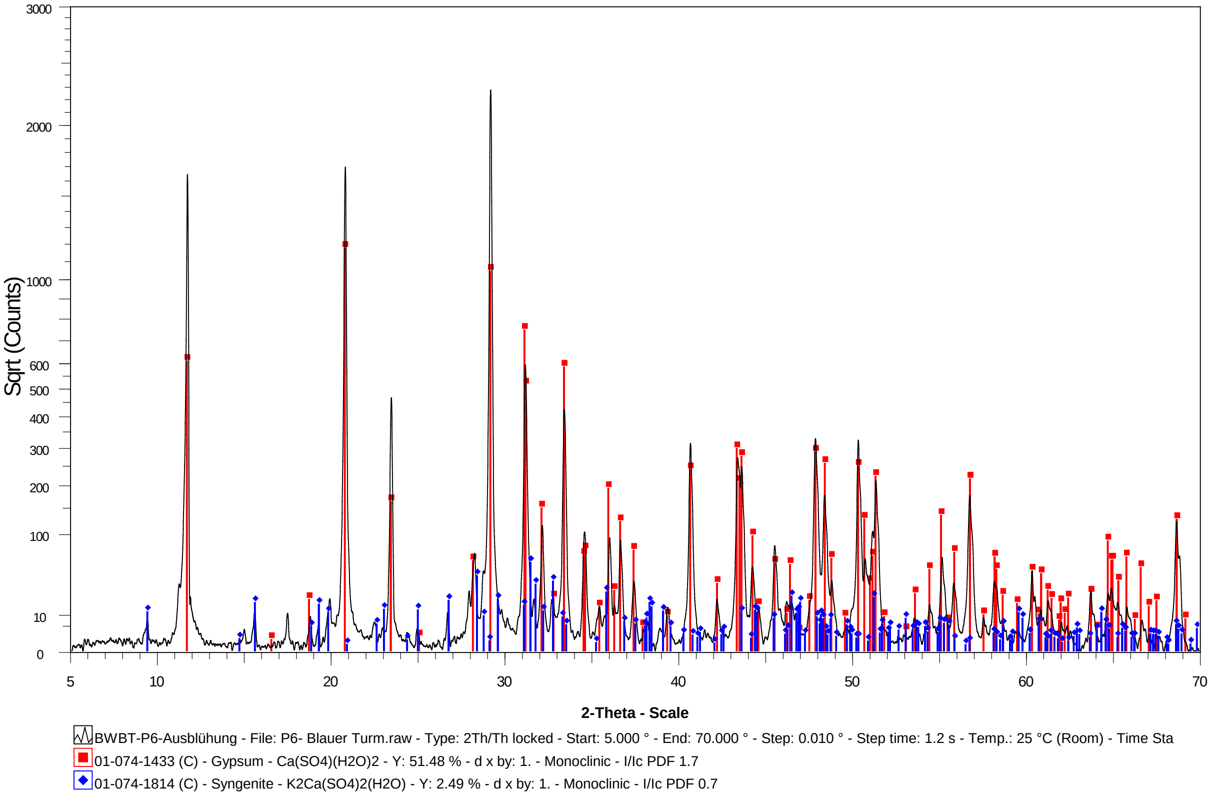

Fig. 1: X-ray diffraction pattern of sample 6, efflorescence, consisting of a lot of gypsum and some syngenite

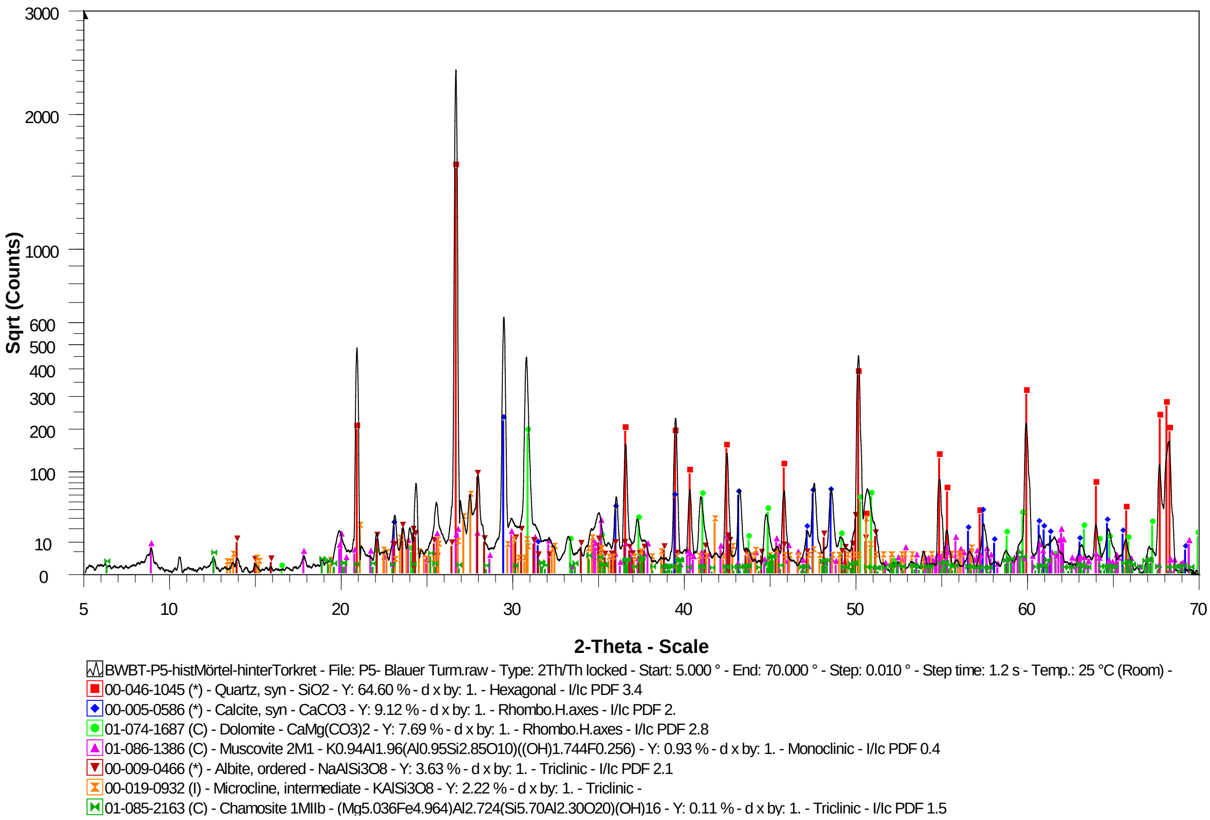

Fig. 2: X-ray diffraction pattern of sample 5, binder of the historical joint mortar below the younger Torkret mortar

An examination of the binder fraction < 0.063 mm of the historic mortar (see Fig. 2) showed almost exclusively calcite as a binder phase in addition to small amounts of dolomite.

Hydrocalumit (a calcium aluminate hydrate) was found in some samples. The remaining phases (quartz, feldspar, etc.) come from non-extractable residual proportions of rock aggregates. From the phase inventory of the binder samples, the use of a limestone with only small amounts of clays (impurities) for quicklime production in the Staufer period can be deviated.

The phase analysis on dolomitic limestone (see Fig. 4) has not revealed any unusual mineral composition. It consists of calcite, dolomite, ankerite, small amounts of quartz and aragonite (mussel shells). The dark brown colour is caused by residues of iron oxides/hydroxides formed by deterioration.

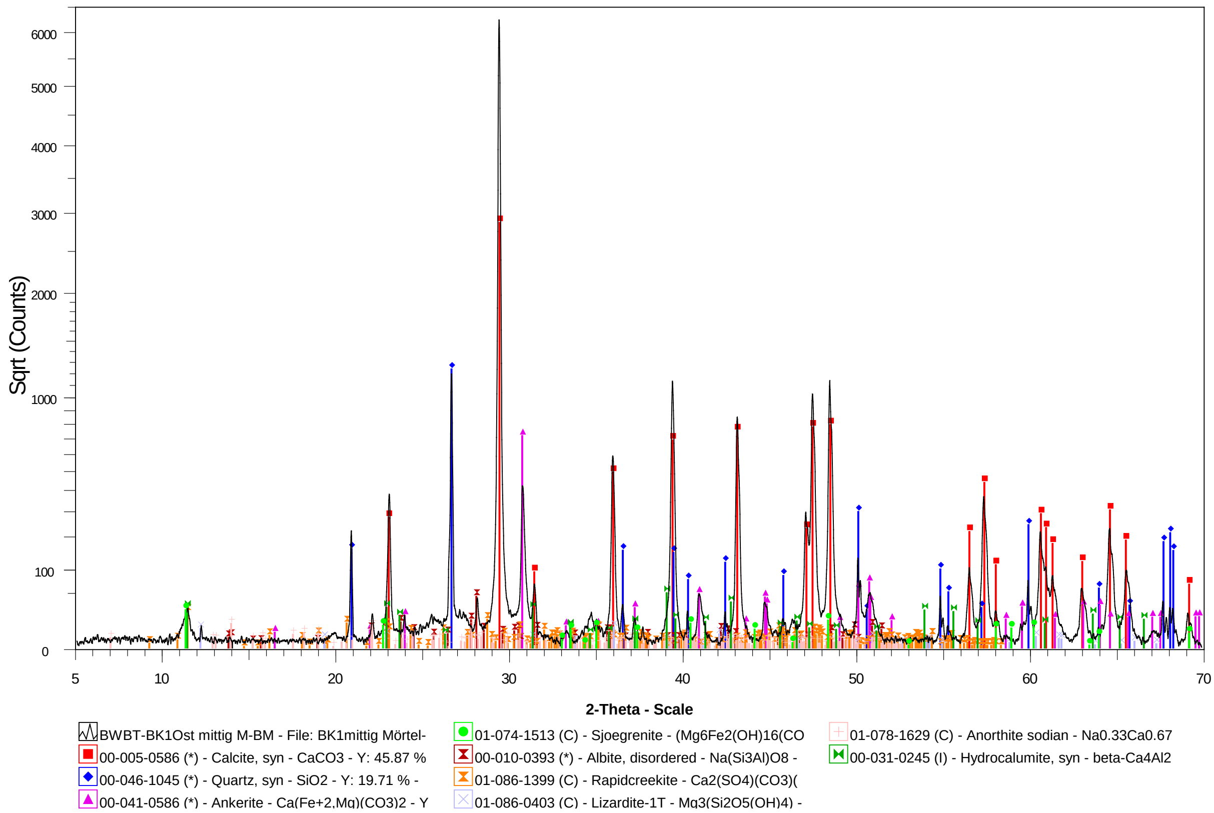

Fig. 3: Drilling core BK 1 east centric, mortar sample, investigation of the binder fraction < 0.063mm, predominantly carbonate bound, small amounts of X-ray amorphous fractions and hydrocalumite indicate marly limestone as raw material of quicklime production

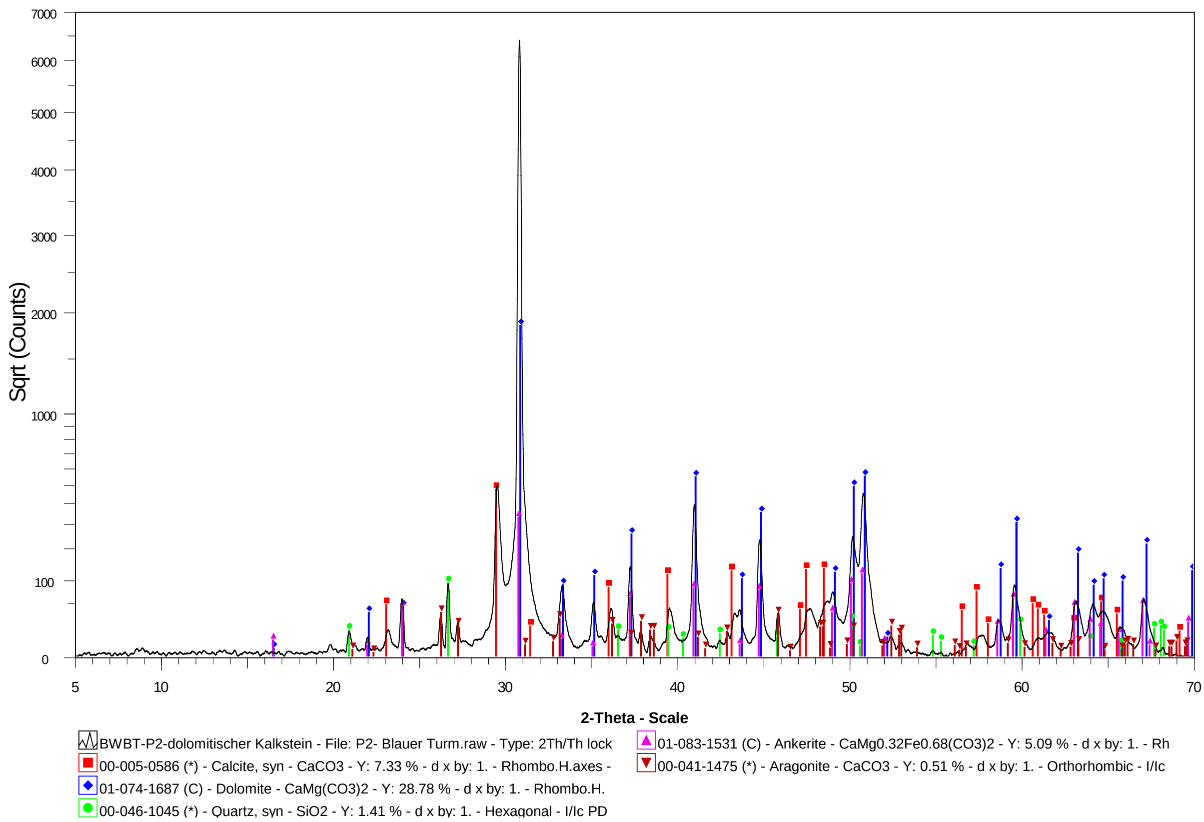

Fig. 4: X-ray diffraction pattern of sample 2, brownish, dolomitic limestone

3.4 EXAMINATION OF THIN SECTIONS OF THE HISTORIC MORTAR

The historic lime mortar in the masonry was made of burnt lime, wet sand and well-rounded gravel from the nearby river Neckar. Thin section analysis showed high porosity and evidence for leaching of the carbonate binder. Lumps and overburnt quick lime (see Fig. 5) indicates mixing of quick lime with wet gravel and sand in tubs (Fig. 6) at the construction site. The use of higher amounts of gravel from the Neckar river and less sand led to gap grading in the grain size distribution curve.

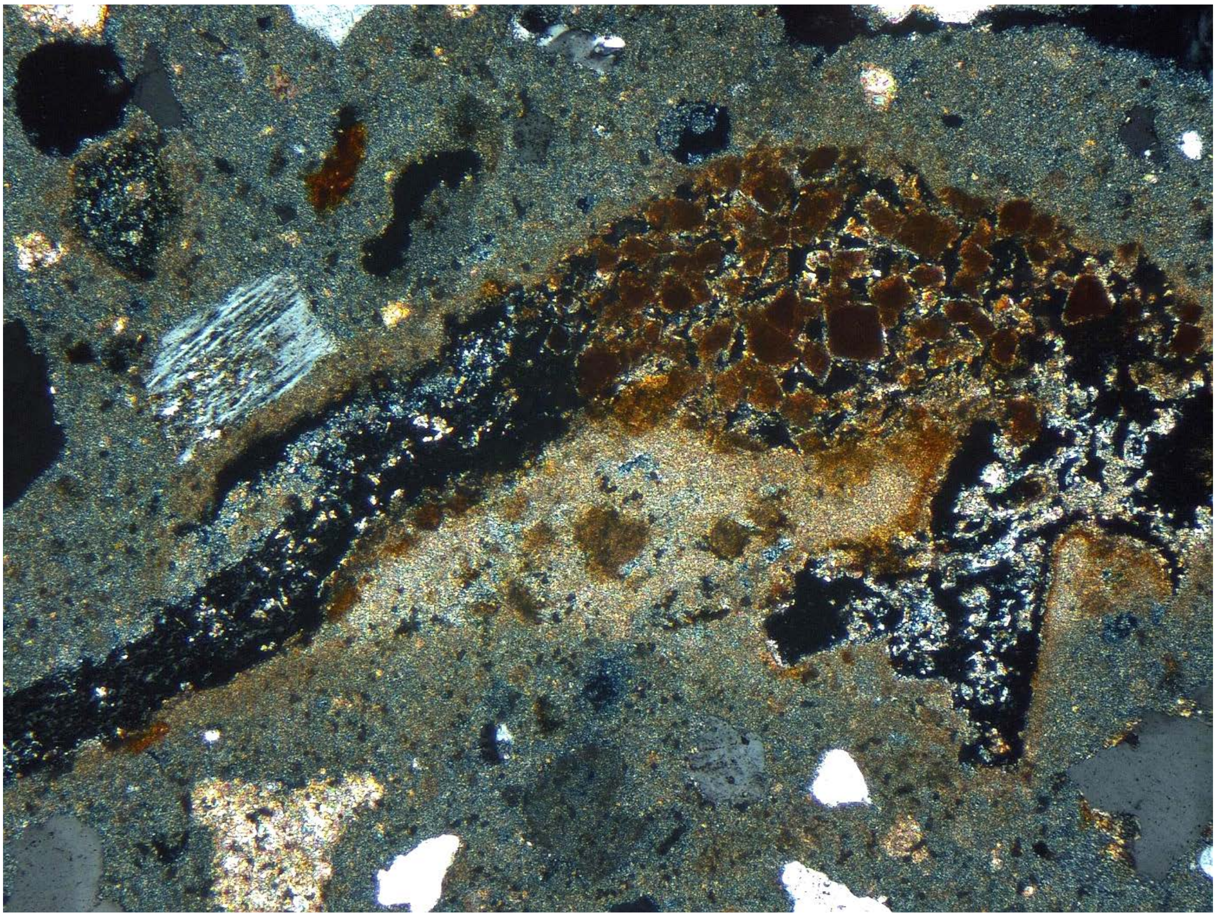

Fig. 5: Historic lime mortar in thin section under crossed polarized light. In the middle of the picture indication of overburnt quick lime is visible

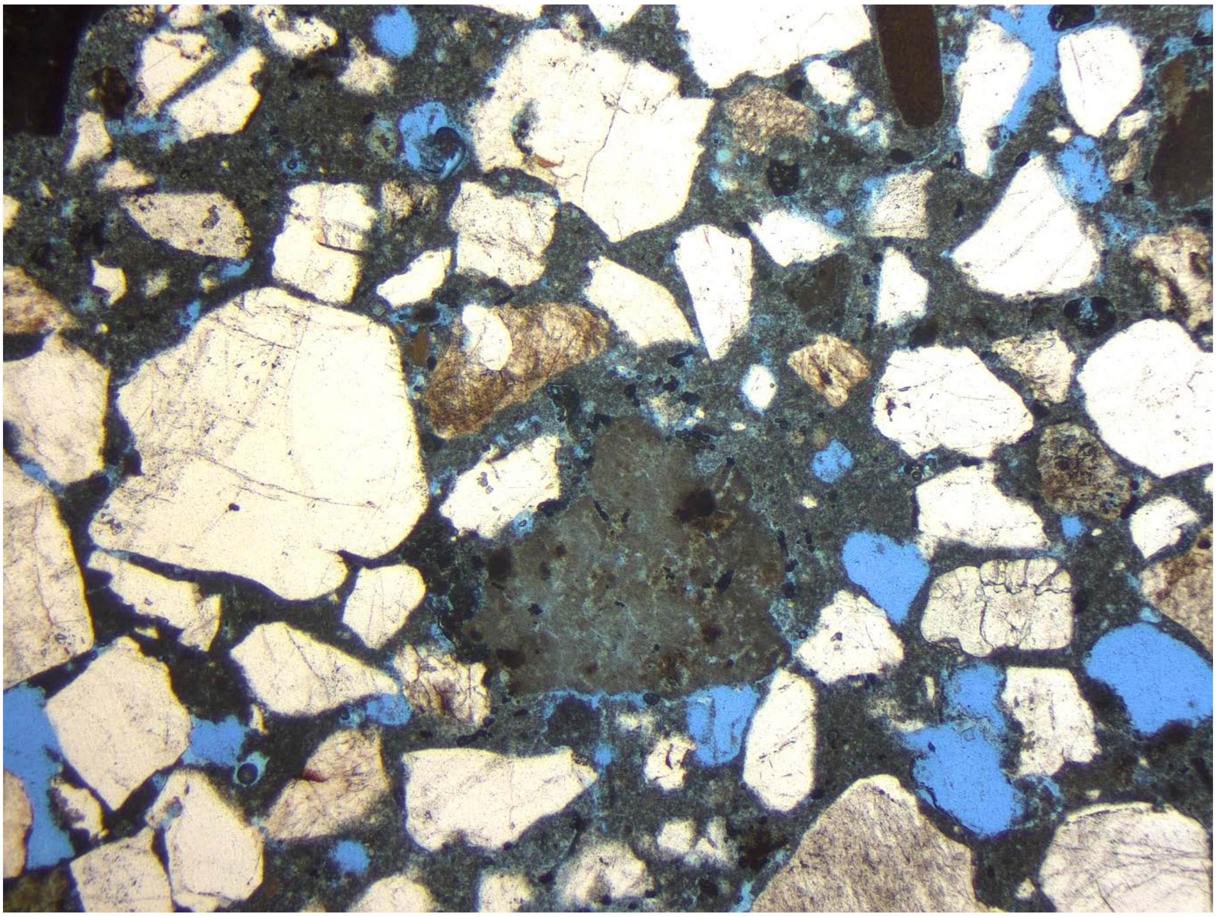

Fig. 6: Historic lime mortar showing lumps, a result of mixing burnt lime with wet sand in a tub, plane polarized light

4. SUMMARY

The investigations of the compressive strength of natural stones showed a mean value of 179 MPa. The statistical evaluation of the data according to [1] resulted in a 5% quantile value for the natural stone of the Blue Tower of 58 MPa.

The tests based on [3] of the compressive strength of the historic mortar gave a mean value of 4.05 N/mm² and a 5% quantile value for the compressive strength of the historic mortar of 1.74 N/mm² (determined without consideration of untypically high individual values).

Based on the test results of the natural stone and the historical mortar, a design value for the historical masonry should be deduced. However, this was not possible due to the bad condition of the tower (many severe vertical cracks in the facade) and the unclear structure of the core masonry of the tower. Therefore masonry openings were made to assess the quality of the masonry and to obtain further samples for material testing. However, these results are not part of this article.

The chemical - mineralogical investigations on the historic mortar resulted in a non-hydraulic lime mortar. This was mixed as dry-leached hot lime mortar at the construction site of burnt lime and wet sand / gravel from the nearby river Neckar. This can be seen from the many lime lumps and the well-rounded aggregates in the mortar.

Most of the salt efflorescences occured close to the historic lavatory bay at the southern facade. The composition consists mainly of nitrates and complex alkali sulphates.

REFERENCES

[1] DIN EN 1926:2007-03 - *Natural stone test methods - Determination of uniaxial compressive strength*

[2] DIN ISO 16269-6:2009-10 - *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

[3] DIN 18555-9:1999-09 - *Testing of mortars containing mineral binders – Part 9: Determination of the compressive strength of hardened mortars in the bed joint*