

# Historic Renders and Their Weathering at the Temple Wat Mahathat, UNESCO World Heritage Site of Ayutthaya, Thailand



H. Siedel, E. Wendler and B. Ullrich

**Abstract** Investigations of renders on buildings of the temple Wat Mahathat in Ayutthaya showed that two different types of mortars have been applied. The original mortars from the period before 1767 are lime mortars, whereas hydraulic mortars were obviously used for restoration and stabilisation of the ruins in the 20th century. The use of organic additives like starch from boiled rice for historic mortar production is suspected, but could not be proved by analytical means. The analysis of probable additives is made more difficult due to microbiological activity in tropical climate which might have led to enzymatical decomposition of the primary organic compounds. The porosity and the hardness of renders, analysed in situ by easily applicable, non- or less-destructive investigations like Karsten tube measurements and drilling resistance, reflect a wide range of different weathering states. Therefore, appropriate restoration measures must be planned in detail for every part of the buildings; an overall treatment with water repellents cannot be recommended. The formation of peculiar, alveolar-like structures on some renders is caused by hardening of the surfaces along cracks due to intensified transport of dissolved components.

**Keywords** Rendered brickwork · Lime mortars · Hydraulic mortars  
Organic additives · Weathering

---

H. Siedel (✉) · B. Ullrich

TU Dresden, Institute of Geotechnical Engineering, Dresden, Germany  
e-mail: Heiner.Siedel@tu-dresden.de

B. Ullrich

e-mail: Bernd.Ullrich@tu-dresden.de

E. Wendler

Munich Stone Conservation Laboratories, Munich, Germany  
e-mail: e.wendler@t-online.de

## 1 Introduction

The temple Wat Mahathat, a former royal monastery, is one of some historic temple complexes at the site of the old capital of Thailand, Ayutthaya, which was destroyed by Burmese invaders in 1767 and fell into ruins after the capital was moved to Bangkok. Ayutthaya is situated about 70 km north of Bangkok. The entire site which became part of the UNESCO World Heritage in 1991 is located on the banks of the Lop Buri River. An oxbow of this river offered a natural defence to the old capital on the north, west and south, whereas a canal on the east across the neck of land made the city an island and completed its defences as early as in the 14th century (Van Beek and Invernizzi Tettoni 1999). The buildings and walls of Wat Mahathat erected between the 14th and the 18th century are made of bricks covered with renders and plasters, and ornamented with stucco. The complex of the temple consisted of a central prang (sanctuary), i.e. a tall building with rounded top, ringed by open courtyards, enclosed by a wall and smaller prangs, a construction scheme which goes back to the older Khmer style architecture (Van Beek and Invernizzi Tettoni 1999). A large ubosot (the congregation and ordination hall of a monastery, reserved solely for the monks) and some vihans (assembly halls for monks and laity) can still be recognised by remnants of bases and walls. The rebuilt, second central prang from 1633 which had a height of about 50 metres collapsed again in 1911. Today only its base has remained. Little is known neither about the history of the site since the destruction nor about younger restoration measures from the 19th and 20th century, respectively. In 1956 the Fine Arts Department of Thailand undertook excavations around the central prang. Although in ruins today, the temple is still one of the most impressive places in historic Ayutthaya and attracts thousands of visitors every year. A field campaign at Wat Mahathat aimed at the characterisation of the remnants of renders on the walls of the buildings and of the enclosure. Furthermore, the weathering state of the remnants is characterised.

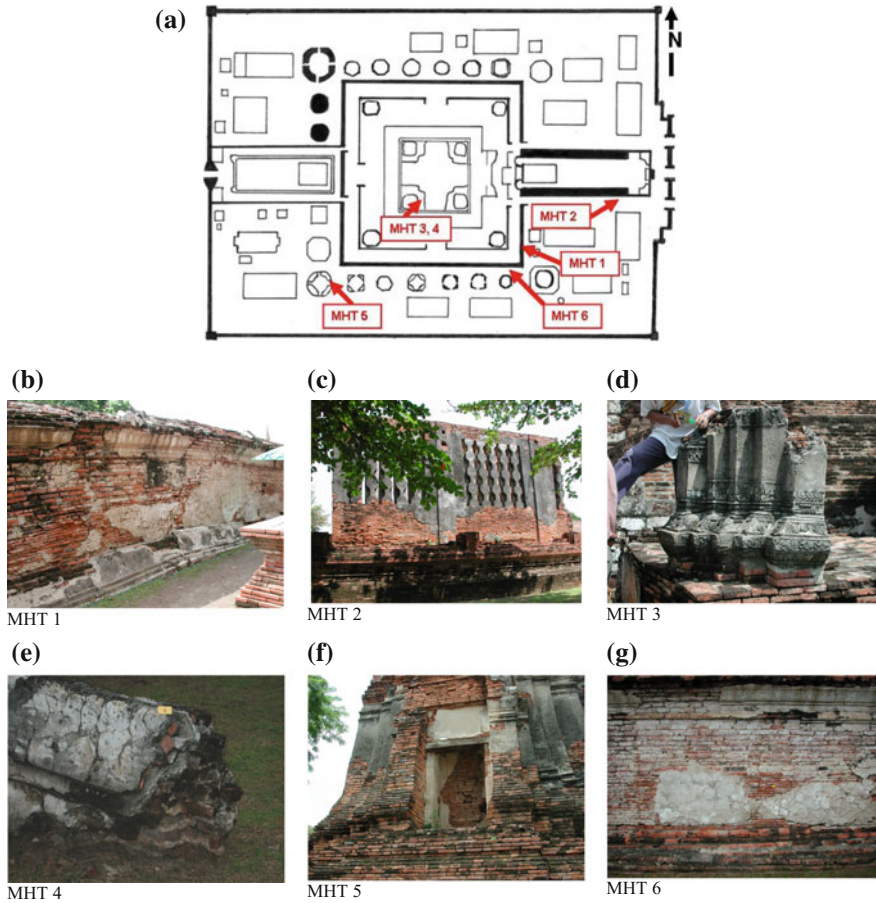
## 2 Setting and Sampling Strategy

At first sight, the remnants of renders exposed on the brick walls show visibly different states of weathering or preservation, respectively. Some of them seem to be weak with rough, sandy surfaces. Others are rough, but stable and stained by thin black surface layers, whereas another group shows dense, smooth and sometimes glossy surfaces. The thickness of the renders reaches from some millimetres up to some centimetres; the thicker ones were applied in at least two layers. Since the possibility to take samples was limited at the Heritage site, representative, visually different types of mortars were sampled at six points selected together with Thai experts from the Fine Arts Department and the Silpakorn University Bangkok (Table 1; Fig. 1). Unfortunately, the samples could not be assigned to certain construction or restoration periods, because detailed knowledge about the construction history and also about younger restoration measures is still lacking. Most

**Table 1** Locations of sampling and in situ measurements and the investigated mortars

Sampling place	Description	Mortar	Peculiarities
MHT1	East side of the inner enclosure wall, near the SE corner; render	Light grey to brownish mortar; brick in the aggregate; lime lumps (MHT1/S2 and S3)	Different weathering states from smooth (“polished”) to rough, back-weathered surface; cracks, in places alveolar-like structures
MHT2	Fragment of the southern wall of the ubosot (congregation and ordination hall), east of the inner enclosure; render	Light grey mortar; lime lumps, brick in aggregate; rarely shell fragments (MHT2/S6)	Stained black on the rough surface
MHT3	Architectural fragment with pillar bases from the central prang, render/stucco with ornaments, three layers (ca. 5 cm thick)	Light grey mortar with lime lumps (sample from the outermost, 2 cm thick layer = MHT3/S7)	Black stained, rough surface
MHT4	Isolated architectural fragment fallen from the central prang, with thick render (at least five layers on brick)	Outermost grey render mortar with smooth, dense surface (MHT4/S8)	Partly stained black
MHT5	Render from a niche of the smaller prang outside the enclosure wall at the SW corner	Light grey mortar in two layers (MHT5/S10)	Rough on the surface; limestone pieces in the aggregate
MHT6	South side of the inner enclosure wall, near the SE corner; render	Light grey to brownish mortar (samples: MHT 6/S12 = smooth render; / S13 = joint mortar); brick in the aggregate; lime lumps	Different weathering states from smooth (“polished”) to rough, back-weathered surface; cracks, in places alveolar-like structures

likely the original renders belong to the last rebuilding period in the 17th and 18th century. The selected samples cover the range of different mortars that can be found today at Wat Mahathat and their weathering behaviour in tropical climate. Non-destructive and less-destructive in situ measurements (capillary water uptake with Karsten tube and drilling resistance) completed the investigation programme. Bearing in mind that in South East Asia and India there is an old tradition of using organic additives like molasses (from sugar cane) or water from boiled rice in making plasters, renders and stucco (Sirirat 1999; Chandra 2003), laboratory investigations were carried out to detect eventual small amounts of such additives. Moreover, special attention was drawn to the alveolar-like weathering structures on the walls of the inner enclosure.



**Fig. 1** a–g: Sketch map of Wat Mahathat (a) and documentation of places (b–g) where material samples were taken and in situ measurements were carried out (cf. Table 1)

### 3 Methods

Capillary water uptake per time was measured at various points on the surface of renders in situ by Karsten tube. In case of normal capillary suction (without water transport parallel to the surface or to the depth due to cracks), a  $w$ -value [ $\text{kg}/\text{m}^2 \text{h}^{0.5}$ ] comparable to the  $C$ -value according to DIN EN 1925 can be calculated from the obtained curves (Snethlage and Wendler 1989; Siedel and Siegesmund 2014).

Drilling resistance (DR) (Wendler and Sattler 1996; Siedel and Siegesmund 2014) was measured with a “Durabo” apparatus to test the hardness of renders with high resolution from the surface to the depth. Since the diameter of the drill bit is only 3 mm, the method can be considered to be a ‘less-destructive’ investigation.

The binders of all samples were concentrated by carefully grinding them in an agate mortar and segregating coarse aggregate by sieving. These were characterised for their constituent phases by analysis with X-ray diffraction (XRD) and combined differential thermal analysis (DTA) and thermogravimetric analysis (TG). After thermal analyses with up to 1000 °C heat treatment, they were characterised by XRD again. XRD was performed with Siemens D5000 equipment ( $\text{CoK}\alpha$ , 40 kV, 30 mA, 5–80°, step 0.02°, step time 4 s), DTA/TG with a Netzsch STA 409 PG (in static air, temperature range 25–1000 °C, heating rate 10 K/min). Polished thin sections and rough, broken mortar pieces of selected samples were additionally studied with optical and scanning electronic microscope (SEM). For investigations under SEM analysis was conducted using a Zeiss EVO 50 coupled with a ROENTEC detector XFlash 3001 for standardless elemental analysis by energy-dispersive spectroscopy (EDS). The respective samples were coated with Au/Pd.

Portions of the powdered mortar specimen (some 200 mg) were dispersed in 3 ml of distilled water in an ultrasonic bath for 10 min and then heated up to 80 °C in a water bath for a further two hours. After centrifugation at 4800 U/min for 5 min, the pH and the amount of nitrate in the filtrate have been measured. Then, small portions of the clear solution were analysed qualitatively for starch by a iodine/potassium iodide solution. The clear liquid was evaporated on a glass plate, and FTIR spectra were taken from the deposits (ATR technique, JASCO FTIR spectrometer 4100).

Since starch from rice was the most probable organic component to be expected, a reference sample was produced using pure quartz sand and pure calcium hydroxide (proportion 2:1). A mortar from these components has been prepared using the water from boiled rice. For completion of the mortar curing (carbonation), the specimen was wetted with distilled water once a week for three month. The pH dropped towards neutral within an outermost 3 mm layer showing that calcium carbonate formation was completed in this zone.

To hydrolyse possible traces of oils/fats or proteins, the remainder from the water extraction was treated with 2 N hydrochloric acid and, after completion of the  $\text{CO}_2$  formation from the carbonates, extracted with chloroform (trichloromethane). After removal of the solvent by evaporation on glass plates, FTIR spectra have been taken from deposits (if present).

## 4 Results

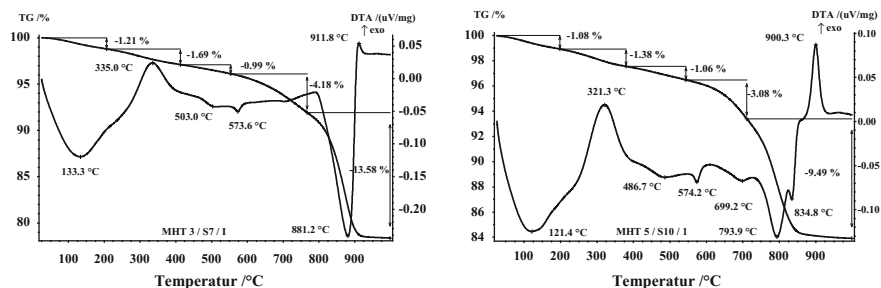
### 4.1 Phase Analysis of the Binders

The results of phase analyses are given in Table 2; typical DTA/TG patterns are displayed in Fig. 2. According to the results of phase analysis of the binders, all samples could be assigned to one of two groups: pure or slightly hydraulic lime

**Table 2** Results of phase analysis of the binders

Sample no. <sup>b</sup>	Calcite (XRD) <sup>a</sup>	Calcite (DTA)	Exothermic reaction 320–340 °C (DTA), weight loss TG (%)	XRD after DTA (1000 °C)
MHT 1/S2 I and II	+/+/+	+/+/+	1.03/1.23	Lime, little larnite
MHT 1/S3 II	+	+	1.79	Wollastonite, little lime
MHT 2/S6 I and II	+/+/+	+/+/+	1.78/1.57	Lime
MHT 3/S7 I	++	++	1.69	Lime, little larnite
MHT 4/S8 I	+	+	1.65	Wollastonite, no lime
MHT 5/S10 I and II	+/+	+/+	1.38/1.21	Wollastonite, no lime
MHT 6/S12	+	+	1.01	Wollastonite, no lime
MHT 6/S13 joint	++	++	1.13	Lime, little larnite

Quartz and feldspar from the aggregate occurred in all samples and are not mentioned in the table<sup>a</sup> assessed by relative peak height<sup>b</sup> Roman numerals: I—near surface; II—behind surface



**Fig. 2** Typical DTA/TG diagrams of mortars from Ayutthaya: MHT 3/S7 I (lime mortar/stucco, left) and MHT 5/S10 I (hydraulic mortar, right)

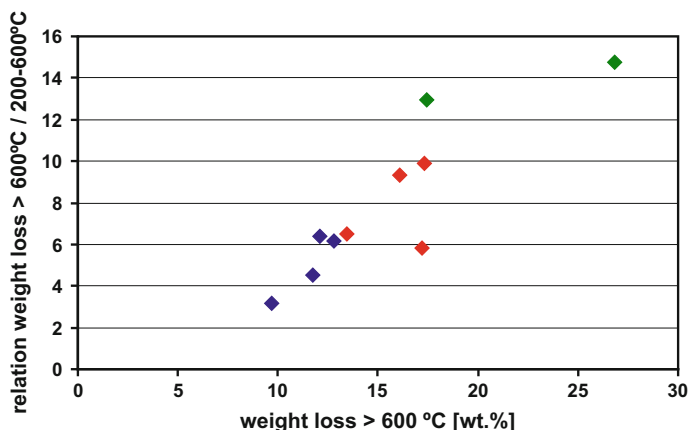
mortars (MHT 1/S2, MHT 2/S6, MHT 3/S7, and the joint mortar MHT 6/S13) and hydraulic mortars (MHT 1/S3, MHT 4/S8, MHT 5/S10 and MHT 6/S12). At least some of the latter seem to be modern cement mortars with little calcite, which might have been produced by carbonation of the surface layer. They are regarded as materials of younger restoration measures from the 20th century, which are not well documented at Wat Mahathat. EDS analyses of binder areas in a thin section of MHT 6/S12 under the SEM showed high contents of SiO<sub>2</sub> beside CaO (in a relation of about 1:2). The formation of a wollastonite phase (CaSiO<sub>3</sub>) and no or little lime (CaO) after 1000 °C heat treatment suggests a remarkable content of reactive SiO<sub>2</sub> in the binder, whereas the mortars with high calcite contents form high lime

contents and sometimes traces of larnite ( $\text{Ca}_2\text{SiO}_4=\text{C}_2\text{S}$ ) after heat treatment. The latter might be due to low contents of hydraulic phases (e.g. formed by reaction of brick fragments in aggregate or minor clay contents in the sand).

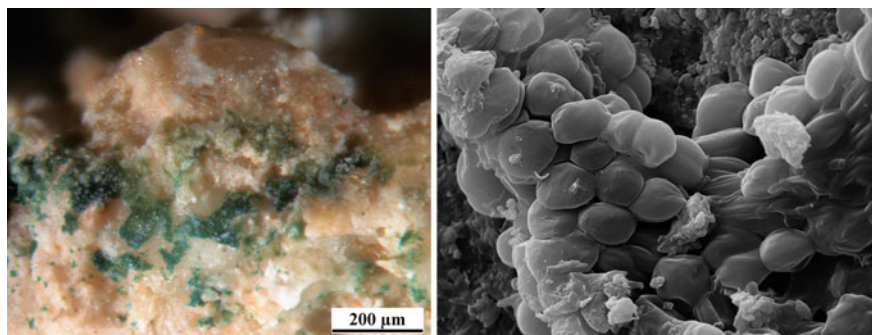
Obviously, the stucco with ornaments from a fragment of the central prang, the blackened render fragments on the brickwork of buildings as well as the analysed joint mortar are lime mortars. Hydraulic mortars, presumably younger additives, occur in some places on the walls of the inner enclosure, on a fragment of the central prang and in the niche of a smaller prang outside the inner enclosure.

Figure 3 shows the relation of the weight losses according to TG at temperatures between 200 and 600 °C (mainly assigned to hydraulic phases which cannot be clearly distinguished in thermal analysis due to their continuous weight loss over a wide range of temperatures, cf. Fig. 2) and >600 °C (assigned to carbonate phases; Moropoulou et al. 1995, 2005) for all investigated samples. The weight loss between 200 and 600 °C used for calculation was corrected by subtracting the weight loss assigned to ignition of organic matter, indicated by an exothermic reaction in DTA (see below). The results, which are in good accordance with the results of XRD analysis (cf. Table 2), allow to distinguish between the pure lime mortars (samples MHT 2/S6 I and II, green), weakly hydraulic limes (MHT1/S2 I and II, MHT 3/S7 I, MHT 6/S13 joint, red) and hydraulic limes (blue).

Some mortars (MHT 1/S3, MHT 2/S6, MHT 3/S7, MHT 4/S8) show a remarkable exothermic reaction in the DTA, connected with weight loss in the TG in the temperature range between 200 and 400 °C (Table 2). This might be due to the ignition of organic matter at these temperatures. The respective mortars show blackened surfaces (MHT 2/S6, MHT 3/S7 and MHT 4/S8) or green staining underneath the surface (MHT 1/S3, Fig. 4) due to microbiological activity.



**Fig. 3** Weight losses in TG indicating carbonate phases vs. those indicating hydraulic phases (Moropoulou et al. 1995, 2005) for the investigated samples. Green: pure lime mortars (MHT2/S6); red: slightly hydraulic mortars (MHT 1/S2, MHT 3/S7 and MHT 6/S13), blue: hydraulic mortars (MHT 1/S3, MHT 4/S8, MHT 5/S10 and MHT 6/S12) (Color figure online)



**Fig. 4** Organic matter in the surface zone of mortar MHT 1/S3 in higher magnitude under the optical microscope (left) and SEM (right; right figure margin = 20  $\mu\text{m}$ ). EDS analyses of the structures in the SEM micrograph showed very high carbon contents

## 4.2 *Investigations into Organic Additives*

Because of the tradition of mortar making with organic additives in Thailand and taking into account the results of the phase analysis from Table 2, additional laboratory analyses were made on selected samples to extract and determine potential organic compounds. The main criterion chosen was the content of lime (as a marker for original historic mortar material).

As can be seen from Table 3, starch is not present in the investigated samples of the monument. However, it is most probable to assume that it has been decomposed after centuries with the help of microorganisms which might be rather active under tropical conditions. Two of the mortars contain significant amounts of nitrate which might be a product resulting from protein decomposition.

As expected from Table 3, the FTIR spectrum of sample MHT 1/S3 II does not fit to the vibration bands of starch extracts (Fig. 5a). However, C–H-vibrations at some  $2900\text{ cm}^{-1}$  can be clearly recognized. Comparing with the spectrum of gum arabic (Fig. 5b), there is a much better correlation though there are some deviations in the fingerprint region due to contaminations with clay and lime. Identical (gum) spectra have been obtained with samples MHT 1/S2 II and MHT 3/S7 I. Some of the samples contained small amounts of oils, and the joint mortar sample MHT 3/S7 I even showed some trace of a nitrogen-organic compound (but no protein could be found).

## 4.3 *Surface Hardness and Water Uptake of Mortars*

Mortars with different weathering states were investigated with respect to their surface hardness and capillarity suction. These parameters are essential for the planning of conservation measures: hard surfaces do not need to be strengthened,



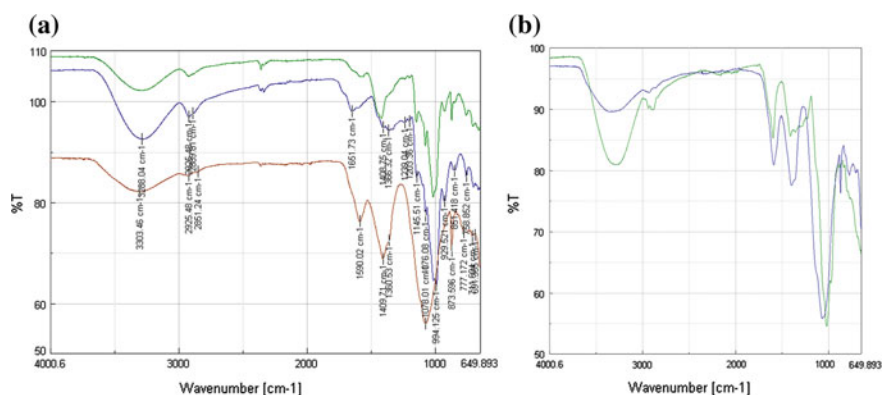
**Table 3** Results of qualitative analysis of organic additives, supported by pH and nitrate content (wt%) of the aqueous extractions as well as by FTIR analysis (n.d. = not determined)

Sample no.	Starch	Gums	Oils/ protein	pH	NO <sub>3</sub> <sup>-</sup> (%)	Comments
MHT 1/S2 II	–	+	±	6.5	<0.1	
MHT 1/S3 II	–	+	++	n. d.	n.d.	carboxylic acids <sup>b</sup>
MHT 2/S6 II	–	–	+	6.0	1.2	carboxylic acids <sup>b</sup>
MHT 3/S7 I	–	+	±	6.0	<0.1	
MHT 6/S13	–	–	? <sup>d</sup>	6.0	1.0	N-containing organic comp <sup>c</sup>
Reference <sup>a</sup>	+	–	–	6.0	–	

<sup>a</sup>Artificial lime mortar admixed with water from rice boiling

<sup>b</sup>after acid hydrolysis in CHCl<sub>3</sub>-extraction. <sup>c,d</sup>after acid hydrolysis in water-extraction

<sup>d</sup>chemical composition not detectable by FTIR

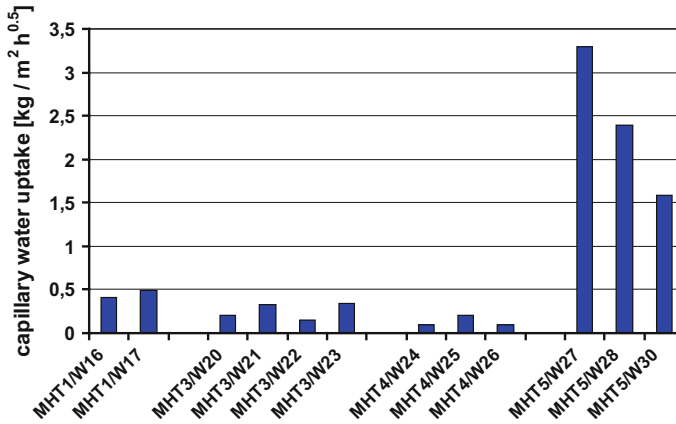


**Fig. 5** **a** FTIR-Spectra from: hot water extractions of starch-containing reference mortar (green) and of sample MHT 1/S3 II (brown); water from boiling rice (blue); **b** FTIR-Spectra from hot water extractions of: sample MHT 1/S3 II (blue) and gum arabic (green) (Color figure online)

and the rates of capillary water absorption give information about the possibility to apply liquid consolidants or water repellent agents. However, the use of the latter is only useful if the uptake of rain water is certainly known to be the predominant factor of weathering.

Especially at the inner enclosure wall (MHT 1, MHT 6), humidity measurements show a high degree of moisture immediately below the render surface, which may lead to a transport and enrichment of dissolved components towards the surface (along the gradient of evaporation).

Dense mortars showing low capillary water uptake can be found in visibly intact areas with smooth, “polished” surfaces (on the enclosure wall, MHT 1 and 6, and on the fragment from the central prang, MHT 4, see Fig. 6). These renders normally consist of two layers: as confirmed by DR measurements, the polished surface is



**Fig. 6** Capillary water uptake ( $w$  values) calculated from Karsten tube measurements. The values displayed for area MHT 1 are also representative for area MHT 6

very hard due to sinter formation, while the interface between the two layers shows a low strength (insufficient contact), and in many cases, the outermost layer is already missing. In these cases, a hardened zone can also be found on top of these secondary surfaces, due to further transport of dissolved electrolytes (lime, silica) and deposition in the surface structure. Generally, the contact between the render and the brick underneath is rather poor in many cases.

Mortars with rough but stable surface and black staining may show a high capillary water uptake (MHT 2). Water absorption coefficients ( $w$ -values) for area MHT 2 could not be calculated due to irregular behaviour of the water uptake (influenced by water transport along cracks or parallel to surface), therefore results for this area are not displayed in Fig. 6. On the other hand, similar surfaces may have reduced capillarity (MHT 3), possibly due to “sealing” of the pores with organic matter.

All in all, the measured capillary water uptake scatters between 0.1 and 3.5 kg/m<sup>2</sup> h<sup>0.5</sup> (Fig. 6). The highest values were measured at a very soft render on the smaller prang (MHT 5), which is a poor hydraulic mortar with high portion of aggregates in a sheltered position inside a niche. In many cases, the results obtained from Karsten tube measurements suggest different pathways of water transport besides regular capillary water uptake, i.e. transport along cracks or parallel to the surface.

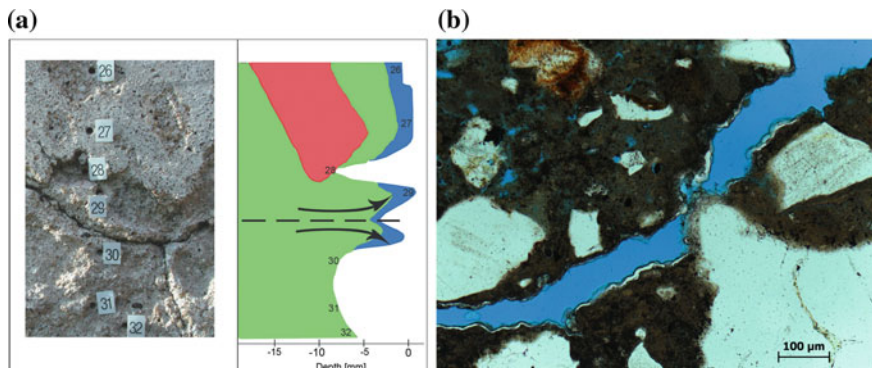
#### 4.4 Patterns of Differential Erosion

Bizarre weathering structures frequently occur on the walls of the inner enclosure (MHT 1 and 6, Fig. 7). Similar patterns are also known from other places and are



**Fig. 7** Alveolar weathering of renders on the enclosure wall (MHT 1, left, and detail from MHT 6, right). As can be seen on the right, the ridges are often preserved along cracks

often explained as a result of the formation of Liesegang patterns during the carbonation process (Rodriguez-Navarro et al. 2002) and subsequent differential erosion (Delgado Rodrigues 2016; Rodriguez-Navarro 2012; Dotter 2010). On the other hand, they are similar to those called “alveolar weathering” or “honeycomb weathering” on natural stones (e.g. Siedel 2010) with small “walls” or ridges that in parts still represent the original surface, surrounding deep, back-weathered “holes” between them. Although salts are often a driving force in the formation of alveolar structures in natural stone, no efflorescence or other activity of soluble salts could be detected in case of the renders in Ayutthaya. Most of the ridges are flanking a system of connected cracks in the mortar surface which might have already developed during shrinking of the thick render layers at an early stage of setting. Ridges along a directly connected network of shrinkage cracks in renders were also observed by Delgado Rodrigues (2016), who interpreted these structures as the result of higher weathering resistance of the respective areas due to intensified carbonation, facilitated by better access of  $\text{CO}_2$  from air. However, the typical concentric, ring-shaped wall structures within the “cells” surrounded by the above mentioned ridges with cracks are lacking in Wat Mahatat. These patterns, called “flos tectorii” in Italian literature, might be assigned to differential erosion of “Liesegang rings” with higher or lower concentrated carbonated binder (Delgado Rodrigues 2016). In contrast, in the renders described here irregular shaped “isles” and “holes” within the cells marked by the surrounding system of cracks can be found. Measurements of DR topography of a weathered render surface show hardened surfaces on the ridges (and on the smooth surface of the visibly intact outer render layer), whereas the surfaces at the bottom of the adjoining holes are softer (Fig. 8a). Microscopic investigations on a thin section of a ridge structure displayed thin layers of silica coating the surfaces along the crack between the two flanks of the ridge (Fig. 8b). This indicates an intensified capillary transport of dissolved matter ( $\text{Ca}(\text{OH})_2$ /lime, soluble silica) from the mortar to the evaporation zones along the cracks (arrows in Fig. 8a) and also on even surfaces in the neighbouring areas. As shown by Karsten tube measurements (cf. Fig. 6), the latter

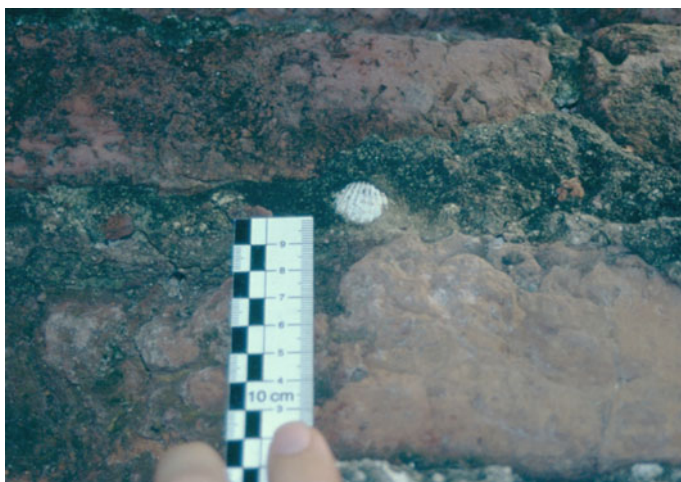


**Fig. 8** **a** Drilling resistance measurements no. 26 to 32 along the surface topography of a render structure. Blue: very hard material on the surface of the outermost render layer (26, 27) as well as on the flanks of the cracks (29). Red: very soft zone between the two render layers = zone of detachment. Green: normal strength of the inner render layer. Dashed line: crack. Arrows: transport of electrolytes ( $\text{Ca}^{2+}$ ,  $\text{OH}^-$  and mobile silica?) towards the surface zone, reinforcing the flanks by deposition of minerals. **b** Thin section across a ridge with two flanks and a crack in between at higher magnitude. The edges of the crack show a light, thin layer of silica (as chemically analysed by EDS in SEM) (Color figure online)

are dense, which is in good accordance with the higher DR measured near the surface. The intensive wetting of walls and ground during the rainy season in tropical climate provides enough water for intensive capillary transport of soluble components to the evaporation surfaces during the drying process in the dry season. Selective hardening of the border zones flanking the crack areas might thus lead to their better resistance against surface weathering. At the same time, the zones beneath the render surface next to the hardened zones along the cracks are depleted in binder, thus losing contact to the underlying material when stressed by hygrothermic changes. It seems worth to be mentioned that the areas showing these deterioration patterns are mainly situated near the bottom of the walls, where the moisture is continuously rising from the ground into the wall even in the dry season. The transport rate of dissolved matter through the render near the ground is higher compared to that on the upper parts of the wall. Observations and measurements at the walls of Wat Mahathat lead to the assumption, that the driving force for the formation of differential erosion in the renders in our case is capillary transport, migration and precipitation of dissolved  $\text{Ca}(\text{OH})_2$  or lime, respectively.

## 5 Discussion and Conclusions

The investigation of representative samples from renders of the temple Wat Mahathat in Ayutthaya showed different types of mortars. Lime renders (some of them slightly hydraulic), often blackened on the surface due to microbiological



**Fig. 9** Shell in a joint mortar in area MHT 2

activity, can be found on ruins of the halls and prangs and in some places on the enclosure walls. Samples taken from the enclosure walls, a niche of a smaller prang as well as on a brickwork fragment from the central prang turned out to be hydraulic mortars. They might be assigned to younger restoration measures from the 20th century, whereas the lime renders are most likely original historic mortars. The limestone for lime production might have come from a deposit of Permian, purely calcitic limestones at the Pasak River, north-east of the town Saraburi, which is the nearest outcrop of limestones in the surroundings of Ayutthaya (40 km away). Remnants of shells in some renders and joints (Fig. 9) indicate that a use of lime deposits from the sea (Gulf of Siam) is also possible. The location of Ayutthaya at the confluence of big rivers, the Pasak and the Chao Phya, might have facilitated the transport of lime from these sources to the site.

TG analysis clearly showed the presence of 1–2% of organic matter. Although the use of organic additives during ancient mortar production in Thailand is likely, analytical approaches carried out to prove this hypothesis were not successful. Small amounts of starch in a reference mortar made with water from rice boiling could be easily detected, whereas the same test was negative on the historic samples. It has to be taken into account, however, that intensive rain and microbiological activity in tropical climate have most probably lead to enzymatic decomposition of the primary organic compounds within some hundred years. Other organic components like oils, gums or even N-containing compounds could be identified, but these may also come from biochemical conversion of precursors, from a present biocolonization itself or even from material input of younger restoration measures.

The weathering state of the renders is different with respect to their drilling resistance and porosity (i.e. capillary water uptake). Therefore, decisions about

appropriate restoration measures for certain parts of the buildings should be made step-by-step on the basis of easy, non- or less-destructive measurements (Karsten tube, DR). An overall hydrophobic treatment of the entire surface of buildings cannot be recommended because of the very different capillary suction of the material surfaces and due to the risk of moisture infiltration through cracks which would even lead to severe damage.

The peculiar structures of differential erosion found on some surfaces of renders on the inner enclosure wall can be explained by local depletion and enrichment of binder contents due to dissolution, capillary transport and deposition of binder compounds. The strong wetting-drying cycles in tropical climate might have intensified this process. More detailed research is needed to completely understand the formation of inhomogeneities in the renders and the mechanism of their different weathering.

**Acknowledgements** Thanks are due to the Deutsche Forschungsgemeinschaft and the National Research Council of Thailand for financial support of the field campaign of H.S. and E.W. in Ayutthaya. Special thanks to Chompunut Prasartset (Silpakorn University, Bangkok), Malatee Taiyaqupt and Pongsak Pongprayoon (Chulalongkorn University, Bangkok), Sumalee Sirirat (The Fine Arts Department of Thailand) and all other Thai colleagues who helped with organisation, sampling and information. Thanks also to Ute Steinhäusser for the FTIR investigations and to John J. Hughes for critical comments which helped to improve the manuscript.

## References

- Chandra, S. (Ed.). (2003). *History of architecture and ancient building materials in India*. New Delhi: Tech Books International.
- Delgado Rodrigues, J. (2016). Liesegang rings in differential deterioration patterns of lime mortar. *Journal of Cultural Heritage*, 21, 819–822.
- DIN EN 1925. (1999). Natural stone test methods—Determination of water absorption coefficient capillarity, Deutsches Institut für Normung e.V., Berlin, 6pp (in German).
- Dotter, K. R. (2010). Historic lime mortars: Potential effects of local climate on the evolution of binder morphology and composition. *Geological Society London Special Publications*, 331, 119–126.
- Moropoulou, A., Bakolas, A., & Anagnostopoulou, S. (2005). Composite materials in ancient structures. *Cement & Concrete Composites*, 27, 295–300.
- Moropoulou, A., Bakolas, A., & Bisbikou, K. (1995). Characterization of ancient, Byzantine and later historic mortars by thermal and X-ray diffraction techniques. *Thermochimica Acta*, 269 (270), 779–795.
- Rodriguez-Navarro, C. (2012). Binders in historical buildings: Traditional lime in conservation. In J. M. Herrero & M. Vendrell (Eds.), *International Seminar on Archeometry and Cultural Heritage: the Contribution of Mineralogy* (Vol. 09, pp. 91–112). Bilbao: Seminarios de la Sociedad Española de Mineralogía.
- Rodriguez-Navarro, C., Cazalla, O., Elert, K., & Sebastian, E. (2002). Liesegang pattern development in carbonating traditional lime mortars. *Proceedings of the Royal Society London A*, 458, 2261–2273.
- Siedel, H. (2010). Alveolar weathering of Cretaceous building sandstones on monuments in Saxony, Germany. *Geological Society London Special Publications*, 333, 11–24.

- Siedel, H., & Siegesmund, S. (2014). Characterization of stone deterioration on buildings. In S. Siegesmund & R. Snethlage (Eds.), *Stone in Architecture. Properties, Durability* (pp. 347–410). Berlin, Heidelberg: Springer, ISBN 978-3-642-45154-6.
- Sirirat, S. (1999). Conservation treatments of Stucco in Thailand. In *Conservation of Monuments in Thailand I, Proceedings of the First Seminar on Thai-Japanese Cooperation in Conservation of Monuments in Thailand* (pp. 102–107). The Fine Arts Department, Thailand and Tokyo National Research Institute of Cultural Properties, Japan.
- Snethlage, R., & Wendler, E. (1989). Der Wassereindringprüfer nach Karsten - Anwendung und Interpretation von Messwerten. *Bautenschutz und Bausanierung*, 12, 110–115.
- Van Beek, S., & Invernizzi Tettoni, L. (1999). *The arts of Thailand*, Periplus Editions (HK) Ltd., ISBN 962-593-262-3, 248pp.
- Wendler, E., & Sattler, L. (1996). Bohrwiderstandsmessung als zerstörungsarmes Prüfverfahren. In F. H. Wittmann & A. Gerdes (Eds.), *Proceedings of the 4th International Colloquium Material Science and Restoration* (pp. 145–160). Freiburg: Aedificatio Publishers.