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SALT LOAD AND DETERIORATION OF SANDSTONE AT THE TEMPLE OF ANGKOR WAT, CAMBODIA

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Abstract

Investigations into salt occurrence, quantity of salt load and salt distribution at sandstone surfaces of the Temple of Angkor Wat have shown that salt load has been a relevant factor for stone deterioration on this building. The main source for the salt-induced stone deterioration is bat guano (excrements).

Keywords: sandstone, salt load, gypsum, phosphate, nitrate, bat guano

1. Introduction

The temple of Angkor Wat (fig. 1, left) was built in the 12th century and is part of the UNESCO World Cultural Heritage since 1992. The whole temple area which covers nearly two square kilometres is surrounded by an enclosure and a moat. The central sanctuary in the middle of the huge temple mountain made of laterite and sandstone is about 60 metres high and surrounded by three enclosures with galleries. Surfaces of the sandstone ashlars are covered with numerous bas-relief carvings showing mythological and historical scenes, divinities and celestial dancers (Apsaras) or just ornaments.

In many places the sandstone surfaces are affected by weathering. Contour scaling (fig. 1, right) and flaking are the most typical weathering forms. Salt efflorescence can

Fig. 1a, b: General view of the Angkor Wat temple from southeast (a, left) and detail with contour scaling of the sandstone and salt efflorescence in a gallery (b)

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often be observed in weathering zones. The question, to which extent and in which way salts force the weathering process is crucial for the understanding of the weathering phenomena as well as for a proper conservation concept. Moreover, information on the sources of salt ions is needed in order to explain (and probably prevent) salt formation.

Investigations into these problems were performed in the framework of the German Apsara Conservation Project (GACP). They aimed at a survey of occurring salts, their distribution and possible sources as well as at the potential they have to force damaging processes.

2. Building materials, climate and environment, restoration history

The building stone of Angkor Wat is local Mesozoic sandstone quarried in the Phnom Kulen Mountains, about 40 km away from the temple. Moreover, the foundations and the core of the temple mountain contain laterite blocks behind the sandstone surface. The masonry was laid dry (i.e. without any joint mortar).

Recent petrographical investigations (Reucher et al. 2007) have shown that the building sandstones are feldspathic graywackes in the sense of Pettijohn et al. (1987). Their hygric dilatation scatters from 0.6 to more than 3 mm/m, depending on clay mineral content (Leisen et al. 1996).

The climate in the region of Angkor is tropical with wet and dry season. Rainfall is extremely rare between December and April but frequent from May to October. Mean monthly relative humidity is about 75 % in dry season and between 80 and 90 % in rainy season. Mean monthly temperatures are above 20 °C the whole year long and rise to 30 °C in the rainy season. The surface temperature of building sandstone at south and west exposed façades can reach maximum temperatures up to 45 °C (Leisen et al. 1996). Hyvert (1969) even mentioned maximum surface temperatures between 52 and 62 °C.

The Temple of Angkor Wat is situated near the town Siem Reap in NW Cambodia. The area is not industrialized and there are no emissions from heating because of the mild climate, but from cooking on open fires. The open galleries and towers have offered accommodation to a great number of bats for centuries. As known from old reports their excrements formed thick layers of guano at the floors in the past. Even if the floors are frequently cleaned today, one can notice the strong smell in parts of the temple.

Several restoration measures were performed during the 20th century. The French École Française d`Extrême-Orient established the Angkor Conservation Office in 1908 and started restoration operations mainly applying anastylosis. During the sixties detailed studies including material investigations and testing areas for conservation were carried out by Hyvert (1969) and others. Between 1986 and 1993, the Archaeological Survey of India performed structural stabilization, stone cleaning as well as impregnation with biocidal agents and PMAA for strengthening. Since 1995 the GACP has carried out emergency interventions and conservation work at the high-rated sandstone reliefs together with Cambodian conservators (Leisen & v. Plehwe-Leisen 1999).

3. Samples and analytical methods

3.1 Sampling

Because of the value of the object only little affecting sample methods could be used. Most of the samples were scratched from the weathered surface zone where original surface had already been lost. The idea was to develop a general view of occurring salt types in weathering surface zones and their possible relation to environmental factors or former restoration measures (e.g. the use of Portland cement). The samples should be each representative for typical weathering situations influenced by different exposure, height, direction etc. The number and position of samples is given in fig. 2.

At two places with typical weathering forms a more detailed investigation was possible by taking drill core profiles in different positions from the surface to the depth. Drill cores AW I to AW IV were taken from a pillar in the open gallery of the third enclosure to the north at different height levels (see figs. 2 and 4a). Another two drill cores (AW V and VI) were taken from a surface with contour scaling near the eastern entrance of the second enclosure (figs. 2 and 4b).

To characterize the environmental situation, rain water was collected in wet season to analyze soluble sulphate content. Sampling of atmospheric SO_2 was performed with surface active monitoring (SAM) filters. Furthermore, bat guano was collected in the SE tower of the second enclosure to analyze its sulfur content.

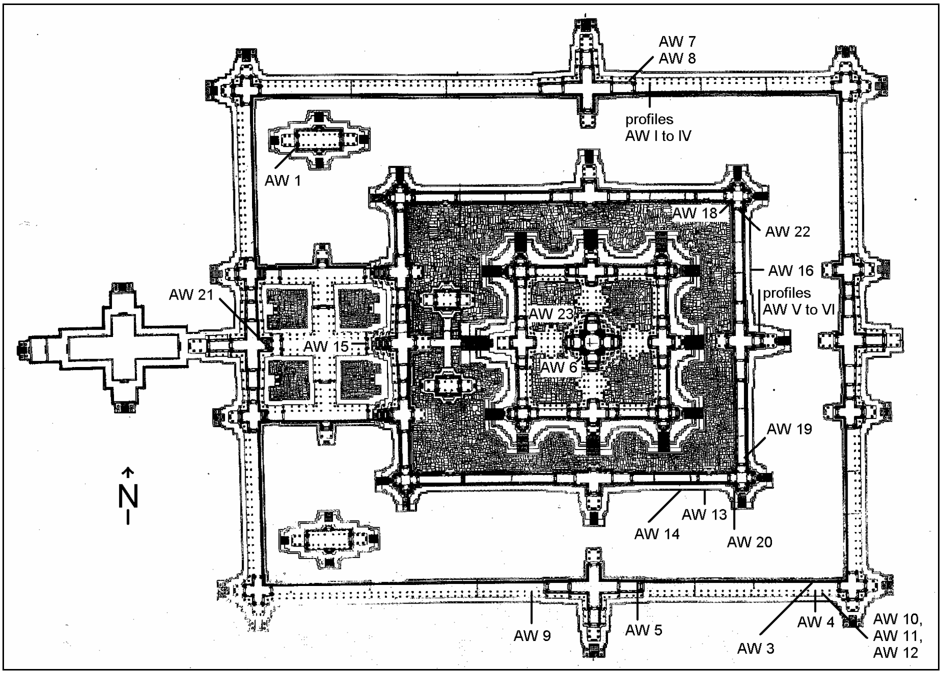

Fig. 2: Sketch map of Angkor Wat with position of the samples (modified after Jaques 1999)

3.2 Analytical methods

In case of visible efflorescence or crusts the salt compounds were analysed by X-ray diffraction (XRD) analysis (Siemens D5000 diffractometer). Soluble ions were extracted from surface samples as well as from drill powder samples using deionised water. Ion contents in the solution were analysed by a spectrophotometer (HACH system) using standardized reagents with the exception of Na (ion sensitive electrode). The results were referred to dry sample (wt-%).

4. Results and discussion

4.1 Crusts and efflorescences

Salt compounds could be determined by XRD in 20 samples from efflorescence and crusts. Gypsum was the most frequent salt mineral (found in 17 samples). Phosphate minerals (whitlockite ($Ca_9(Mg,Fe)[PO_3OH | (PO_4)_6]$) and newberyite $MgHPO_4 \cdot 3\ H_2O$) were found in 4 samples of brown crusts in addition to gypsum. Niter ($NaNO_3$) and halite (NaCl) were determined together twice only at the south side of the second enclosure (AW 13, 14) where the temperatures of sandstone surfaces caused by insolation were extremely high. Calcite was found together with gypsum in two samples and together with aragonite in another sample.

4.2 Chemical analysis of weathering surfaces

The salt ions analyzed in weathering sandstone surfaces are displayed in table 1. Phosphate contents were not determined in these samples but might be present in some weathering zones. The dominant ions are sulfate and calcium. This corresponds well to the results of XRD analyses of efflorescence. Furthermore, nitrate is present in medium to extremely high concentration in all samples.

Table 1: Salt content of weathering sandstone surfaces by weight %

Sample no.	**Total dissolved solid**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**Na^+**	**SO_4^{2-}**	**Cl^-**	**NO_3^-**
AW 1	2.23	0.55	0.11	0.04	0.02	1.00	0.02	0.41
AW 3	4.21	1.25	0.15	0.03	0.03	2.67	0.04	0.44
AW 4	1.30	0.16	0.02	0.06	0.05	0.38	0.02	0.43
AW 5	4.43	1.10	0.07	0.06	0.04	2.06	0.02	0.59
AW 7	7.26	1.47	0.09	0.22	0.07	4.66	0.09	0.94
AW 9	4.61	1.00	0.03	0.09	0.05	2.45	0.03	0.59
AW10	2.77	0.70	0.01	0.01	0.02	1.90	0.02	0.11
AW12	4.61	1.20	0.03	0.02	0.03	2.66	0.03	0.27
AW18	4.38	0.81	0.21	0.17	0.13	1.70	0.08	1.21
AW19	6.30	1.66	0.09	0.04	0.08	3.80	0.03	1.05
AW20	5.96	1.50	0	0.02	0.05	3.21	0.02	1.05
AW21	7.03	1.98	0.14	0.01	0.02	5.31	0.01	0.36
AW23	5.19	0.91	0.09	0.11	0.06	3.07	0.04	0.78

4.3 Salt distribution in drill profiles

Results of the chemical analysis of salt distribution in a pillar (fig 4a) are displayed in fig. 3. Magnesium contents in the pillar are generally low (< 0.04 wt.-%) and could be neglected. Salt distribution in the pillar shows the "classical" pattern of rising damp

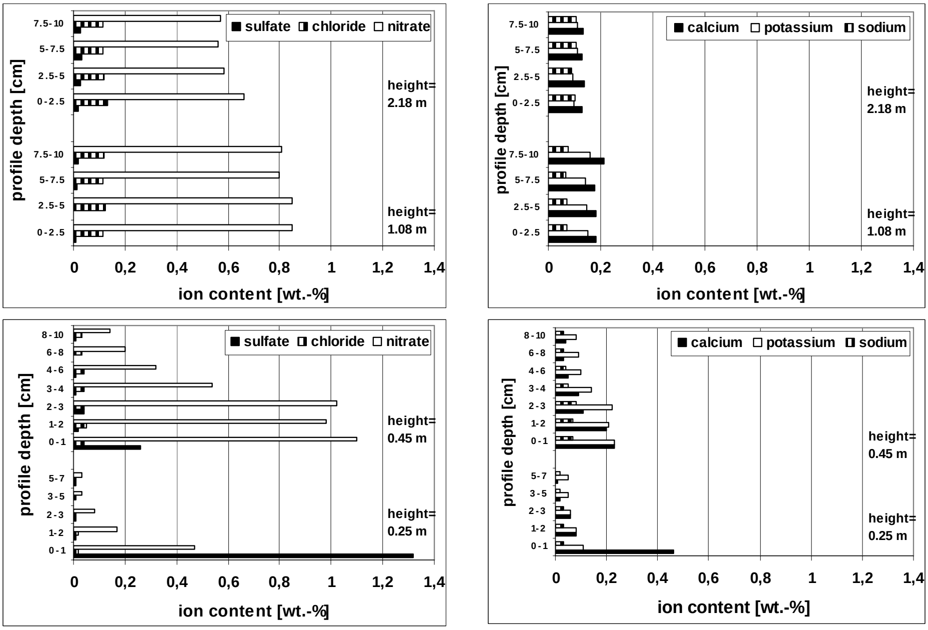

Fig. 3: Salt distribution of anions (left) and cations (right) in depth profiles at several height levels on a pillar in the gallery of the third enclosure to the north

Fig. 4 a, b: Pillar from the northern gallery of the third enclosure (a, left) and surface with contour scaling (b, right)

(Arnold & Zehnder 1988). Gypsum (Ca^{2+} and SO_4^{2-}) is concentrated near the stone surface in the lower profile parts (h = 0.26 m and 0.45 m) with active stone deterioration and loss of material. In the upper parts (h > 1 m) sulfate contents are very low. In contrast to sulfate, chloride contents are very low in the lower parts of the pillar but rise to medium concentration levels above a height of 1 m. A similar tendency was obtained for nitrate. What is noticeable about the nitrate and chloride distribution is the steep slope in concentration from the surface to the depth in lower profile parts in contrast to a more or less equal distribution to the depth in the upper parts of the pillar. The first is driven by capillary moisture movements caused by periodic moistening-drying cycles of the lower part of the pillar. Rain events cause capillary rise of rain water from the floor into the pillar. In dry period it evaporates through the stone surface again, where dissolved ions are precipitated. The latter depends on the hygroscopic behavior of nitrates and chlorides. Since their mixtures have relatively low deliquescence humidities they are always in solution under the high relative humidity of air in the tropic climate. At moisture content equilibrium of the sandstone these ions can move slowly, only following the concentration gradient until a balance in concentration is reached over cross-section of the pillar. Areas with high load of nitrate and chloride are characterized by a visibly darker surface.

Figure 5 shows the salt distribution in a stone block with contour scaling (cf. fig. 4b). The profiles are representative for a detached part of the surface (sounds hollow by knocking) and the neighboring area which seems still to be stable. The dominating ions in both profiles are calcium and sulfate. Chloride (< 0.02 wt.-%) and nitrate (< 0.05 wt.-%) as well as magnesium, sodium and potassium are far below critical concentrations and can be neglected. Gypsum is concentrated in a depth of 1.5 to 2 cm, i.e. in the crumbling zone behind the detached scale. A comparable distribution at a slightly lower concentration level, however, was obtained for the neighboring "stable" area. It seems to mark the initial stadium for further deterioration.

After wetting-drying cycles with saturated gypsum solution Wendler (1991) obtained in the laboratory a very similar pattern of gypsum distribution for the argillaceous German Schilfsandstein with comparable physical properties. He discussed it as a cause for scale formation. On the other hand, Wendler & Prasartset (2000) demonstrated that

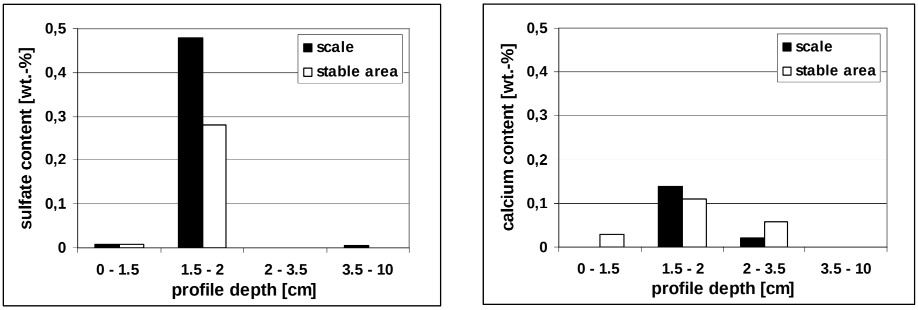

Fig. 5 a, b: Ion distribution of calcium (a, left) and sulfate (b, right) in depth profiles of a surface with contour scaling (hollow) and the neighboring, stable area contour scaling on Khmer temples in Thailand occurs without any salt load only by wetting-drying cycles and hygric swelling. Nevertheless, a high gypsum concentration might additionally force the contour scaling process of Angkor sandstones.

4.4 Environmental influences

Results of the environmental analyses are given in table 2. As the dominating salts are sulfates, special attention was payed to sulfur. Since the sulfur deposition from airborne SO_2 and from rain water is very low compared with the situation in Central Europe (e.g. Dresden, Germany), a relevant contribution of airborne sulfur to salt formation at Angkor Wat is unlikely.

Table 2: Results of the analyses of environmental factors at Angkor Wat from literature and own investigations (data from Dresden, Germany for SO_2 and rain water for comparison after Klemm & Siedel 1999)

Soluble ions in bat guano [wt.-%], after Hyvert 1969	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**PO_4^{3-}**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**
	0.18	1.12	1.24	0.11	0.18	0.52	0.05	0.11
Soluble sulfur in bat guano [wt.-%]	0.54 (Hyvert 1969: 0.41)							
Airborne SO_2 deposition rate [mg/m^2d]	0.05 (Dresden 1988: 191; 1997/98: 3.3 to 9.7)							
Sulfate in rain water [mg/l]	0.9 (Dresden 1996-1999: 4.1 to 54.1)							

Bat guano contains all ions found in the harmful salts in the building stones. The content of soluble sulfate and nitrate is particularly high. Furthermore, soluble phosphate contents in bat droppings give a hint towards the formation of phosphate minerals in crusts. Witlockite and newberyite found in brown crusts at Angkor Wat have also been detected in natural guano deposits (Nriagu & Moore 1984). Hyvert (1969) and Uchida et al. (1999) discussed bat guano as the main source of salt formation on Khmer temples. From this study it could be clearly demonstrated that high concentration of salts together with stone deterioration can always be found in places where rain water

- has penetrated the walls and pillars by capillary transport from the floors of open galleries or
- has seeped through open joints in the roof construction.

In both cases rain water had come in contact with bat guano before because the temple had not been cleaned over long periods in the past. Soluble ions were dissolved and transported into the stone, leading to the typical salt distribution patterns described above.

5. Conclusions

Sandstone deterioration at Angkor Wat is often connected with high salt load. Beside hygric swelling of the sandstones, high gypsum content near the surface is a crucial factor for flaking and contour scaling. Nitrate salts also show high contents in the sandstone but are, like chlorides, in dissolved state under the conditions of high relative humidity of the air in tropic climate. Only in places where sandstone is exposed to direct insolation with high surface temperatures over a long time (southern façade) they can precipitate and also contribute to stone damages. In the shadow of the galleries as well as at the northern side nitrate remains in solution and doesn't precipitate at all. Thus, no stone deterioration by nitrate occurs there, even if the nitrate content is very high and the stone is kept permanently wet by its hygroscopic behavior.

6. Endnotes

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