Science and Art: A Future for Stone

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Published: 01/01/2016

Citation for published version (APA):
Hughes, J., & Howind, T. (Eds.) (2016). Science and Art: A Future for Stone: Proceedings of the 13th International Congress on the Deterioration and Conservation of Stone, Volume 1. Paisley: University of the West of Scotland.

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SCIENCE and ART: A Future for Stone

Proceedings of the 13th International Congress on the Deterioration and Conservation of Stone – Volume I

Edited by
John Hughes & Torsten Howind

CONTOUR SCALING AT THE ANGKOR TEMPLES: CAUSES, CONSQUENCES AND CONSERVATION

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Abstract

Contour scaling is the main weathering form observable at the Angkor monuments. In this study comparisons are made between the building stone and crust material from the Phnom Bakheng Temple and fresh stone material used for restoration. A significant difference in hydric and especially in thermal expansion of the crust and sandstone is shown in this study. This leads to an extensional effect and is a force for delamination (scale formation). By using an object-specific conservation treatment, the hydric and thermal expansion of the crust material was reduced.

Keywords: clay, moisture expansion, thermal expansion, mineralogy, conservation

1. Introduction

The temples and ruins of Angkor are located amid forests and farmland to the north of the Tonlé Sap and south of the Kulen Mountains, near Siem Reap City of Cambodia/Asia. The area was designated as a World Culture Heritage site in 1992. The legendary Angkor served as the seat of the Khmer Empire, which flourished from approximately the 9th to the 15th century and hosted the largest temples on earth (Fig. 1).

2. Site and conditions

2.1. Climate, rock material and weathering

2.1.1. Climate and environmental condition

The Angkor region is situated near two different types of climate, the tropical wet and dry climate and the tropical monsoon climate. The site has a wet tropical summer that is hot with dry, mild winters. The mean temperature is 28.5°C. Total annual precipitation averages 1425 mm. Precipitation takes place during the rainy season starting from March and ending in November. According to Waragai *et al.* (2012), the daily humidity during the dry season shows a minimum of 54 % in January and March. During the rainy season from May to October a high relative humidity of 80-90 % is measured.

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2.1.2. Geological setting and stone material

The Angkor monuments in Cambodia are built of sandstone and can be classified into three types used for different temples and based on the color, texture, chemical composition and constituent mineral (Delvert 1963): gray to yellowish brown sandstone (Angkor Group), red sandstone (Banteay Srei) and greenish graywacke used for the Ta Keo Temple (Fig. 1e). Most natural building stones were brought from the Kulen Mountains by boat were different historical quarries could be identified (Carò 2009, Fig. 1). All stone types can be described as fine-grained porous sandstones. Recent petrographic investigations (Reucher *et al.* 2007) have shown that the building sandstones are feldspathic graywackes in the sense of Pettijohn *et al.* (1972). Graywackes are matrix-rich sandstones that are poorly sorted and derived from sediments, which were transported a relatively short distance before being deposited and contain chemically unstable minerals.

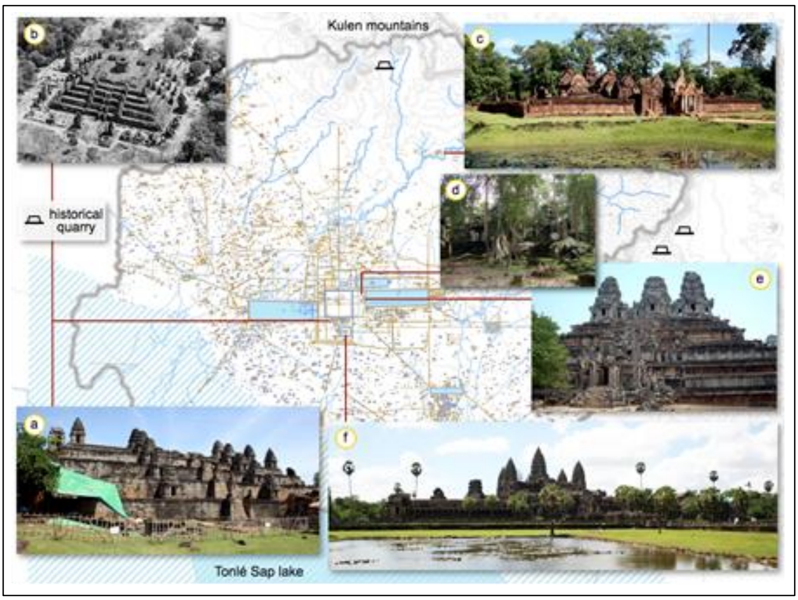

Fig. 1: Schematic map illustrating the historical Angkor complex and provinces with the major elevated temples indicated (source of the map: NASA); a) The Phnom Bakheng Temple made from gray sandstone that underwent restoration in 2009; b) The temple after being cleared of trees and plants in the 1920's; c) The Banteay Srei Temple constructed from red sandstone; d) The Ta Nei Temple surrounded by trees; e) The Ta Keo Temple made from green sandstone; f) The famous Angkor Wat temple made from gray sandstone.

2.1.3. Main weathering forms

Contour scaling is described as the main weathering forms observable in the Angkor buildings (Leisen 2002, André *et al.* 2008, UNESCO 2012). Contour scaling is defined as: "scaling in which the interface with the sound part of the stone is parallel to the stone surface. In the case of flat surfaces, contour scaling may be called spalling" (Vergés-Belmin 2008). This phenomenon is often related by crust formation and to the accumulation of whitish efflorescences and crusts made of calcite ($CaCO_3$). Calcite within or underneath scales is most likely derived from the calcite cement in the sandstone, which creates crusts in the first few millimeters of the material (Fig. 2a, b). Small amounts of barite ($BaSO_4$) and gypsum can also be found (Hosono *et al.* 2006). In cross section the crust shows a distinct zonation where the first few millimeters display a brownish color followed by a bright discoloration (Fig. 2c). The bright discoloration was identified as calcite precipitation, which was also determined by cathodoluminescence microscopy (this study) and several other authors (e.g. Hosono *et al.* 2006 and André *et al.* 2008). This calcite mineralization results from the dissolution of calcite within the stone material due to chemical weathering and the remobilization near the drying surface as well as within cracks or weak zones within the stone material.

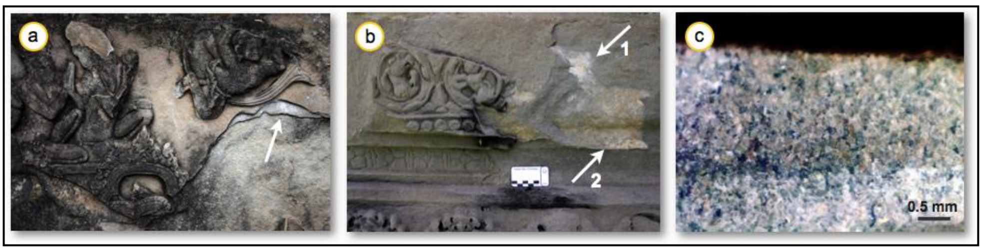

Fig. 2: a) Layered contour scaling with calcite precipitation underneath a recently lost scale (arrow); b) Calcite precipitation (arrow 1) and calcite and iron precipitation (arrow 2) between a recently lost scale; c) Cross section of the crust showing a distinct zoning - a brownish zone at the surface and a whitish one beneath.

3. Investigations

3.1. Methods and sample materials

The investigation included the determination of the pore space properties like porosity, density using hydrostatic weighting (DIN 52 102), mercury porosimetry measurements and hydric and thermal dilatation. Application of cathodoluminescence microscopy was used to give information on the alteration process and the distribution of calcite in the stones. This paper will focus on the weathering forms observed in the gray sandstone, the greenish graywacke type used for the Phnom Bakheng Temple as well as for the Angkor Wat Temple. They include the original building stone for the Phnom Bakheng Temple (PB), the weathering crust as well as the material that is now used for restoration (PBr). The sample material acquired in this study originates from the restoration team of the Phnom Bakheng Temple in 2009.

3.2. Mineralogical investigations

Cathodoluminescence microscopy (CL) was done on thin sections of the sandstone varieties to delineate alteration processes, to visualize possible microstructures and to determine what the differences are between the unaltered and altered building stones. Both sandstone varieties show evidence of alteration in minerals such as feldspar.

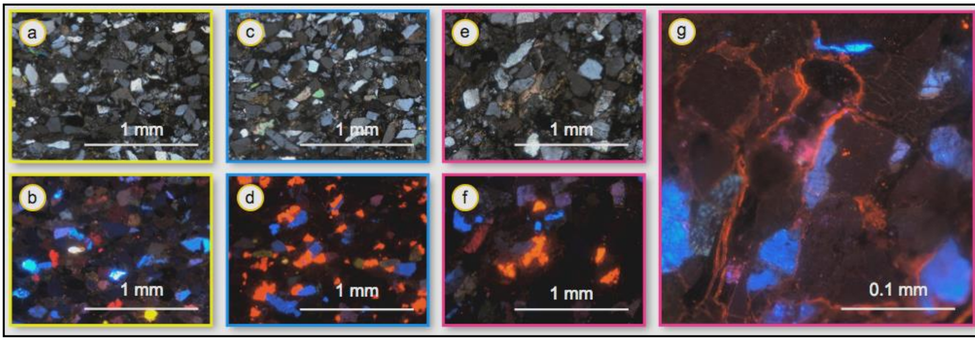

Fig. 3: a - b) Thin section of the Phnom Bakheng sandstone (PB) and c - d) of the restoration material (PBr.). e, f, g) Thin section of the weathering crust. a, c, e) Samples under polarized light and b, d, ,f, g) under cathodoluminescence. g) Detail of sample under CL showing the finely precipitated calcite within cracks and along the grain boundaries between grains of quartz (very low luminescence) and feldspar (blue). Coloured image frames correspond to the figures below.

The CL investigations clearly show the presence of calcite within the stone. Only a small amount of calcite, averaged around 2 % occurs in the PB variety (Fig. 3b), whereas the PBr variety has a calcite content of more than 7 % as is clearly visible by the orange CL color (Fig 3f). Alteration is also evident in the weathering crust (Fig. 3e). More calcite is observable in the crust of the Phnom Bakheng Temple than in the PB sample (Fig. 3f). A closer look shows that calcite precipitated along grain boundaries and microcrack formations (Fig. 3g).

Tab. 1: Pore size properties of the investigated stone material

Sample	**Porosity, %**	**Pore radii distribution [%]**				
		Micropores, µm		*Capillary pores, µm*		
		0.001– 0.01	0.01 – 0.1	0.1 - 1	1 - 10	>10
PB	12.3	44.02	39.37	10.92	14.45	1.75
crust	17.6	0	0	23.39	56.4	20.21
PBr	11.5	0	0	83.53	11.3	5.37

3.3. Petrophysical properties

The sandstones can be characterised as medium porous sandstone types with a porosity ranging between 11.5 % and 12.3 %. A porosity of 17.6 % however was measured in the crust (Tab. 1). The pore radii distribution of the crust and the PBr sample is dominated by macropores, whereas the PBr-sample shows a high amount of pores in the pore class of 0.1-1 with 83 % (Tab. 1). Microporosity in the case of the PB stone reaches 83 % and 0 % for the restoration material (PBr) and the crust. The main pore space properties of the sandstones are listed in Tab. 1.

3.4. Thermal dilatation experiment and hydric expansion

The crust sample has a dimension of around 2 by 2 centimeters and a thickness of around 4 mm. In order to compare the results with the stone material, the same or similar dimensions were used to perform the test on samples of the Phnom Bakheng sandstone as well as the restoration material (PBr). To test the thermal expansion of a thin and small piece of crust and stone material a simple but effective testing device was developed: The sample is placed on a massive cylinder of quartz glass. Another cylinder of quartz glass with thinner dimensions is put on the top of the sample. This cylinder is connected to an electronic dial gauge. Heat is applied by an infinitely variable fan heater concentrated on the sample. The temperature of the sample is measured by a digital contact thermometer placed directly at the back of the sample. Heating starts at 25°C (room temperature) and is continuously increased up to 100°C within 30 min. After reaching 100°C the heating is stopped and the cooling process starts until the sample reaches room temperature again. A length reduction occurs during the cooling process in all samples and in all directions. However, this length reduction shows a different behaviour. The thermal expansion measured at 60°C ranges between 1 mm/m and -0.2 mm/m with very high anisotropies (Fig. 4). The highest values were measured in the case of the PBr sample (0.227 mm/m, XY-direction) and the crust (1.036 mm/m, XY-direction), however the highest anisotropy was measured in the weathered crust. The gray sandstone of the Phnom Bakheng Temple has a hydric dilatation of nearly 2 mm/m in Z-direction, perpendicular to the bedding. Within the XY-direction an average dilatation of 1.165 mm/m is reached. Both values produce an anisotropic relation of 42 %. The weathered crust sample shows a dilatation of 1.55 mm/m in the Z-direction and 0.96 mm/m in XY-direction. Moisture expansion of the fresh quarry material (PBr) is comparably low, with values ranging between 0.2 to 0.4 mm/m.

4. Causes

The investigated samples differ in pore space radii distribution and mineral content. The gray sandstone of the Phnom Bakheng variety shows a pore radii distribution dominated by micropores probably due to high clay content.

4.1. Contour scaling due to hydric expansion?

Contour scaling of the sandstones of Angkor Wat can be explained by very high rates of hydric swelling of up to 4 mm per meter (Leisen 2002). Leisen assumed that the periodical processes of moisture expansion and shrinking by drying have weakened the structure of the stone. Hydric dilatation of the crust with 1.55 mm/m in the Z-direction is lower than the altered building stone (PB). The dilatation of the crust in the XY-direction with a value of 0.96 mm/m is quite similar to the XY-direction of the PB building stone (Fig. 4a). However, the process of dilatation differs in time and form in regards to the weathered crust or the building stone. During the first two and a half minutes of wetting the dilatation of the crust is faster than the dilatation of the building stone (Fig. 4b). This can be traced back to the higher porosity of the crust, which is only dominated by capillary pores and does not seem to contain many clay minerals. After that the dilatation of the crust takes much more time to reach the final value than the dilatation of the PB sample. This process can lead to a pull effect and is a force for delamination (Fig. 4b).

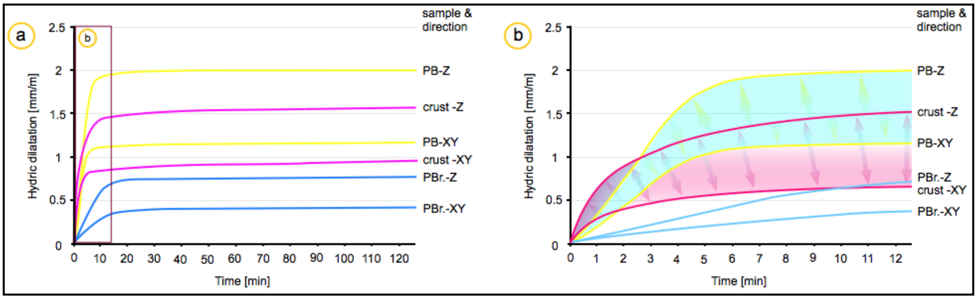

Fig. 4: a) Hydric dilatation of the PB sandstones. b) The dilatation of the PB sandstone within the first few minutes of water suction. The arrows indicate possible forces that may be responsible for the delamination of the crust from the building stone.

4.2. Contour scaling due to thermal expansion?

Thermal expansion of the various stone types and the crust shows considerable differences. The crust shows a maximum thermal expansion of 1.03 mm/m in XY-direction and 0.48 mm/m in Z-direction at 60°C with an anisotropy of 95%. However, the thermal expansion of the Phnom Bakheng building stone in the Z-direction with 0.049 mm/m is around ten times smaller than the crust (Fig. 5a). In the XY-direction a shrinking takes place that attains a value of - 0.2 mm/m at 60°C (Fig. 5b). This leads to an anisotropy greater than 100 %. The fresh quarry material attains a value of 0.14 mm/m in the Z-direction and 0.167 mm/m in XY-direction with a comparably low anisotropy of 15 % (Fig. 5b).

Thermal expansion of the crust is much higher than in the two building stones. The anisotropy of 95 % between the Z- and the XY-direction leads to shear stresses within the crust as well as between the crust and the stone material. A possible explanation of why the thermal dilatation within the XY-direction is much higher than in the Z-direction is that calcite precipitates in the cracks and empty spaces formed by the loss of clay minerals parallel to the bedding. The loss of clay minerals within the crust is also shown by the absence of any microporosity, whereas the building stone exhibits a microporosity of more than 80 % (Tab. 1).

In general, shrinking in the Phnom Bakheng sandstone is related to clay minerals during the cooling process. At around 60°C clay minerals begin to lose their crystal water. This sometimes leads to a depression of the thermal expansion during the heating process. On the other hand, the presence of clay minerals can reduce the thermal expansion of sandstone because the quartz grains expand, whereas the clay minerals show shrinkage at the same time. This decreases the expected thermal dilatation that is mainly related to the thermal expansion of quartz. Shrinking during cooling takes place because the thermal expansion of quartz decreases and the crystal water within the clay minerals is still lost. This leads to a collapse of the internal structure and a reduction in length, which has been observed in all sandstone varieties of the Phnom Bakheng Temple (Fig. 5b).

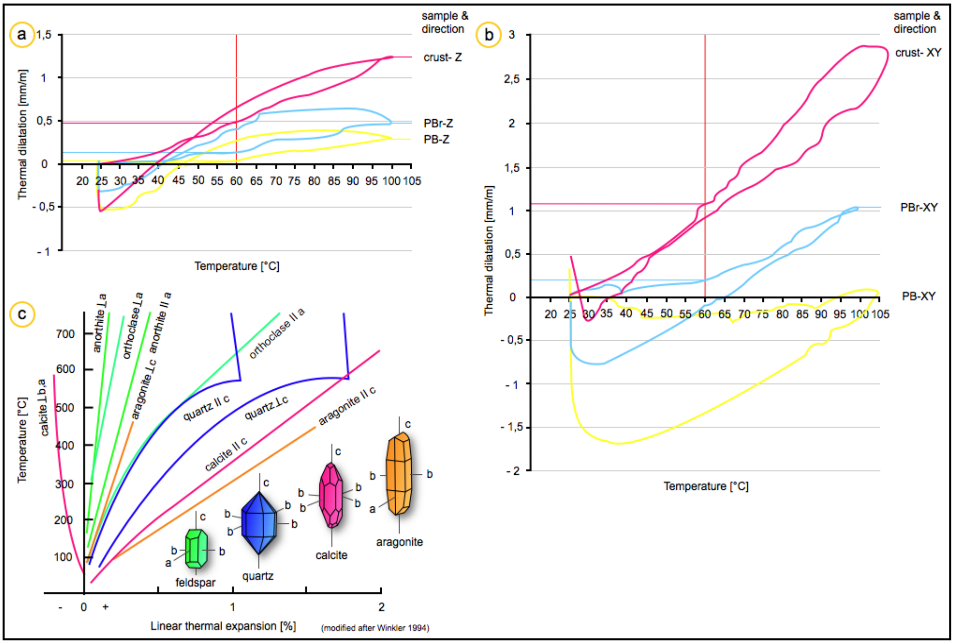

Fig. 5: Thermal dilatation of the crust, the PB building stone and the PBr stone in the Z-direction. b) Thermal dilatation of the crust, the BP stone and the stone used for restoration (PBr) in the XY-direction. c) Thermal expansion of different minerals.

5. Consequences

Consequently, all the investigations show that thermal dilatation seems to play a major role in the object specific deterioration form of contour scaling at Angkor. Furthermore, the CL investigations in this study have shown that an accumulation of calcite occurs in the crust. It is well known that calcite has a high coefficient of thermal expansion. The thermal coefficient of calcite is three times higher than quartz, the main mineral comprising sandstones (Fig. 5c).

6. Conservation

The investigations show that scaling is associated with the accumulation of calcite. Therefore, one option might be to reduce the calcite mineralizing out and to decrease the thermal expansion of the crust zone. To evaluate this hypothesis the tested crust sample was treated with a 5 % HCL solution. A small sample was placed in the solution for one hour and afterwards was washed with distilled water. The weight was reduced by 0.7 M-% after the treatment, probably due to the dissolution of calcite. However, as a result of the dissolution no loss of cohesion due to the separation of single grains could be detected.

The results of thermal expansion measurements show that only a slight change took place for the Z-direction in comparison to the thermal expansion before treatment. Both measurements show a thermal expansion of around 0.5 mm/m at 60°C, whereas the treated sample decreased to around 0.48 mm/m with a reduction of 13 % (Fig. 6a).

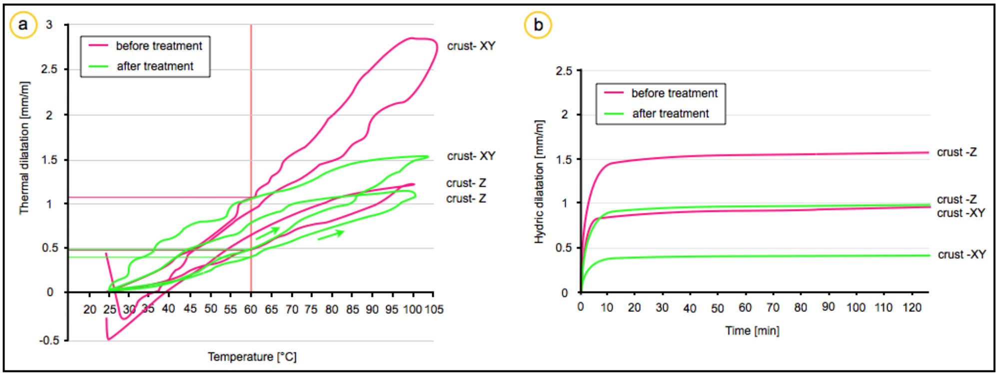

Fig. 6: a) Thermal dilatation before and after treatment and b) hydric dilatation before and after treatment of the crust.

In the case of the XY-direction of the crust a significant decrease of the thermal expansion was determined: The thermal expansion is still slightly higher than in the case of the Z-direction, but reached less than half at 60°C. The dilatation was reduced to 47 %. The anisotropy between the Z- and XY-direction was also reduced from 95 % to 15 %, which is significant in that we can expect the effect of scaling forces to become smaller. Hydric dilatation after the acid treatment also becomes smaller. A reduction of around 30 % takes place in the Z-as well as in the XY-direction (Fig. 6b). This can be explained by the increase of porosity because of the dissolution of calcite. Part of the clay cement can expand within this free pore space, and therefore does not have any influence on further expansion.

7. Final conclusions

Contrary to the assumption that hydric dilatation is the reason for contour scaling; the main causes of deterioration identified are chemical weathering by the precipitation of calcite at the surface combined with insolation-affected thermal dilatation. The recrystallization and precipitation of the case-hardening agent (calcite) throughout the surface rind is a probable formation mechanism for the crust. Insolation and the increase of thermal dilatation due to the accumulation of calcite, lead to shear stresses and scaling. Salt efflorescence and weathering related to bat guano and single mineral components of the stone material itself is a serious threat to the monument decorations (Siedel et al 2010). Both weathering factors can interact with each other and lead to an increase of weathering processes.

Our experimental investigations show that petrophysical properties can be measured even on small-dimensioned crust material. This leads to an understanding of the weathering processes involved in contour scaling. Acid treatment may be a promising approach to reducing the thermal expansion of the material and weathering due to contour scaling. The acid treatment is also an option for reducing the calcite accumulations within the weak zones and cracks behind the weathering crusts.

More onsite investigations as well as laboratory experiments are necessary to complete the picture and to add further knowledge in our understanding of the weathering mechanisms. The development of a suitable conservation treatment in combination with the up-to-date performed conservation techniques (UNESCO, APSARA 2012) has to be established in order to reduce the weathering from contour scaling, thus preventing further deterioration of the decorations at the Angkor temples.

Acknowledgments

We would like to thank the restoration team of the Phnom Bakheng Temple and the local authorities that safeguard Angkor (APSARA) and for their friendly cooperation. Our work was supported by the Hans-Boeckler-Foundation.

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