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TECHNICAL NOTE

Evaluating the Condition of Sandstone Rock-Hewn Cave-Temple Façade Using In Situ Non-invasive Techniques

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1 Introduction

Rock-hewn cave-temples are a form of Buddhist temple architecture. They are important elements of world cultural heritage. Cave-temple art entered China and thrived after the introduction of Buddhism in A.D. 65 (Chan 1957). The majority of Chinese cave-temples are found along the Silk Road; with, for example, approximately 170 sites containing cave-temples in Gansu province in the north-west of the country.

The conservation of rock-hewn cave-temples is a matter of historical, artistic and cultural importance. Since 1949 a range of conservation practices has been implemented on many rock-hewn cave-temples in China which have largely solved large-scale structural instability problems. However, small scale weathering processes affecting the rock surfaces at these sites have not been well-studied, although they can negatively affect the appearance of the site, damage valuable carvings and produce further large-scale instabilities. The lack of scientific research on the deterioration of rock-hewn cave-temples, especially in terms of investigating and evaluating the condition of the rock mass, is currently a serious problem affecting the formulation of further conservation strategies (Wang and Chen 2018). The difficulties lie in the lack of effective in situ testing measures and evaluation criteria. Therefore, this paper aims to carry out a preliminary study to assess the condition of the façade of rock-hewn cave-temples using in situ non-invasive portable methods commonly used on stone-built heritage.

2 The Site

The North Grotto Temple (NGT), the representative of rock-hewn sandstone cave-temples of the Longdong region (eastern Gansu Province), China, is located in Qingyang city, Gansu Province (35°36′35″ N and 107°32′00″ E) at an altitude of between 1064 m and 1083 m above sea level. It was initially constructed in A.D. 509 during the North Wei Dynasty and enlarged periodically until A.D. 1722. The NGT comprises two main components—larger caves and smaller niches. Hundreds of niches are carved into the west-facing sandstone façade (see Fig. 1(1)) and are the focus of this study with in situ measurements carried out on and around five niches within the façade.

Geographically, the site is located in a loess-covered landscape. The NGT was hewn from the westward-facing scarp slope of Fuzhong mountain, which has two geological units: cretaceous sandstone at the bottom and Quaternary loess cover above (Li 2006). Horizontal bedding planes can be observed on the surface of the sandstone. Today, the area experiences a continental semi-arid climate (in 2017 the NGT Preservation Institute recorded an annual average temperature of 12.7 °C and an annual average relative humidity of 60.11%). According to official records, five areas of the façade were consolidated with high-modulus potassium silicate consolidants 30 years ago. These areas were avoided in this study to prevent any interference caused by the consolidation.

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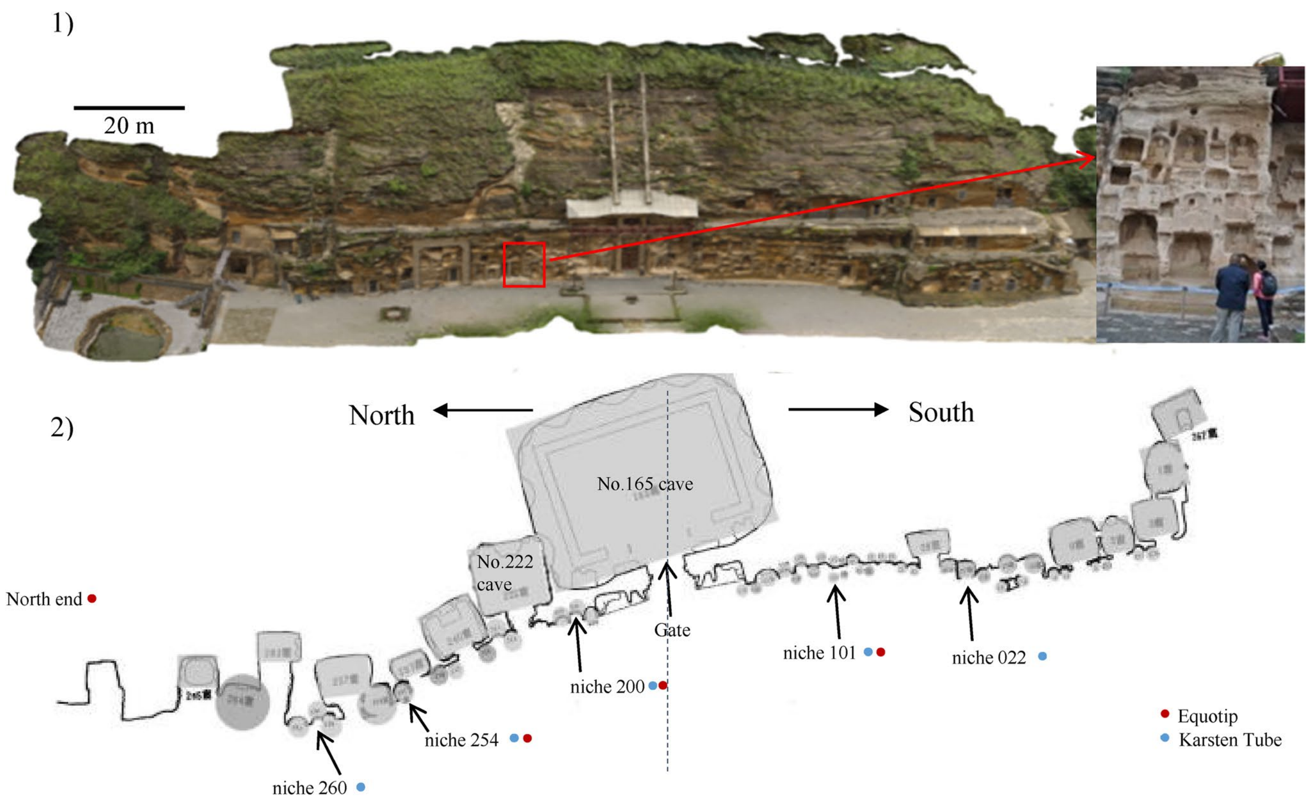

Fig. 1 3D model of the North Grotto Temple and plan view of the site and measurement locations

3 Methodology

Field studies on the NGT sandstone façade were undertaken between 25th August 2017 and 2nd September 2017 (average temperature and relative humidity over this period: 18.3 °C, 81.8%). Six measurement locations were selected from NGT façade (see Figs. 1 and 2). After the survey of deterioration patterns on each measurement location (ICOMOS-ISCS 2008), two pieces of portable non-destructive equipment were utilised.

First, following the BS EN standard 16302:2013, the Karsten tube was applied to determine the amount and rate at which water is absorbed through the sandstone surface of five niches (see Figs. 1(2) and 2(1)–(5)) for the evaluation of the water absorption capacities. Karsten tube can effectively reflect the current state of rock, it is, therefore, widely used on the assessment of porous building materials (Svahn 2006). However, after long-term practices, researchers found that the accuracy of the test results can be affected by experimental errors (i.e. reduction of effective contact area between water and rock surface due to sealant deformation) and changes in the shape of wetted zone inside rocks (Hendrickx 2013). To eliminate these affects, Hendrickx (2013) improved the calculation method of water absorption coefficient by combining the analytical solution of soil permeability in soil science with geometric analysis of wetted volume and provided formulas for calculation. Based on the formulas, sorptivity [S, the capacity of a porous medium to absorb or desorb liquid by capillarity (Philip 1957)] and capillary saturated moisture content [θ_{cap}, the volume of water that the rock needs to became saturated through capillarity (Hendrickx 2013)] were obtained. They can be used to characterize the water absorption capacity of rocks.

Second, the hardness of each sandstone bed (up to 1.5 m above the ground) at four sites (three niches and the natural rock face to the north of the NGT façade) was measured using a Proceq Equotip 3 hardness tester (with D probe) (see Figs. 1(2) and 2). This non-invasive hardness tester can be used to estimate rock strength (Verwaal and Mulder 1993) and has been used to infer the deterioration of stone heritage (Mol and Viles 2010; Viles et al. 2011; Wilhelm et al. 2016; Desarnaud et al. 2019) due to its high sensitivity to the weathered layer on the stone surface, small impact energy and small impact area (Aoki and Matsukura 2007).

The Single Impact Method (SIM), where one rebound reading is taken at a range of measurement points, was used here because SIM values have been found to reflect the strength of the rock surface, rather than the intact rock

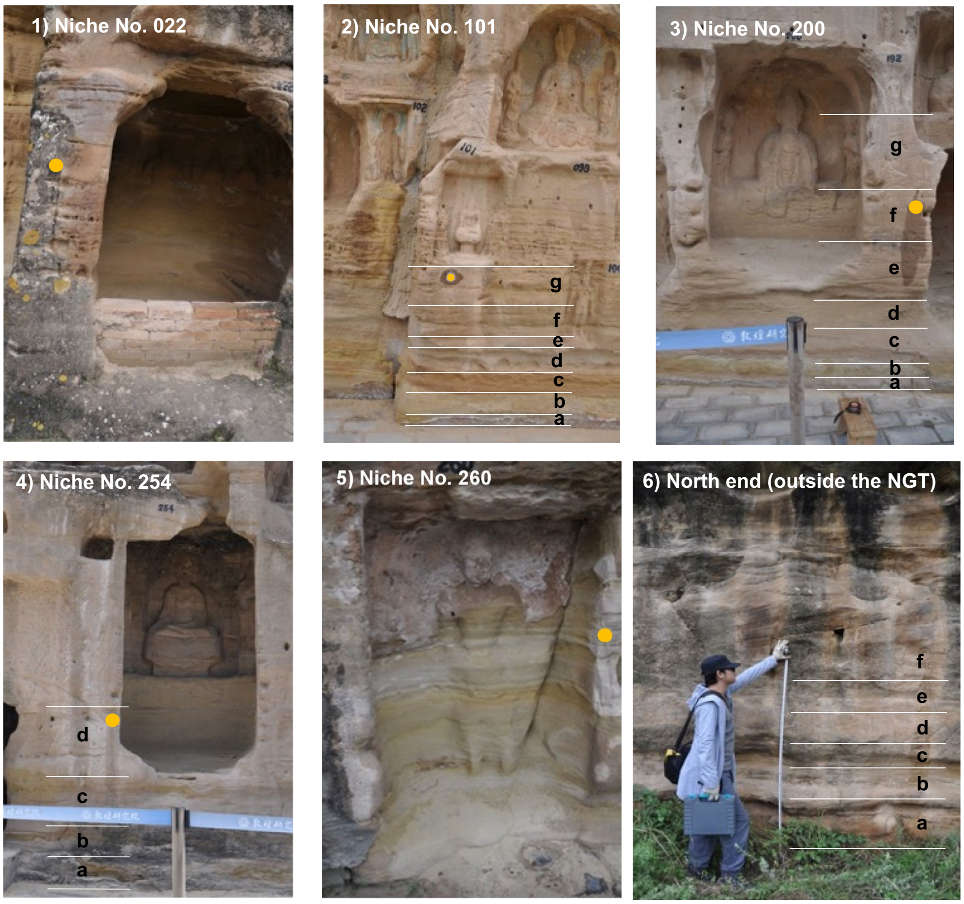

Fig. 2 Images of the six measurement sites on the façade of NGT and the adjacent natural rock outcrop. The letters in 2), 3), 4), 6) stand for layers of beds from which surface hardness were measured. The yellow circles in 1)–5) show the Karsten tube measurement locations

strength, and help to understand the deterioration occurring on it (Aoki and Matsukura 2007). Eight SIM measurements were randomly taken from each sandstone bed and an average calculated (see Table 2). Due to biological colonization and powdering surface, rebound readings could not be obtained from niche 022 and 260.

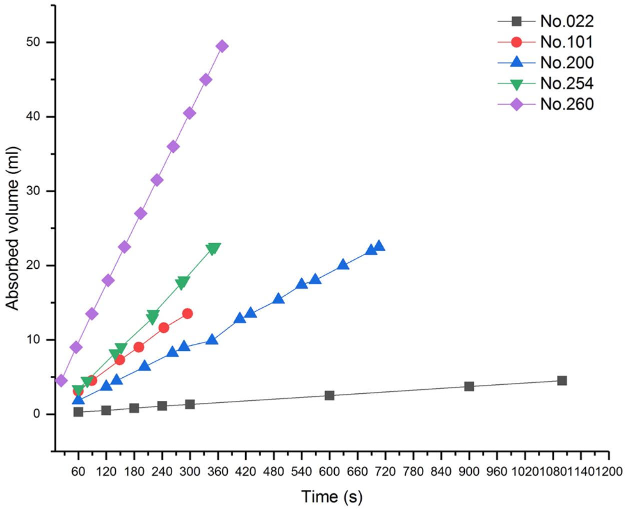

Fig. 3 Karsten tube test results (absorbed water volume in ml plotted against time in *s*) from five niches on the façade of NGT

4 Results and Discussion

4.1 The Capacity of the NGT Sandstone to Absorb Water by Capillarity

As shown in Fig. 3, the water absorption rate generally shows a gradual upward trend from niche 022 at the southern end to niche 260 at the northern end and the same trend is presented from sorptivity and θ_{CAP} (see Table 1). This variation demonstrates a heterogeneous feature of NGT sandstone from south to north and probably implies greater mean pore radius in the northern NGT sandstone due to the positive correlation between water absorption coefficient and mean pore radius of rock (Benavente et al. 2007). Comparing with the value of sorptivity and θ_{CAP} (see Table 1) and the deterioration patterns (see Fig. 2), the magnitudes of sorptivity and θ_{CAP} are consistent with the degree of deterioration observed. Greatest sorptivity and θ_{CAP} was obtained from the sandstone surface of niche 260 which is seriously deteriorated and contains a series of different deterioration patterns, including powdering,

Table 1 Sorptivity (S), capillary saturated moisture content (θ_{CAP}), surface hardness and deterioration patterns around each Karsten tube measurement point

Orientation in NGT	Measurement location in NGT (Niche No.)	S (kg/m$^2\sqrt{s}$)	θ_{cap} (ml/ml)	Surface hardness (HL)	Deterioration patterns at the sandstone bed where Karsten tube was applied
South↕North	022	0.078	0.065	–	Biological colonization
	101	0.295	0.074	g. 355	Horizontal hair crack, pitting
	200	0.277	0.087	f. 325	Pitting, scratch
	254	0.589	0.226	d. 346	Soiling,pitting, powdering, scratch
	260	1.001	0.288	–	powdering, sanding, crust,efflorescence,flaking

The surface hardness is the average surface hardness of the bed where the Karsten tube was applied. The letter in front of the surface hardness value represents the layer of the bed on the specific location

Effective readings of surface hardness were not obtained from the Niche 022 and 260 due to biological colonization on the sandstone surface and powdering surface, respectively

sanding, crust, efflorescence and flaking (see Fig. 2(5)). Niche 200 has only minor deterioration features (several small pits and fine scratches) (see Fig. 2(3)) and has relatively small sorptivity and θ_{CAP}. Niche 254 has intermediate levels of deterioration (see Fig. 2(4)) matched by intermediate values for sorptivity and θ_{CAP}. Niche 022 colonizing by vegetation (see Fig. 2(1)) has the smallest sorptivity and θ_{CAP}. In summary, deterioration probably plays a significant role in the modification of pores to NGT façade so that can further promote the water transportation on the rock surface, except for bio-deterioration on niche 022.

Furthermore, its worth noting that the south-to-north upward trend of water absorption rate does not present in the results obtained from niche 101 and 200. Table 1 shows that the sorptivity of niche 101 is greater than that of niche 200, although θ_{CAP} of niche 101 is smaller (see Table 1). This means that niche 101 has strong water absorption capacity but require less amount of water to reach saturation through capillarity. It can be seen in Fig. 2(2) that water absorption forms a horizontal spindle shape wetted zone around the Karsten tube on the sandstone surface at niche 101. This indicates that the water would penetrate horizontally towards the left and right. The existence of the wide vertical fissure filled with mortar on the left hand side of niche 101 (see Fig. 2(2)) are probably responsible for this phenomenon. No matter what causes of the fissure are, secondary cracks extending towards the vertical fissure are very likely to form in the interior of the sandstone here, because the formation of large fissures can promote the redistribution of stresses within the rock, influencing the development of secondary cracks (Huang and Huang 2010) and the direction of water penetration in the stone (Wang et al. 2005).

4.2 Surface Hardness and Deterioration of NGT Façade

The surface hardness varies across the four measuring locations from the north to south and from ground level upwards (0 m–1.95 m above the ground). The data from niche 101, 200 and 254 show much greater standard deviation than that from the natural sandstone rock face to the north of the NGT facade, indicating higher variability in surface hardness on the carved façade, i.e. niche 101, 200 and 254 (see Table 2). From the amount and types of deterioration patterns observed, more severe deterioration is also found on the carved façade, such as cracking, powdering, sanding and flaking. (see Fig. 2(2)–(4)). This implies that the significant variation of surface hardness across the beds on the carved façade is very likely to be caused by more intense deterioration. And the deterioration is probably subject to the existence of more environmental intervention, such as stronger insolation effects due to the west-facing direction of the carved façade, which can accelerate deterioration (Weiss et al. 2004).

Comparing the surface hardness results in Table 2 with the deterioration patterns in Fig. 2, it is clear that, at each site, those sandstone beds with little visible deterioration have higher surface hardness values. Most of the harder beds are located higher up the measured profiles, such as the top layer at niche 101, 200 and 254.

Lower surface hardness values are found on sandstone beds with powdering, efflorescence, black crust and flaking such as layer b at niche 101, layer a at niche 200 and layers a and b at niche 254. When efflorescence and crust are both present on a sandstone bed, the surface hardness is greater than that of beds where only efflorescence forms, but still lower than the average surface hardness of all beds at the measurement location, such as layers a and b at niche 200. In addition, it is worth noting that where alveolar weathering is found, surface hardness values are slightly greater than the average surface hardness of all beds at that measurement location, such as layer d at niche 101.

Table 2 Surface hardness values obtained from four measurement locations on the façade of NGT and the adjacent natural rock outcrop

Niche 101			Niche 200			Niche 254			North end (outside NGT)		
Bed No.	Thickness (cm)	Mean hardness (HL)	Bed No.	Thickness (cm)	Mean hardness (HL)	Bed No.	Thickness (cm)	Mean hardness (HL)	Bed No.	Thickness (cm)	Mean hardness (HL)
g	40	355	g	45	407						
f	30	327	f	35	325				f	15	321
e	15	280	e	45	319				e	15	354
d	15	308	d	20	342	d	45	346	d	20	333
c	20	267	c	30	349	c	45	165	c	30	362
b	15	240	b	10	308	b	30	207	b	40	309
a	10	232	a	10	330	a	30	232	a	50	332
Average		285	Average		340	Average		238	Average		335
Standard deviation		40	Standard deviation		30	Standard deviation		67	Standard deviation		18

5 Conclusion

Deterioration of sandstone on the façade of NGT causes variation in sorptivity and hardness. The capacity of the sandstone to absorb water by capillarity is positively correlated with the degree of deterioration when there are no internal cracks or biological colonization. Surface hardness is more variable on the rock-hewn façade than on the natural outcrop, and harder surfaces are generally found towards the top of the measured profiles (which also display less deterioration), with the softer surfaces found towards the base, with higher degrees of deterioration.

The research has demonstrated the value of in situ, non-invasive measurement methods, alongside observations of visible deterioration, in diagnosing the severity of deterioration on the façade of sandstone rock-hewn cave temples. Both the Equotip and the Karsten tube provide information about the near-surface characteristics of the façade, without the need for invasive sample collection. Further research is needed to produce larger datasets which can provide more detailed guidance for future conservation efforts.

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Appendix

Formulas for calculating sorptivity (S) and capillary saturated moisture content (θ_{cap})

$$x(t) = R_{\mathrm{wet}}(t) - R_e \tag{1}$$

$$V_{\mathrm{wet}}(t) = \frac{2}{3}\pi\left(x(t)^3 + R_e x(t)\right) + \pi R_e^2 x(t) \tag{2}$$

$$\theta_{\mathrm{cap}} = \frac{V_{\mathrm{abs}}(t)}{V_{\mathrm{wet}}(t)} \tag{3}$$

$$V_{\mathrm{abs}}(t) = \pi R_e^2 S\sqrt{t} + \frac{\pi R_e \gamma S^2}{\theta_{\mathrm{cap}}} t \tag{4}$$

$x(t)$: penetration distance of wet front at time t. $R_{\mathrm{wet}}(t)$: radius of wetting area at time t. $V_{\mathrm{wet}}(t)$: wetted volume of stone at time t. R_e: radius of effective contact zone. θ_{cap}: capillary saturated moisture content. V_{abs}: absorbed water volume, i.e. decrease in volume of water observed in Karsten tube. γ: constant, 0.75. S: sorptivity, capacity to absorb water by capillarity.

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