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Effect Analysis of Steam Cleaning Technology on Surface Damage of Stone Cultural Relics

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Abstract

Stone cultural relics, due to their significant historical value and irreproducibility, necessitate cleaning and preservation with the paramount principle of ensuring the safety of the relic itself, followed by achieving effective cleaning. Based on cultural relics from the Hangzhou region as examples, the steam cleaning experiments on limestone were conducted to investigate the impacts of various technical parameters on the surface damage of these stone relics. Through non-destructive testing methods such as infrared thermography, high-definition digital cameras, and visual observation, the changes in surface color, microstructure, mass, and temperature before and after cleaning were analyzed to assess the degree of surface damage caused by the steam cleaning parameters and to determine their safety control ranges. Results show that, the key technical parameters for the safe implementation of steam cleaning are cleaning time, cleaning distance, cleaning angle, and cleaning pressure, with cleaning time having the greatest impact on safety. The safe ranges for steam cleaning are as follows: a cleaning distance of 1-5 cm, a cleaning pressure of 2-8 bar, a cleaning angle of 30-90°, and a cleaning time of 1-5 min. By controlling the parameters of the steam cleaning technology, the impact of steam cleaning on the surface damage of stone cultural relics can be effectively minimized, providing valuable references for practical engineering applications of stone cultural relics.

Keywords: Stone cultural relics, Steam cleaning, Technical parameters, Non-destructive testing, Damage degree

1. Introduction

Stone cultural relics serve as important carriers and witnesses of China's historical and cultural heritage, thus possessing remarkable historical value and irreplaceability [1]. Therefore, when undertaking cleaning work on these relics, ensuring their safety and selecting safe and effective cleaning methods are crucial tasks. The cleaning and protection of stone cultural relics hold profound historical and practical significance and represent one of the key challenges in current cultural heritage conservation efforts. Research on the preservation of stone cultural relics, both domestically and internationally, frequently focuses on refining cleaning techniques and evaluating their effectiveness. However, most studies fail to provide a systematic analysis and quantitative assessment of the potential damage to the relics that may occur during the cleaning process, especially in terms of the impact of various cleaning parameters on the physical and chemical properties of the stone surface [2].

Selecting an appropriate cleaning method can effectively remove pollutants while mitigating the degradation of relics, thereby paving the way for subsequent pollutant removal through various cleaning techniques. However, scant attention has been paid to whether these methods might compromise the integrity of the stone, whether residual contamination might persist, or to assessing the cleaning efficacy. Steam cleaning, recognized as a safe, controllable, environmentally friendly, and efficient cleaning technique, fulfills the current demands for the cleaning and preservation of stone cultural relics. While steam cleaning technology has been widely employed for cleaning stone surfaces in China, early practices required the use of substantial amounts of steam and physical tools to remove surface contaminants, causing significant damage to the relics [3]. Presently, inadequate evaluation of the safe operational parameters of steam cleaning technology still persists, hindering the full assurance of its safety and effectiveness in practical applications.

The primary objective in protecting stone cultural relics is to safeguard their integrity, with the cleaning effect serving as a secondary consideration. Therefore, this article conducts experiments to assess the potential damage caused by steam cleaning technology on stone relics. The goal is to identify the key cleaning parameters that affect the relics' safety and establish corresponding safe operational ranges. The results of this study will serve as a guideline for safely utilizing steam cleaning technology in the preservation of stone cultural relics, ensuring the safety of the relics while maximizing cleaning effectiveness. Additionally, it offers the more detailed technical support for the conservation of stone cultural relics. This research possesses significant academic value and practical application importance.

2. State of the art

In recent years, with advancements in science and technology and an intensified national emphasis on cultural relics protection, traditional cleaning methods have failed to meet the current goals and principles of cultural relics conservation. Steam cleaning, known for its eco-friendliness,

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cleanliness, pollution-free nature, efficiency, and convenience, has gained significant favor among cultural relics conservators [4]. He and Zhang [5] conducted a comprehensive review of the emergence, evolution, mode of action, and practical applications of steam cleaning technology, offering invaluable insights to cultural relics conservation professionals in China. Early technicians noticed that hot steam could effectively remove oil stains from garage floors, prompting initial research into steam cleaning technology [6, 7].

By developing a theoretical analysis model for steam cleaning technology and integrating it with practical cleaning operations, researchers can simulate the impact of technical parameters such as steam temperature, pressure, and velocity on the surfaces of stone artifacts. This provides targeted reference data that aids in optimizing cleaning processes [8]. Li and Lou combined steam cleaning with ultrasonic cleaning techniques, achieving promising results in mechanical cleaning processes, which demonstrates the potential of combining different technologies for enhanced cleaning effectiveness [9]. Furthermore, steam cleaning is widely recognized as an energy-efficient and environmentally friendly cleaning method [10]. Numerous scholars have conducted extensive research on steam cleaning technology, revealing that high-temperature steam exhibits bactericidal properties against microorganisms. Specifically, steam injection durations of 3 to 5 sec have been shown to remove over 50% of persistent bacteria, underscoring the technology's potential for sanitization [11]. Kravchenko et al. [12] proposed a heat transfer model for cleaning object surfaces using abrasive jet steam, which contributes to a better understanding of the cleaning mechanisms involved and may lead to the improvement of cleaning techniques. Feng and Hua [13], on the other hand, utilized fluid simulation software to analyze steam nozzle flow patterns. Their research determined the optimal cleaning distance and subsequently led to the development of a corresponding cleaning machine, showcasing the practical applications of steam cleaning technology in real-world scenarios.

Some scholars have utilized numerical simulation methods to study steam cleaning technology. Zhao [14] conducted numerical simulations of steam cleaning parameters, and provided corresponding cleaning processes for sandstone artifacts based on effective cleaning parameters and the safe control range of steam. Yan and Xu [15] employed finite element software to optimize the parameters of steam nozzles, demonstrating that a straight cylindrical nozzle with a 20 mm hole size could effectively remove dirt and cause detachment and vaporization over a certain air flow length.

Currently, research on stone artifact detection technology continues to advance, evolving from initial contact detection to non-destructive testing, and now incorporating multiple combined detection methods. Hu et al. [16] evaluated the cleaning effect by measuring residual microbial amounts on the rock surface after cleaning using a microscope. Huang et al. [17] assessed the preventive effects of nanomaterials on biological damage to stone artifacts through microscopic morphology analysis. Wang et al. [18], through concrete examples, illustrated the crucial role of infrared thermography technology in analyzing the causes of cultural relic damage and evaluating their preservation status. Stoveland et al. [19] employed ion chromatography to evaluate the cleaning effectiveness of stone gate artifacts. Zina-Sabrina et al. [20] utilized a novel spectral imaging method to detect the depth of surface pollutants on stones, effectively visualizing the cleaning depth and enabling high-precision detection. Additionally, some researchers have combined ultrasonic and moisture content detection techniques to assess the safety of rock surfaces regarding damage and weathering [21-23].

Steam cleaning technology, as a method for the preservation of stone artifacts, offers advantages such as safety, cleanliness, non-pollution, and effective cleaning. It is anticipated to become one of the important cleaning techniques for stone artifacts. However, attention should be given to operational details and the careful selection of technical parameters in practical applications, to ensure cleaning effectiveness while minimizing potential damage to the stone artifacts. Overall, research on stone artifact detection technology spans multiple disciplines. Additionally, through comprehensive detection and analysis, a deeper understanding of material properties, disease characteristics, and preservation requirements can be achieved, providing a scientific foundation for subsequent engineering implementations.

The rest of this study is organized as follows. Section 3 introduces steam cleaning principles and test plans, while Section 4 presents an experimental study on surface damage from steam cleaning using various conditions and detection methods. Optimal parameters and safe ranges for limestone relics are determined. Finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Research protocols

The steam cleaning process primarily generates a steam flow with an impact force, achieved through high-temperature steam compression. This is accomplished via the combined effects of surface impact friction, high-temperature dissolution, and steam blasting on the substrate surface, ultimately yielding a cleaning effect. However, if operational parameters, such as the duration of steam cleaning, are not properly controlled, unnecessary damage may occur to the surface of stone cultural relics. Therefore, the selection of these operational parameters is crucial for the safe application of steam cleaning technology in the field of cultural heritage conservation, and it constitutes the focus of this study.

For the experiment, limestone samples were selected from Baifo Rock in the Wushan Scenic Area of Hangzhou, along with limestone test blocks made of the same material. After undergoing indoor cutting and surface polishing, rock thin slices with dimensions of 10 cm × 5 cm × 0.5 cm were prepared, totaling 5 groups, each containing 20 pieces. These samples were utilized for surface damage tests and to investigate the impact of different steam operating conditions. Fig. 1 shows the original limestone samples and the processed test blocks.

3.2 Influences of contacts on structural stresses

3.2.1 Rock composition detection

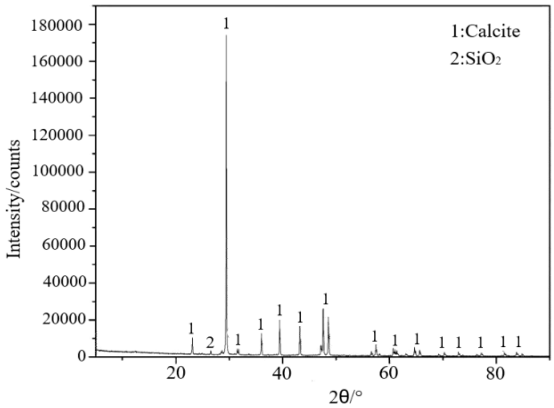
First, the powdered limestone specimen is tested using the SmarLab9KW X-ray Diffraction (XRD) instrument, with the instrument's detection parameters set at an X-ray source λ = 0.15418 nm, a voltage of 40 kV, and a current of 40 nA. Subsequently, the test results are analyzed using the corresponding software, and the composition analysis results are plotted using Origin software.

Fig. 1. Sawn limestone slab

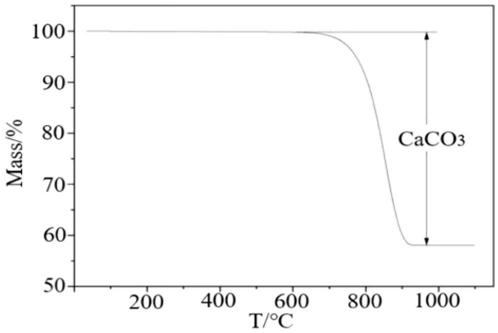
According to the analysis, the limestone test block from Baifo Rock in Hangzhou is observed to primarily consist of calcium carbonate (in the form of calcite mineral), with a content exceeding 50%. The remainder is composed of carbonaceous organic materials. Additionally, thermal gravimetric analysis is conducted to examine the mass change of the rock as it is heated. The results indicate that mineral components in the rock experience substantial loss at temperatures exceeding 600 °C. Fig. 2 illustrates the composition analysis results of the limestone sample.

3.2.2 Steam cleaning equipment and materials

Owing to the precious nature of stone cultural relics, achieving effective detection results solely through visual inspection methods is a challenge. Therefore, selecting appropriate non-destructive testing methods to evaluate the cleaning efficacy of surface contaminants on stone cultural relics has utmost importance. The study primarily employs the following three non-destructive testing techniques: color difference analysis, microscopy, and infrared spectroscopy, to establish a theoretical foundation for the subsequent assessment of the cleaning experiment's effectiveness.



(a) XRD detection chart



(b) XRD detection chart

Fig. 2. Composition analysis results of limestone sample

The cleaning experiment utilizes a multifunctional cleaning machine, with a cleaning temperature range of 110 °C to 140 °C, which falls within the safe tolerance range for the rock. Table 1 shows the operational parameters of the high-temperature steam cleaning equipment.

Table 1. Cleaning experiment equipment list

Category	Instrument name	Model	Working parameters
Cleaning equipment	Steam cleaning machine	KY-H10	Steam pressure: 2-8 bar, Steam temperature: 120-140 °C
Detection tools	3nh precision colorimeter	3NH-NR110	Light source: D65, Aperture: 8 mm, Detection temperature: 0-40 °C
	High-resolution digital camera	DSX1000	Magnification: 23-8220 x, Field of View: 50-19200 μm
	High-resolution microscope	DDL-M1	Magnification: 1-400 x
	Infrared thermal imager	FOTRIC 326Q	Temperature range: -20-120 °C; 0-350 °C

3.2.3 Steam cleaning conditions

Steam cleaning is primarily influenced by the following five technical parameters: temperature, injection angle, injection distance, pressure, and time. Among these, the steam temperature is dictated by the equipment's performance, while the surface temperature of the test block is influenced by the remaining four technical parameters. Therefore, this study concentrates on simulating the cleaning conditions for the parameters of time, distance, angle, and pressure. The selected cleaning conditions encompass the minimum and maximum values for each parameter, as well as two additional sets of conditions where all parameters are set to intermediate values. These conditions aid in determining the extent of surface damage inflicted by steam cleaning.

First, a soft-bristled brush was used to remove dust from the surface of the test block. Subsequently, prior to cleaning, steam was applied to dampen the surface of the test block, thereby preventing cracking due to sudden temperature changes. The steam cleaning experimental conditions are presented in Table 2.

Table 2. Steam cleaning damage experimental conditions

Condition ID	Injection distance (cm)	Cleaning angle (°)	Injection pressure (bar)	Cleaning time (min)	Steam temperature (°C)
A	0.5	15	2	0.5	130
B	1	30	4	1	130
C	3	60	6	3	130
D	5	90	8	5	130

4. Result Analysis and Discussion

Owing to the uniqueness of stone cultural relics, cleaning procedures should aim to minimize surface damage and morphological changes within a controllable range, ensuring the safety of the relic's surface throughout the cleaning process.

Currently, China lacks specific standards for controlling the safe range of cleaning and conservation practices for stone cultural relics. In the field of cultural heritage conservation, the primary principle is to preserve the original appearance of the relics. This study assesses the damage caused by steam cleaning technology to the surface of stone cultural relics using four common detection methods, namely, color difference measurement, infrared thermal imaging, microscopy, and mass measurement. The evaluation is carried out from the following four perspectives: surface analysis, internal inspection, microscopic examination, and overall assessment.

4.1 Temperature change detection of test block surface

The surface temperature changes of the test block before and after cleaning were detected using an infrared thermal imager (emissivity 0.7, reflective temperature 20 °C, ambient temperature 20 °C, target distance 0.5 m). The results were imported into the corresponding analysis software, AnalyzIR, for image processing. The temperature changes were represented in two-dimensional temperature maps and three-dimensional temperature distribution maps [24]. Finally, the temperature variation amplitude was analyzed using charts. Figs. 3 and 4 display the infrared detection results.

As shown in Figs. 3 and 4, the surface temperature of the test block before steam cleaning is at room temperature, with the average surface temperature of the test block remaining stable at room temperature. As the steam cleaning time increases, the heat dissipation rate from the test block's surface accelerates.

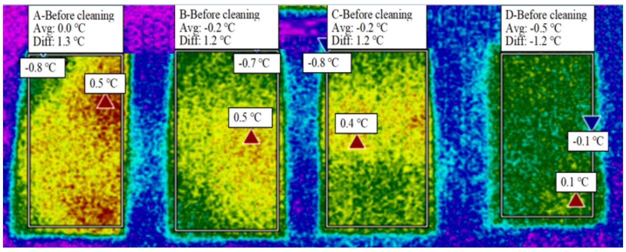


Fig. 3. Infrared thermal imaging of test block before steam cleaning

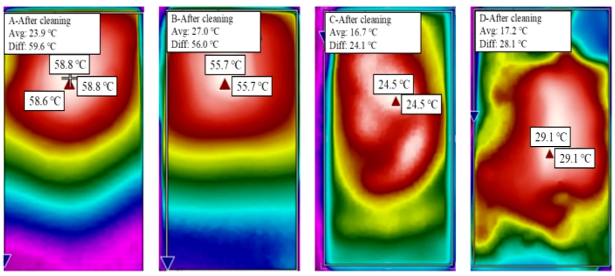
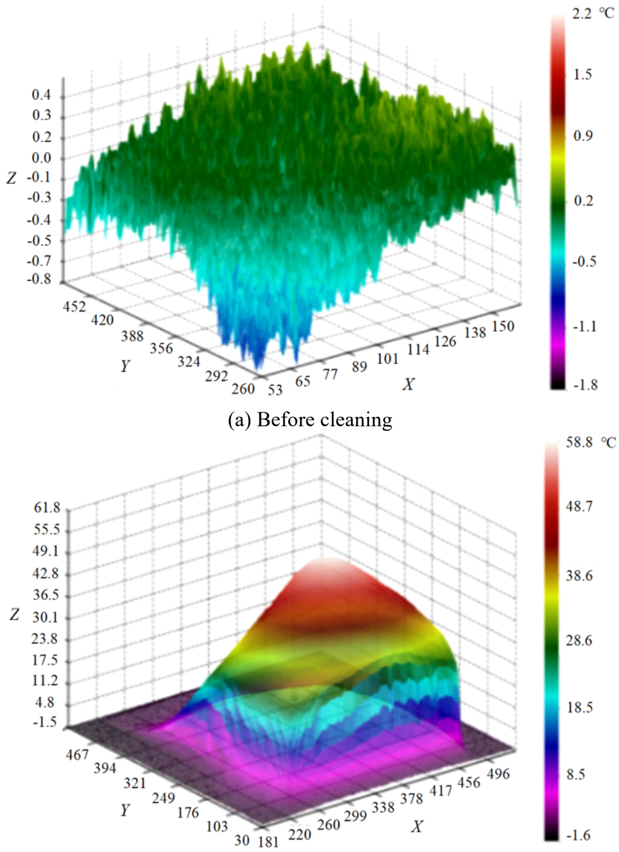


Fig. 4. Infrared thermal imaging of test block after steam cleaning

Under prolonged exposure to high-temperature steam, the moisture inside the test block rapidly evaporates. Meanwhile, as cleaning time increases, the overall temperature distribution of the test block spreads outward. Fig. 5 shows the results.



(a) Before cleaning

(b) After cleaning

Fig. 5. Overall 3D temperature distribution of test block

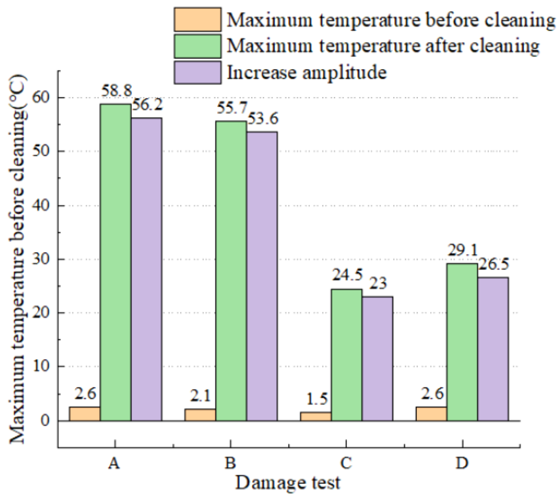


Fig. 6. Temperature variation on test block surface before and after cleaning

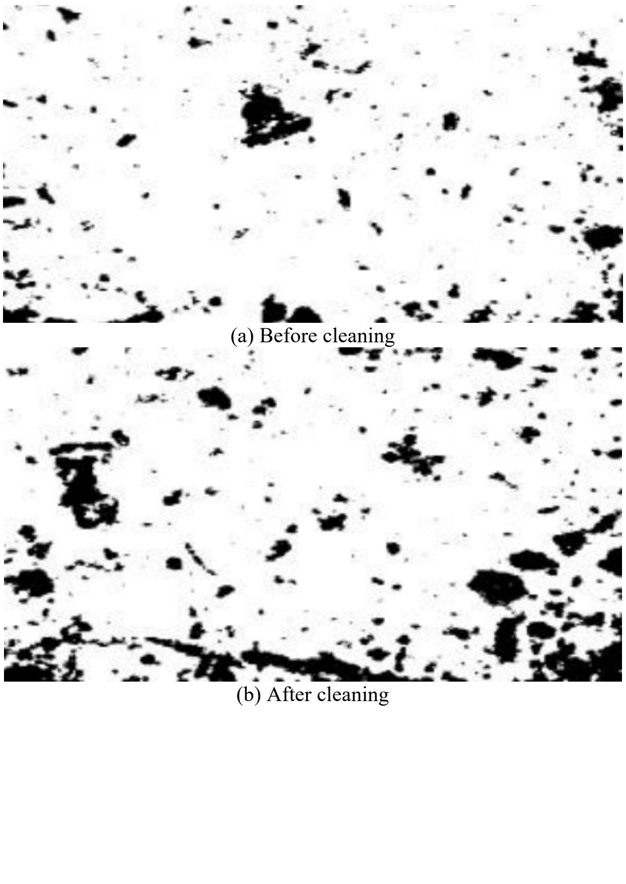
From the comparison in Fig. 5, before high-temperature steam treatment, the surface temperature distribution of the four sets of test blocks is relatively uniform, with hot spots concentrated at the center of the steam jet. After high-temperature steam treatment, when the steam nozzle is near the rock surface (0.5 cm to 3 cm), the highest temperature on the rock surface is concentrated at the jet center. However, when the distance between the steam nozzle and the rock surface is increased to 5 cm, the temperature distribution of the test block becomes uneven, and the highest temperature is no longer concentrated at the jet center but spreads outward. The 3D temperature distribution results indicate that the closer the steam injection distance to the test block surface, the higher the overall temperature of the rock, and the more concentrated the heated area. Additionally, the longer the steam injection time, the faster the temperature diffusion of the test block. Fig. 6 illustrates the temperature variation before and after steam cleaning of the test block surface.

As shown in Fig. 6, under the four different cleaning conditions, from Conditions A to D, the temperature increase on the test block before and after cleaning gradually decreases. The maximum temperature rise on the test block surface occurs under Condition B. The highest temperature is primarily concentrated in the central area of the steam jet. By contrast, Condition D shows a relatively low temperature increase, because under Condition D, the temperature distribution of the cleaning area on the test block surface tends to spread outward.

4.2 Damage detection of test block surface

The test blocks under the four different steam cleaning conditions were analyzed using a portable microscope, with a magnification of 100x. By comparing the microscopic images across the four cleaning conditions, the degree of surface morphology change on the test block can be observed to decrease. The loss of mineral components on the rock surface is more pronounced in Conditions C and D.

Image Processing: First, the color microscopic images were imported into the Hiver software and converted into grayscale images for denoising, thereby improving the clarity of the images. Next, the grayscale images were converted into binary black-and-white images to show the damage changes on the surface of the test blocks. The binary images were then imported into the MATLAB software for further analysis. In the binary microscopic images, the recessed areas on the test block surface are represented by black pixels (0), while the flat areas are represented by white pixels (255). Fig. 7 presents the binary microscopic images and their analysis results.


(a) Before cleaning

(b) After cleaning

Fig. 7. Binary image of test block before and after steam cleaning

Global Thresholding Method: The area ratio of black pixels to the total image area represents the porosity. An initial threshold of 0.5 was selected, and the average value was calculated after multiple iterations. The result provides the surface porosity of the test blocks under different steam cleaning conditions in the specified area.The calculation formula is as follows:

$$P = \frac{S_{\text{black}}}{S_{\text{total}}} \tag{1}$$

where, P is the porosity (%). S_{blacl} is the area of the black pixel region. S_{total} is the number of the pixels in the entire image region.

The degree of rock surface damage under different steam injection parameters is determined by the difference in porosity before and after high-temperature steam treatment. The damage degree is categorized into the following four levels: no damage (<10%), slight damage (10-30%), moderate damage (30-50%), and severe damage (>50%). The calculation results of surface damage ratios of test blocks under different high-temperature steam cleaning conditions are shown in Table 3.

Table 3. Surface porosity and damage degree of test blocks under different cleaning conditions (%)

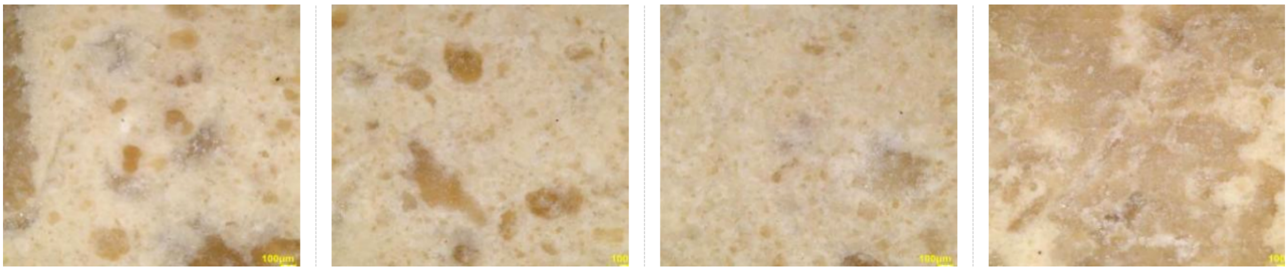
Cleaning condition	A	B	C	D
Porosity before cleaning P_1	9.86	10.12	12.23	10.61
Porosity after cleaning P_2	17.28	21.22	26.71	45.45
Porosity difference	7.42	11.10	14.48	34.84
Damage degree	Slight	Moderate	Moderate	Moderate

4.3 Microstructural morphology of test block damage

The damage degree of the test blocks under different cleaning conditions was deeply examined using a DSX1000 digital microscope. The analysis primarily relied on 2D microscopic images, 3D high-depth-of-field images, and 2000× micro-particle composition detection. The 2D images were used to observe changes in the surface morphology of the test blocks and analyze surface damage. The 3D high-depth-of-field images highlighted the uneven regions of the test block surface, and contour maps of surface roughness were generated. The 2000× microscopic examination was used to investigate the surface damage mechanism of the test blocks.

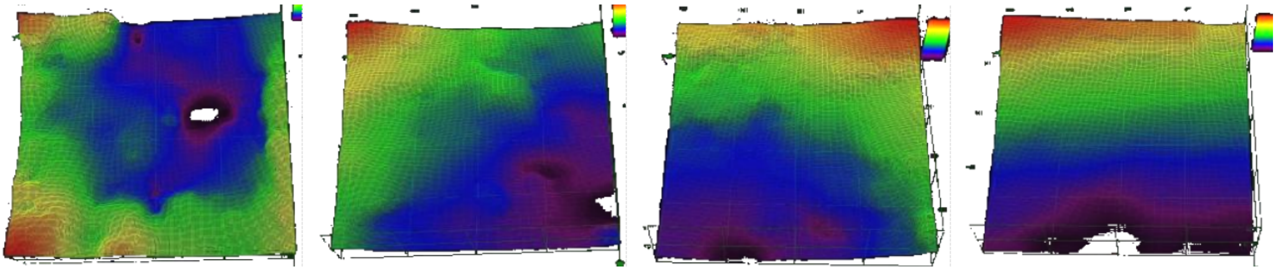
4.3.1 Surface damage of test blocks and its relationship with steam cleaning conditions

High-definition digital images and 3D high-depth-of-field images of the damaged test blocks are shown in Fig. 8. As illustrated in Fig. 9, the closer the steam distance and the smaller the injection angle, the more significant the damage to the test block surface becomes. When the steam distance is between 0.5 cm and 1 cm, and the steam injection angle is between 15° and 30°, severe damage occurs on the test block surface (Conditions A and B). When the steam injection distance exceeds 5 cm, the effect of cleaning time on the surface damage of the test block becomes less noticeable.



(a) A (b) B (c) C (d) D

Fig. 8. High-definition digital photos of surface damage of test blocks under different cleaning conditions (700×)



(a) A (b) B (c) C (d) D

Fig. 9. 3D high-depth-of-field images of surface damage of test blocks under different cleaning conditions (700×)

Analyzing the 3D high-depth-of-field images in Fig. 9, the concave regions on the surface of the test block under Cleaning Condition B can be observed to be larger and more prominent. By contrast, under Cleaning Condition D, noticeable change is nearly unnoticeable than the pre-steam cleaning image. This finding indicates that the steam injection distance and angle are the primary factors affecting the degree of surface damage, followed by steam pressure and cleaning time. The smaller the steam injection angle, the greater the frictional force between the steam flow and the test block surface. When this frictional force exceeds the bonding force of the mineral components on the test block surface, detachment occurs, resulting in surface damage. At steam pressures ranging from 2 bar to 4 bar, the surface mineral composition of the rock can be lost; additionally, spalling may occur, leading to an uneven surface. Selecting an appropriate steam injection distance and angle can prevent severe surface damage to the test block while ensuring effective cleaning.

4.3.2 Surface damage characteristics of test blocks

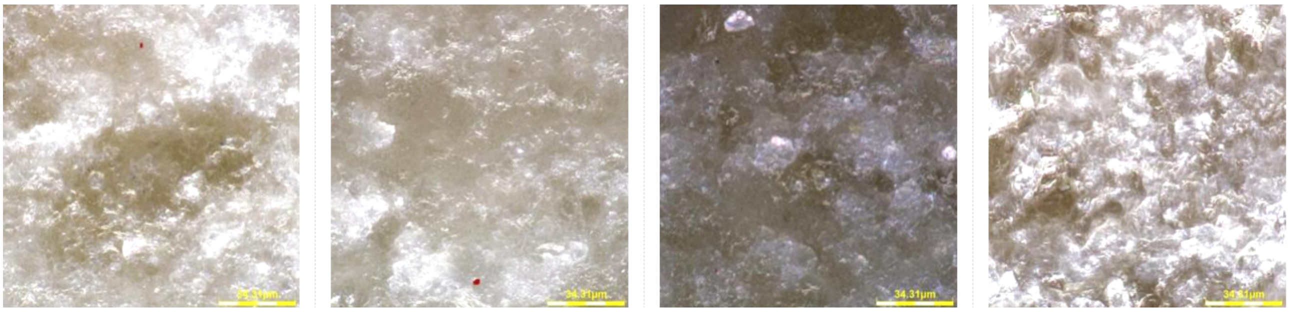
Further analysis of the 3D high-depth-of-field inspection images was conducted to examine the damage characteristics of the surface fracture areas of the four test blocks. The results reveal that the parameter characteristics of Test Blocks B and C are relatively similar; whereas Test Block A exhibits the most significant damage, and Test Block D shows minimal damage. The details are as follows:

During steam cleaning, if the steam injection distance is too close to the surface of the test block and forms a certain angle, surface damage will occur when it exceeds the test block's capacity to withstand the steam. This damage is particularly pronounced around the injection center. This observation is consistent with the infrared detection results. Under Condition A, when observing the surface of the test block under a 2000x microscope, clear oblique depressions were observed, with the depression area being correlated with the injection angle. Under Conditions B and C, the surface of the test block showed slight damage with minor loss of mineral composition. However, no significant depressions were observed, indicating that the cleaning was within a controllable range. Under Condition D, which involved a steam distance of 5 cm, an injection angle of 90°, a cleaning time of 5 min, and a steam pressure of 8 bar, the surface of the test block showed nearly no morphological changes or damage, indicating safe cleaning conditions.

The steam injection time affects the micro-morphology of surface damage on the specimen. As shown in Fig. 10, when the steam injection times for Conditions A and B are 0.5 min and 1 min, respectively, the damage area on the specimen surface due to steam jet impact is relatively concentrated, exhibiting distinct depressions. However, when the steam injection time is extended to 3 min (Condition C) and 5 min (Condition D), the white particulate component (calcium carbonate) on the specimen surface is removed after prolonged exposure to high-temperature steam, resulting in a surface with uneven topography caused by the impact of the steam jet.

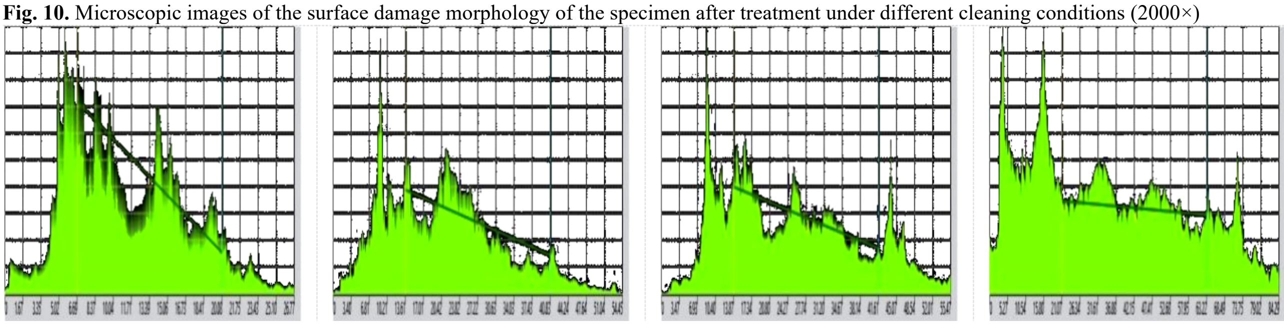
Through geometric analysis of the 3D high-depth-of-field image in Fig. 10, the surface height variation of the specimen within the steam jet impact zone under different cleaning conditions was observed. The results indicate that under Condition A, the height difference on the specimen surface is the greatest. Under Conditions B and C, the surface tilt is moderate; whereas under Condition D, the surface tilt approaches a flat plane. The surface height measurement maps for the specimen under different cleaning conditions are presented in Fig. 11.

By measuring the line roughness of the cross-sectional surface and the overall surface roughness of the specimen, both the degree of surface depression and the degree of height inclination were found to have influenced the surface roughness. Under Cleaning Condition A, the specimen's line roughness (Ra) and surface skewness (Sku) both reached their maximum values, which is consistent with the previously observed measurements of the specimen's surface height inclination. Table 4 presents the line (surface) roughness of the specimen under different cleaning conditions.



(a) A (b) B (c) C (d) D

Fig. 10. Microscopic images of the surface damage morphology of the specimen after treatment under different cleaning conditions (2000×)



(a) A (b) B (c) C (d) D

Fig. 11. Surface height measurement maps of the specimen under different cleaning conditions (700×)

Table 4. Line (Surface) roughness of specimens under different cleaning conditions (μm/°)

Roughness category	A	B	C	D
Line roughness Ra (μm)	0.621	0.354	0.483	0.401
Roughness level	Medium	Smooth	Medium	Medium
Surface steepness Sku (°)	5.343	3.106	3.029	2.761
Roughness level	Rough	Medium	Medium	Medium

4.4 Characterization of surface damage variations of specimen

The damage test results indicate that high-temperature steam can alter the surface morphology and physical properties of the limestone specimen. Under Cleaning Condition D, a noticeable color change occurred on the specimen’s surface, accompanied by substantial changes in surface roughness and mass. As the cleaning time increased, the degree of color change on the specimen’s surface became increasingly pronounced, and both surface roughness and mass varied accordingly. The loss of mineral composition on the specimen’s surface resulted in a decrease in the specimen’s mass. Table 5 presents the color change and mass variation results for the specimen’s surface under different cleaning conditions.

4.5 Discussion of damage test results

The damage test results indicate that steam cleaning has a relatively mild impact on the surface damage of the rock. Within an appropriate cleaning time, neither the surface nor the interior of the rock experiences considerable damage or delamination, and the temperature distribution across the specimen’s surface is relatively uniform after cleaning. The mass test results show that the overall mass change of the specimen before and after cleaning is negligible, indicating that the impact force exerted on the rock surface by the steam cleaning pressure is small, and no noticeable mass loss occurs on the specimen’s surface.

Table 5. Physical property changes of limestone specimens before and after treatment under different cleaning conditions

Detection item			A	B	C	D
Colorimetry	Before treatment	L	79.40	78.74	79.17	75.78
		a	4.04	4.05	3.67	4.69
		b	16.74	16.68	15.79	15.98
		c	17.22	17.17	16.21	16.65
		h	76.43	76.35	76.93	73.65
	After treatment	L	77.56	76.80	77.48	73.15
		a	4.32	4.39	4.20	5.00
		b	16.92	17.26	16.88	16.63
		c	17.46	17.81	17.39	17.37
		h	75.69	75.72	76.03	73.26
	Change	ΔE	4.27	4.51	4.99	6.11
Mass (g)	Before treatment		48.6775	71.5112	56.9221	53.8094
	After treatment		48.5080	71.4384	56.8539	53.7053
	Change		-0.1695	-0.0728	-0.0682	-0.1041

The surface morphology change indicators for the rock include color difference, microstructure, and roughness. Under Cleaning Conditions A-C, the color difference on the specimen’s surface remains within an acceptable range. However, under Cleaning Condition D (a 5-min cleaning time), the color change on the specimen’s surface is significant (ΔE > 6). The microscopic binarized image analysis reveals that prolonged cleaning causes excessive loss of the specimen's surface particles, exposing the internal mineral components, which results in surface depressions and a deepening of the color. Microstructural image analysis shows that under all four cleaning conditions, the specimen's surface experiences some damage, altering its microstructural features. Nonetheless, the changes in surface roughness are within an acceptable range, and the overall roughness remains relatively low. Table 6 presents the calculation results of the steam cleaning damage test.

Table 6. Results of steam cleaning damage tests

Operating condition	A	B	C	D
Mass change result (g)	-0.2657	-0.2434	-0.3378	-0.3613
Color difference result (ΔE)	4.27	4.51	4.99	6.11
Temperature change result (°C)	52.7	56.9	50.2	26.9
Porosity change (%)	7.42	11.10	14.48	34.84
Damage level	Minor	Mild	Mild	Moderate

5. Conclusions

The experiment in this chapter conducted a damage impact test on limestone specimens, analyzing the effects of steam cleaning technology on stone cultural relics through the following three aspects: physical changes to the specimens, changes in surface morphology, and temperature changes. The main conclusions are obtained as follows:

(1) Cleaning time is the primary factor influencing the degree of damage caused by steam cleaning, serving as the first-level indicator. It has a direct impact on the extent of surface damage to the cultural relics. Through real-time observation and analysis of the specimens' temperature changes using an infrared thermography camera, the optimal cleaning time was determined to be within 5 mins. Under safe cleaning conditions, only the cleaned area of the rock surface experiences an increase in temperature, with the highest temperature concentrated at the center of the steam flow injection point. The temperature of the uncleaned area remains essentially unchanged. When the cleaning time is extended but the temperature increase in the cleaned area is insignificant, it indicates that the specimen's surface has already sustained noticeable damage.

(2) Cleaning distance and angle are the second-level indicators for the safe implementation of steam cleaning technology. When the cleaning distance is too close (0.5 cm) or the angle is too low (15°), obvious surface depressions appear on the specimen, and both the surface temperature and the degree of damage substantially increase. Therefore, cleaning operations should avoid excessively close cleaning distances and low cleaning angles. These two technical parameters can be monitored and controlled through microscopic inspection methods.

(3) Cleaning pressure is the third-level indicator for selecting steam cleaning parameters. It is primarily related to the selection of cleaning time, cleaning distance, and cleaning angle. By fixing the other cleaning parameters or adjusting the cleaning pressure in response to changes in the other parameters, the degree of surface damage to the specimen can be controlled. The cleaning pressures selected in the experiment were all within a lower range (2-4 bar), which had a minimal impact on surface damage and resulted in a relatively small impact force of the steam flow on the rock surface. Therefore, it is considered a third-level indicator.

To ensure the safe cleaning of stone cultural relics, the most critical determining factor is cleaning time, followed by cleaning distance and angle, and lastly cleaning pressure and other working conditions. In cleaning operations, prioritizing parameter combinations that involve shorter cleaning times, greater cleaning distances and angles, and lower cleaning pressures is recommended to minimize unnecessary damage to the surfaces of the cultural relics.

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