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The Application of On-Site Analysis and Detection Technologies in the Conservation and Restoration of Polychrome Cliff Carvings

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Abstract: Scientific analysis and testing of cultural relics are often carried out during the design phase prior to restoration, serving as the foundation for subsequent conservation treatment. Given the diversity and complexity of cultural relics, uncertainties are often present at all stages of conservation and restoration, making on-site analysis and testing at the conservation site highly significant for guiding protection and treatment. This paper, focusing on on-site conservation work for polychrome cliff carvings, discusses the application scenarios of several relatively simple and practical analysis and testing instruments—such as infrared thermal imagers, Leeb hardness testers, and spectrophotometers—at conservation and restoration sites.

Keywords: Cultural relic conservation; Polychrome cliff carvings; Non-destructive testing; Infrared thermal imaging; Leeb hardness; Spectrophotometer

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1. Introduction

With the increasing investment in China's cultural heritage conservation efforts and the continuous improvement of various analysis and testing technologies, as well as the decreasing cost of testing, some simple and practical non-destructive testing technologies have become feasible for wider application at conservation and restoration sites. This is highly beneficial for addressing the practical issues encountered during on-site conservation and restoration work. The combination of concrete scientific evidence with traditional experience enables more accurate protection measures to be taken against the deterioration of cultural relics, helps avoid negative impacts on relics caused by errors in on-site judgment, and at the same time, enhances the rigor and scientific validity of conservation and restoration documentation. Taking the conservation and restoration project of the Lotus Cave polychrome cliff carvings at Qianfoya as an example, this paper introduces some of the techniques applied during the project implementation phase, aiming to provide a reference for the application of analysis and testing technologies at conservation and restoration sites.

Testing at cultural relic conservation and restoration sites is different from that in cultural relic conservation laboratories. Laboratory testing in the early stage tends to focus on reproducing the materials and processes of cultural relics to determine the causes of deterioration and develop response plans. Instruments such as FT-IR, XRD, and SEM-EDS are used to conduct targeted testing on the composition and structure of samples—including pigments, coatings, and pollutants—extracted from cultural relics. On-site testing at conservation and restoration sites, however, focuses more on evaluating restoration effects and responding to the needs of on-site detection. The technologies used on site should be simple and reliable to operate, enabling even first-time users to obtain accurate measurement results, with qualitative assessment as the main focus and quantitative analysis as a supplement.

2. Instruments used for on-site detection in the conservation and restoration of polychrome cliff carvings

2.1. Leeb hardness tester

At the conservation and restoration sites of polychrome cliff carvings, a portable Leeb hardness tester is selected for use. The local cliff carvings are made of quartz yellow sandstone, which has loose grains and large pores. If a rebound hammer or a penetration-type mortar strength tester commonly used for ancient brick and stone structures were applied, it would leave obvious impact marks on the carved relics, and in cases of severely weathered sandstone, it could even cause flaking. The instrument used on site is the Equotip 3 portable Leeb hardness tester produced by Proceq, with a type D impact device (impact device mass: 75 g).

The Leeb hardness method was first proposed by Dr. Leeb from Switzerland in 1978. Its basic principle is to use spring force to propel an impact body with a certain mass and indenter towards the surface of the sample. The impact velocity and rebound velocity at a specific distance from the sample surface are measured to calculate energy loss. Utilizing electromagnetic principles, a voltage proportional to the velocity is induced, and the signal processed by electronic technology provides the hardness value for display and storage. The Leeb hardness value is expressed as the ratio of the rebound velocity to the impact velocity of the impact body.

$$HL = \frac{V_r}{V_i} * 1000 \quad (1)$$

In Formula 1, HL stands for the Leeb hardness value; Vr represents the rebound velocity of the impact body; Vi refers to the impact velocity of the impact body.

Although this type of portable Leeb hardness tester was originally designed for testing metal materials, it is also widely used for suitable samples of other materials. For example, the School of Engineering and Technology at China University of Geosciences (Beijing) used Leeb hardness testing on marble cultural relics in Beijing [1]; the Stone Age Archaeology Laboratory at George Washington University used the same model Equotip 3 portable hardness tester to test the mechanical properties of stone samples in research related to stone selection for tool making [2]. Due to the special nature of the cultural relic samples being tested, it is not always necessary to strictly follow the standard procedures described in the user manual. However, the main challenge in testing low-strength samples lies in the fact that the hardness of the sample may be below the measurable range, making it impossible to obtain readings. This is also a common occurrence in on-site analysis and testing: at conservation and restoration sites, the conditions are not always as ideal as in laboratories, with appropriate instruments and materials readily available, so it is important to make full use of existing resources to solve practical problems.

2.2. Spectrophotometer

When evaluating whether the color of a cultural relic has changed or if glossiness has occurred at the conservation and restoration site, such judgments were usually made by visual inspection in the past. However, visual inspection is highly subjective and can easily lead to disagreement, especially under different lighting conditions. With data provided by a spectrophotometer, it is possible to retain quantitative reference values in the conservation and restoration records.

A spectrophotometer contains an optical component that can disperse light. When light is directed onto a sample and reflected to the dispersing element, the principle of dispersion is used to analyze single color information and convert the optical signal into an electrical signal. According to the internally set color space and calculation formula, the chromaticity information is displayed, which can then be converted to Hunter Lab or CIE L*a*b* indices or other chromaticity scales.

Taking the Konica Minolta CM-700d1 portable spectrophotometer as an example, the measurement results are ultimately displayed in the L*a*b* color model. In the application of cultural relic conservation and restoration, the main focus is typically on changes in the L value, i.e., the brightness axis, to determine whether glossiness has developed on the surface of pigments after consolidation. The values for the a and b color channels generally do not change significantly; if there are large fluctuations, it may indicate a color change and should be carefully noted.

2.3. Infrared thermal imager

Infrared thermal imaging, as a non-destructive testing method, is simple and reliable and is suitable for use at cultural relic conservation sites. It helps to safely and rapidly identify situations such as voids and water seepage. By using an infrared thermal imager, the temperature field distribution on the surface of an object can be detected, making it easy to visually identify abnormal temperature regions on the surface of a cultural relic. Combined with site analysis, potential deterioration can be quickly inferred, thus playing a positive role in conservation and restoration work. This paper mainly introduces passive thermal imaging. Although the imaging results are not as pronounced as those produced by active infrared thermal imaging methods—which require high-power flash lamps, hot air, or other thermal stimulation devices—passive thermal imaging is more suitable for conservation site testing, as it is more reliable, lower in cost, and easier to operate [3].

The infrared thermal imager used on site is a FLIR E40, with a thermal image resolution of 320 × 240. The resolution of thermal images is directly related to the price of the thermal imager, and this level of resolution in a handheld device is already sufficient for conservation and restoration work on site. The imager is equipped with a built-in digital visible light camera, which can generate visible light reference images at the same time. However, due to differences in focal length between the infrared and visible light lenses, the imaging area is not consistent. It is therefore recommended to use a separate camera to take visible light reference images. With the advancement of domestic thermal imaging technology, the cost of using such equipment will continue to decrease.

3. Application cases of on-site detection technologies in the conservation and restoration of polychrome cliff carvings

3.1. Application in the conservation process of the lotus cave carvings

According to the technical roadmap for the conservation of the Lotus Cave carvings, the application of detection technologies at each step is described as follows [4]. On-site detection personnel should be familiar with the names, purposes, operation methods, materials used, and corresponding types of deterioration at each step of the conservation and restoration of polychrome cliff carvings, and should understand the sequence of the workflow. Before testing begins, it is necessary to clarify the day's work plan, using the conventional workflow as a framework and refining it in communication with conservators on site. With clear objectives, aimless testing can be avoided.

3.1.1. Removal of inappropriate restorations

The inappropriate restorations referred to here are repairs made with materials that have aged and are highly incompatible with the original relic, negatively impacting the overall harmony and artistic value of the grotto, and all are documented traces of modern repairs [5]. Earlier historical restoration traces are not subject to intervention. As needed, areas that may be vulnerable, such as edges, can be pre-consolidated before and after the removal process [6]. When testing hardness, it is important to distinguish between areas that have undergone pre-consolidation and untreated areas, to avoid confusing the data. After removing inappropriate restorations, the underlying rock surface of the cliff carving is exposed—these areas were previously repaired due to rock flaking and powdering. After exposure, a portable Leeb hardness tester is used to measure and record the surface hardness. The measured hardness values at this stage are usually very low, and in cases of severe powdering, no readings may be obtained; such cases should also be documented for reference.

3.1.2. Dust removal and cleaning

Accumulated dust on the surface of polychrome paintings can seriously affect color detection. As shown in **Figure 1**, only a faint blue pigment layer is visible at the location indicated by the arrow before dust removal, while a larger area of blue polychrome painting is revealed after cleaning [7]. At this point, a spectrophotometer is used to detect and record the color information of the pigment layer. When using the spectrophotometer, it is necessary to accurately record the position of each test point, which can be achieved by marking on drawings or photographing the working position, to ensure that future comparative tests can be carried out at the same point.

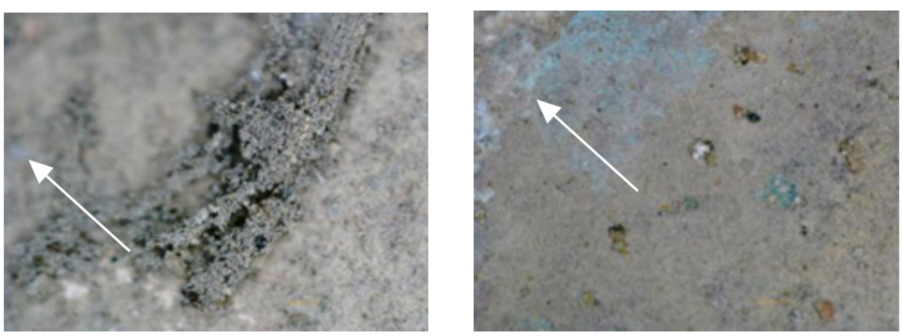

Figure 1. Micrographs of the same area before and after dust removal

3.1.3. Rock consolidation

After rock consolidation, the portable Leeb hardness tester is used again to measure the surface hardness (**Figure 2**). The hardness of the area is taken as the average of multiple test points—generally, 20 points are randomly selected within the area to be measured, and the instrument automatically calculates the average value. If the test area is small, it is sufficient to take the average of the measurements directly [8]. The test data can verify whether the consolidation effect meets the design standard, and should correspond with the results of earlier laboratory and on-site tests, while also confirming that each consolidated area meets the requirements. The detection data should be recorded in the relevant restoration documentation.

Although the portable Leeb hardness tester causes only a minor impact on the sample, the probe tip may still leave marks when pressed against the surface; therefore, it should not be used on polychrome surfaces [9]. Attention should also be paid to the routine cleaning of the probe tip to avoid contaminating the cultural relics it touches.

Figure 2. Testing the surface hardness of rock with a portable Leeb hardness tester

3.1.4. Pigment consolidation

After pigment consolidation, the main concern is color change, including glossiness and brightness variations. Although the safety and effectiveness of the consolidation material have already been verified during preliminary experiments in the design phase, data collected on-site provide a more accurate assessment of the actual protection effect. Once the pigment consolidation material has fully stabilized, the spectrophotometer is used again to test the same points measured after dust removal (**Figure 3**) [10]. The results are recorded in the restoration documentation, and the two sets of data can be quantitatively and visually compared.

Figure 3. Detecting the color of the polychrome surface with a spectrophotometer

3.1.5. Repair

Due to continuous powdering, the rock may become recessed inward. If not consolidated and repaired in time, the weathering depth of the rock will accelerate, resulting in ongoing deterioration in the affected area. The hardness of the repair material should not be too high; it should be similar to the hardness measured on the normal rock surface and the consolidated, powdering rock surface [11]. In the preliminary laboratory tests, these hardness values are compared to select a suitable repair material. After the new repair areas have been cured and hardened, the portable Leeb hardness tester is used to test and record the hardness.

3.2. Meeting on-site testing requirements

3.2.1. Detection of water seepage

The conservation work took place in summer, during a period of frequent rainfall. Although a protective shelter was erected outside the cave to prevent rainwater from entering, water continued to seep through the cave ceiling after heavy rains [12]. Using an infrared thermal imager and on-site inspection, it was determined that the water seepage at the top of Lotus Cave was caused by surface water accumulation near the upper neighboring cave [13]. Once the source of the seepage was identified, timely measures were taken [14]. In the thermal image shown in **Figure 4**, the blue low-temperature area indicates traces of water seepage.

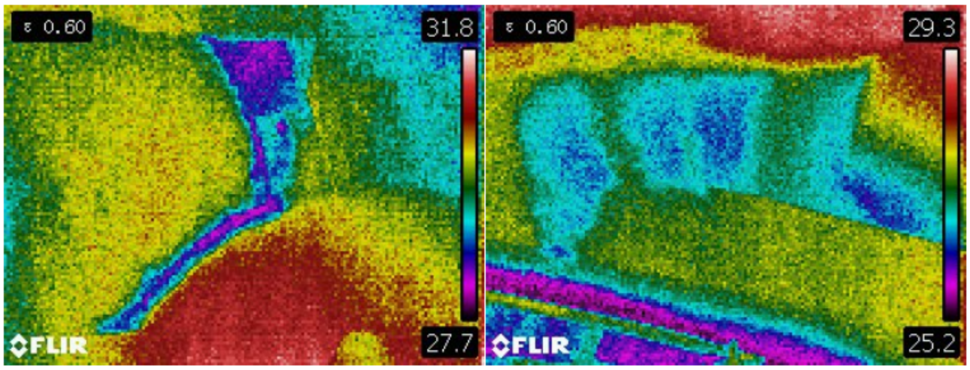

Figure 4. Thermal image of water seepage from cracks in the ceiling of Lotus Cave

3.2.2. Detection of delamination (Hollowing)

In **Figure 5**, the red high-temperature area indicated by the arrow marks the delaminated area at the upper right corner of the carving niche. Due to severe weathering, the entire left side of the niche wall has become an open groove that needs to be filled with grout [15]. Infrared thermal imaging can also be used to inspect the condition of delaminated areas after grouting, providing an assessment of the effectiveness of the restoration.

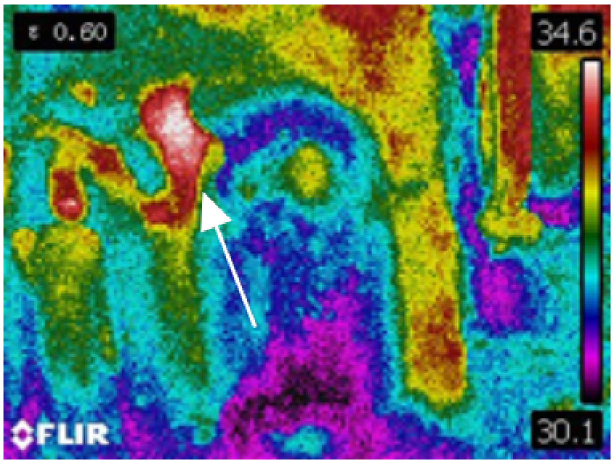

Figure 5. Thermal image of the delaminated area at the edge of the carving niche

4. Conclusion

Cultural relic conservation is a long-term and challenging task, serving to protect the precious heritage of our civilization for our nation and future generations. Scientific work in cultural relic conservation is not only about the development of new technologies, but also about expanding the application of existing testing technologies. Promoting the use of simple and practical on-site analysis and detection technologies to address the actual needs of conservation work is an important mission for the field.

Those engaged in conservation and restoration work need to establish a relatively complete and scientific knowledge system. The implementation of conservation and restoration provides more opportunities for research, especially for uncovering valuable information that is often hidden within cultural relics. However, if great care is not taken during the restoration process, some information may be missed or even lost. The interdisciplinary nature of conservation and restoration makes it particularly important for professionals from different fields to collaborate and divide the work according to their expertise.

Disclosure statement

The author declares no conflict of interest.

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