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ANALYSIS ON THE DAMAGE AND WEATHERING CAUSE OF ARCHITECTURAL HERITAGE ALONG THE MARITIME SILK ROAD: A CASE STUDY OF MINLEDOU WHARF

Xiaoyu WANG[1,*], Jianghua WANG[2], Jing WANG[1], Yue TANG[3]

[1] School of Architecture & Civil Engineering – Shenyang University of Technology – Shenyang City – China, 110870
[2] School of Architecture, Tianjin University, Tianjin City, China, 300072
[3] The Department of Architecture and Built Environment, University of Nottingham, Park Campus, NG7 2RD, United Kingdom

Abstract

To better protect architectural heritage along the Maritime Silk Road, this paper selected Minledou wharf as the research object, field surveys and mapping were carried out; infrared thermal imager photography was conducted, and peeling granite stone samples of cultural heritage were collected on-site for microscope observation, scanning electron microscope, X-ray diffraction, X-ray fluorescence spectrum analysis, and other experiments. The results show that there are six types of damage and weathering on the Minledou wharf. The granite in the wharf's outer layer is mainly composed of potash feldspar, albite, and calcite as cementation materials. The occurrence of damage and weathering is caused by the chemical composition of the stone itself and the chemical, physical, and biological effects of water and acid rain in the preservation environment. The research on the damage and weathering caused by Minledou wharf can lay a solid foundation for the necessary protection of the cultural heritage along the Maritime Silk Road.

***Keywords**: Damage; Weathering; Cause; Maritime Silk Road; Achitectural heritage*

Introduction

As a maritime channel for transportation, trade, and cultural communication between ancient China and foreign countries, the Maritime Silk Road was first proposed by French orientalist Emmanuel Édouard Chavannes in 1913 [1]. The Maritime Silk Road originated in the Shang and Zhou Dynasties, developed in the Spring and Autumn and Warring States periods, formed in the Qin and Han Dynasties, flourished in the Tang and Song dynasties, and transformed into the Ming and Qing Dynasties. It is the oldest known maritime route [2]. There has been much research on the Silk Road on land in China. In terms of architectural heritage, the protection achievements of Dunhuang Grottoes are the most significant [3, 4]. The research scope includes the protection of stone cultural relics [5, 6] and the protection technology of frescoes [7, 8]. In 2014, with the triumphant declaration of the land Silk Road as a World Cultural Heritage, the historical sites along Maritime Silk Road should also be investigated and researched. At present, the primary status of the immovable cultural relics of the Maritime Silk Road in Guangdong Province has been preliminarily clarified and classified [9, 10]. However, the research on surveying and mapping, damage and weathering types, and cause analysis of the specific cultural heritage of the Maritime Silk Road has not been carried out.

* Corresponding author: 704216608@qq.com

Minledou Wharf is one of the largest silk distribution centres in Guangdong province in the Qing Dynasty. It is located at No. 2 Xibei Street, Minle Wei, Xiqiao Town, Nanhai District, Foshan City. It was built at the end of the Ming Dynasty and rebuilt in the fourth year of Guangxu of the Qing Dynasty (1878). Before the Qing dynasty and the Anti-Japanese War, silk was very prosperous near Westqiao Minle. Traffic ships were busily crowded in and around the Minledou wharf. Ferries loaded with silk were transported from Outer Dou to Guangzhou or Jiangmen City through the Marine Silk Road to Southeast Asia, India, the Middle East, and Europe. Minledou wharf witnessed ancient Xiqiao silk development history and was once known as "Silver-ship Wharf" [9].

Now, we will push forward the Belt and Road initiative and make new contributions to the building of a community with a shared future for humankind [11]. In this paper, Minledou Wharf was selected as the research object. We conducted field surveys and mapping, took photos with an infrared thermal imager, collected the peeling granite stone samples of cultural heritage for microscope observation, and then conducted SEM (Scanning Electron Microscopy), XRD (X-ray diffraction), XRF (X-ray Fluorescence), and other experiments on the samples, studying and summarising the damage caused by weathering and formation reasons. We combined the climate characteristics and environmental conditions of Foshan City to determine various factors and the damage and weathering caused by architectural heritage in the area [12]. It will integrate comprehensive analysis and lay a solid foundation for implementing the necessary cultural heritage protection along the Maritime Silk Road.

Damage and weathering of Minledou Wharf

Minledou Wharf is located from the west to the east. The wharf gate is built with a single granite hole, which is 25 metres long, 8 metres wide, 10 metres high, and 3 metres wide. The base is red sandstone, which is granite, and three layers of granite construct the arch. On April 30, 2021, our project team members conducted field mapping and investigation of Minledou Wharf and found that there are mainly six types of damage and weathering (Fig. 1) according to the damage judgement criteria of historical buildings [13].

Alveolization

The first type of damage and weathering is alveolarization. On the outer wall of the upper half and top of Minledou wharf, it can be seen that there is dense alveolarization of different sizes on the stone surfaces (Fig. 1/1).

Higher plants (grass)

The second type of damage and weathering is higher plants (grass). Higher plants are relatively large plants that grow on material rather than just clinging to it. At the top and middle parts of Minledou wharf, especially in the sunny part, there are many strong and growing plants and grass in cracks or gaps of granite mortar (Fig. 1/2).

Erosion/abrasion

The third type of damage and weathering is erosion or abrasion. Stone is affected by erosion or abrasion, and the original material appearance is different, mainly due to material particle loss or wear. At the bottom of Minledou wharf, close to the water surface, you can see extensive gaps and holes in the stone. The edges and corners of the stone have different degrees of erosion and abrasion (Fig. 1/3).

Liverworts

The fourth type of damage and weathering is liverworts. Liverworts do not have roots, are usually attached to the material's surface, and are green, brown, or black. Many liverworts can be seen at the west corner of Minledou wharf (Fig. 1/4).

Moist areas/spots

The fifth type of damage and weathering is moist areas/spots. The stone surface shows moist spots or areas that are darker than the original stone itself. Many dark wet areas or spots can be seen at the Dou gate in the lower half of Minledou wharf (Fig. 1/5).

Spalling

The sixth type of damage and weathering is spalling. Spalling is the stripping inside the rock, usually from the outer surface and then into the material. In the lower half and bottom part of Minledou Wharf, close to the water surface, it can be seen that some stones have large cavities, and some large-sized materials have fallen from the original rocks (Fig. 1).

Fig. 1. Six types of damage and weathering in Minledou Wharf

Methods

To further study the damage and weathering cause of Minledou Wharf [14, 15], we sent the peeling granite stone samples collected on-site (Fig. 2) to the laboratory for detection and analysis using microscope observation, XRD, SEM, and XRF experimental methods.

The microscope and SEM observations can analyse the mineral composition and morphology of Minledou wharf rock. An XRD test can diagnose the mineral composition of rocks. The granite was divided into three powder samples according to the weathering degree and tested by XRF to analyse the chemical elements and oxide mass percentage of the different weathered powder samples (Table 1).

To study the influence of the external natural environment on Minledou Wharf, we adopted the method of field infrared thermal imaging to conduct rock temperature imaging. According to the temperature field distribution of infrared thermal imaging and 3D-IR (3D iterative reconstruction image) (Table 1), the influencing factors of six damage and weathering types of Minledou wharf are analysed.

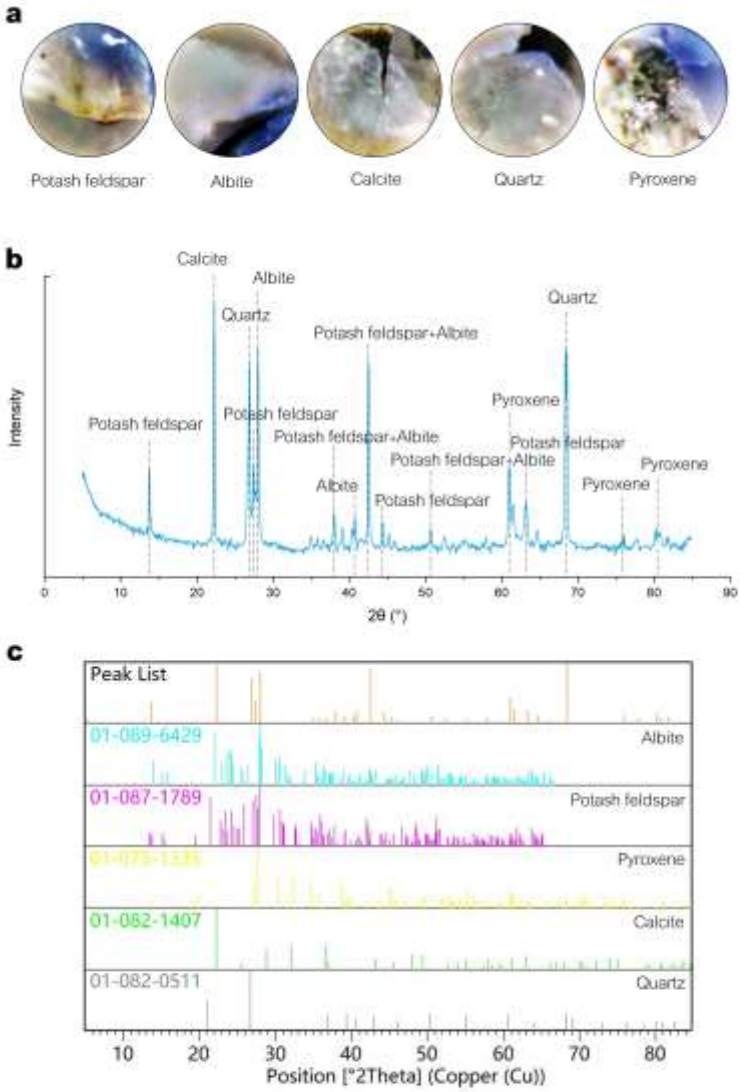

Fig. 2. (a) Microscopic analysis; (b) Typical XRD patterns of granite samples; (c) PDF standard card spectra in XRD

Table 1. Experimental instruments and purposes

Methods	Purposes	Experimental instruments
Infrared thermal imaging	Rock temperature imaging	FLUKE Ti401 PRO Thermal Imager, America
Microscopic observation	Mineral composition morphology of rocks	Fujii RAYMAY Portable microscope, Japan
SEM	The microscopic morphology of rocks	Hitachi S-4800 field emission scanning electron microscope, Japan
XRD	The mineral composition of rocks	Bruck D8 X-ray diffractometer, Germany
XRF	Chemical element and oxide percentage by mass	ZSM PrimusX (wavelength type) X - ray fluorescence spectrometer, Japan

Results and discussion

XRD and microscope observation

According to the PDF standard card spectra in XRD (Fig. 2c), we found the granite of Minledou Wharf contains a large amount of potash feldspar and albite, accounting for 60–70%. The content of calcite is 10–20%; the range of quartz is 10–20%; and a small amount of pyroxene is below 10% (Fig. 2b and Table 2). With the observation and analysis of microscope magnification at 250 times, we found the fleshy red is potash feldspar, white or off-white is albite, light yellow and brown are primarily calcite, and the colourless and transparent texture is mainly quartz. There is a small amount of colourless, grey, and green, and brown is pyroxene (Fig. 2a) in granite. Potassium feldspar and albite belong to unstable feldspar minerals, easily hydrated by water and easily weathered in air. The thermal expansion coefficients of different mineral compositions are different, and the thermal expansion and cold contraction are additional. Mineral components will expand due to heat, dehydrate, disintegrate, and fall off, with mechanical effects between grains and layers affecting the overall stability of the rock.

Table 2. XRD and microscopic results and analysis

Mineral composition	Chemical molecular formula	Content	Color	Main chemical composition
Potash feldspar	$K(AlSi_3O_8)$	60~70%	Red, white, or gray	SiO_2:64.7%; Al_2O_3:18.4%; K_2O:16.9%
Albite	$Na(AlSi_3O_8)$		White, off-white	Na_2O:11.8%; Al_2O_3:19.4%; SiO_2:68.8%
Pyroxene	$MgSiO_3$	Less than 10%	Colorless, gray, green, brown	MgO and SiO_2 are the main components, and the secondary components are Al, Ca, TiO_2 and MnO, and the content of Fe is less than 5%.
Calcite	$CaCO_3$	10~20%	Light yellow, brown black	CaO:56.03%, CO_2:43.97%, often contains Mn and Fe, sometimes contains Sr.
Quartz	SiO_2	10~20%	Colorless and transparent	SiO_2, often contains a small amount of impurities.

XRF results and discussion

The granite is divided into three powder samples according to the degree of weathering and tested by XRF. No. 1 is the original granite powder sample in the wall without any weathering at all. No. 2 is the semi-weathered stone powder sample in the wall; No. 3 is the sample of weathered stone powder on the outermost wall of the wharf (Fig. 3a and b). XRF detection and analysis results obtained the mass percentage of chemical elements and oxides in different powder samples (Figs. 4a and b).

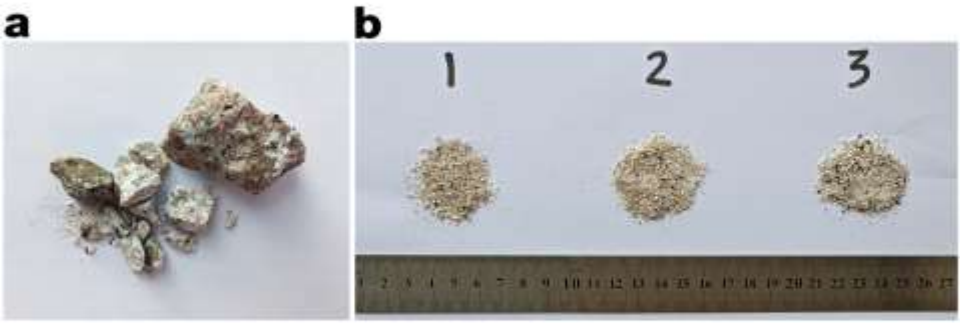

Fig. 3. Photos of experimental samples: (a) granite blocks collected at the site; (b) Experimental powder samples

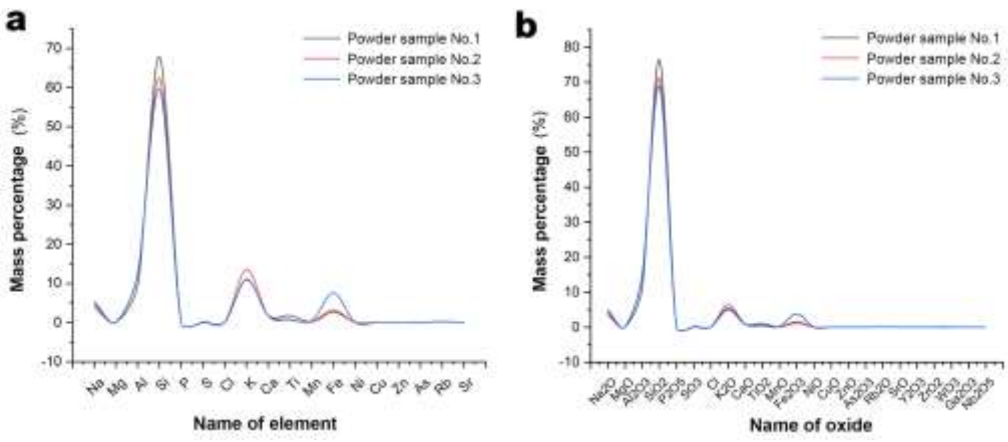

Fig. 4. XRF analysis :(a) Mass percentage of chemical elements; (b) Mass percentage of Oxides

The main chemical composition of granite samples is SiO_2, followed by Al_2O_3. The weathering resistance of rock can be judged indirectly by the content of Al_2O_3. The contents of Fe_2O_3, Na_2O, and K_2O are all over 1%, CaO is close to 1%, and other oxides have a petite range. The SiO_2 content of the No. 3 powder sample is relatively low, while the Al_2O_3, Na_2O, K2O, and CaO content is relatively high. It means the granite on the outer wall has weathered.

SEM results and discussion

The weathered granite on the outer wall and the unweathered granite in the wall were scanned by SEM with a magnification of 50 times, 1000 times, and 5000 times, respectively, and damage and weathering of the granite were observed under microscopic conditions. As shown in figure 5, it can be seen since the main mineral components in granite are potash feldspar and albite; before weathering, the minerals are well connected and have solid integrity and stability (Fig. 5a). After weathering, potash feldspar and albite are relatively loose, lamellar distribution is apparent, and many adhesion particles and small aggregates are produced with large pores and faults. Their integrity and stability are decreased (Fig. 5c). Quartz has a relatively dense texture, is not easily affected by acid, and is unsuitable for corrosion and fragmentation. There is little change before and after weathering (Figs. 5b and d).

Measured analysis of infrared thermal imaging

The total thermal imaging detection time of damage and weathering of Minledou Wharf was at noon on April 30, 2021, when the weather was clear, and it was a rapid warming process. Figures 6①a and ⑥a show the infrared thermal imaging temperature field distribution of six types of damage and weathering in Minledou Wharf. Figures 6①b and ⑥b show the temperature of the damage and weathering region is more than 0.4℃ lower than that in the adjacent area without damage and weathering, and the difference between the spalling and the adjoining area without damage and weathering is the largest, which can reach 10.1℃.

Thermal imaging detection directly reflects the relationship between water and weathering. Since the specific heat capacity of water is much larger than that of granite, the temperature variation of water is smaller than that of granite under the same heating conditions. That is to say, the temperature of water-enriched granite is far lower than that of dry granite. The higher the thermal imaging temperature, the less water content of granite. The blue region in the thermal image has the lowest temperature and the highest water content. The red area has the highest temperature and the lowest water content [16]. By comparing thermal imaging and visible light photos of damage and weathering (Fig. 6), it can be seen that, in general, there is an apparent correspondence between water content and weathering degree of weathering of granite cultural relics. In the area with higher water content, damage and weathering are also more apparent. It fully proves that water is the main factor in producing such weathering.

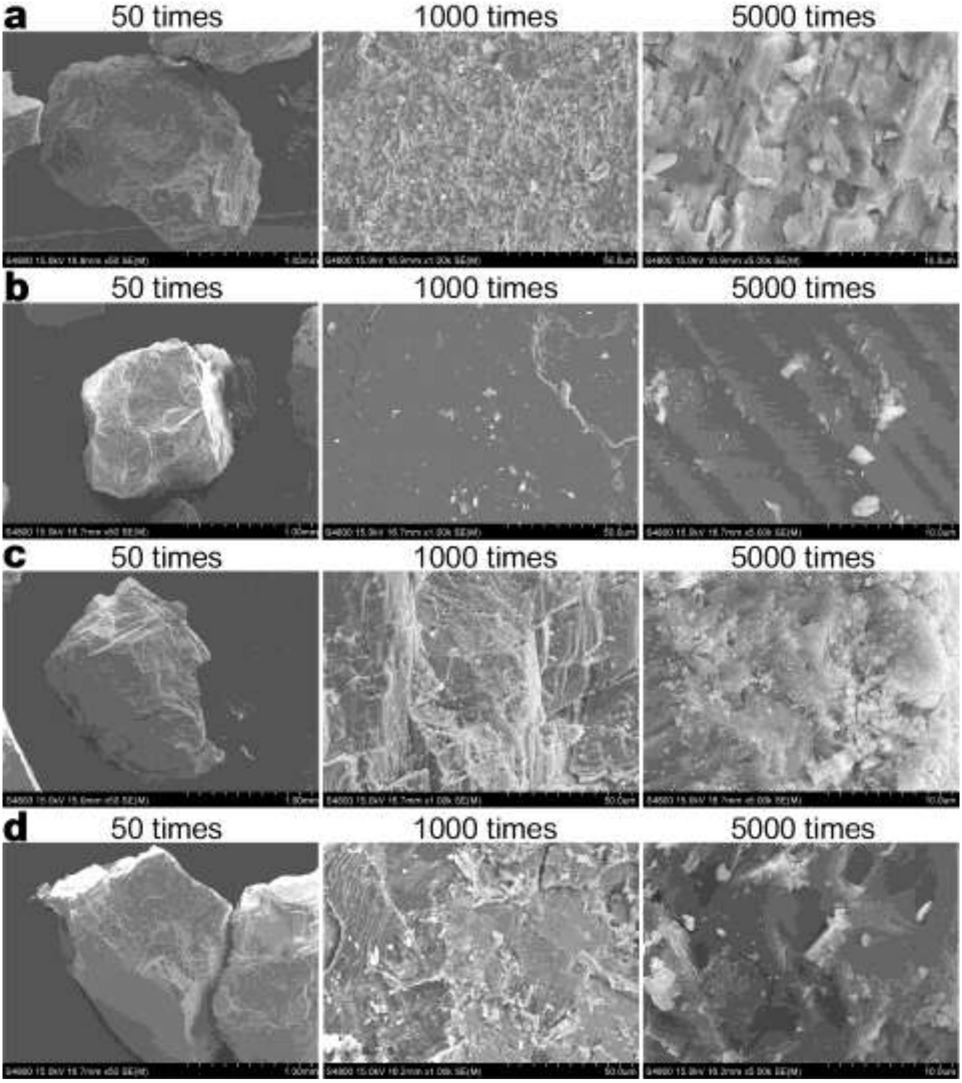

Fig. 5. SEM analysis :(a) Feldspar before weathering; (b) Quartz before weathering; (c) Weathered feldspar; (d) Weathered quartz

Natural environment of Minledou Wharf

Foshan City is located in the central part of Guangdong Province, at 113°06' east longitude and 23°02' north latitude. It has a subtropical monsoon humid climate, mainly under the influence of the ocean's warm wet airflow, abundant rainfall, and an annual average precipitation of 1490.6 mm. The yearly rainfall is primarily concentrated from April to September, frequently producing heavy rain, and the precipitation increases sharply. Foshan City is wet and rainy, with high environmental humidity and rich groundwater. And the wharf heritage in this region is above water. These objective factors provide sufficient conditions for the damage and weathering of granite and red sandstone.

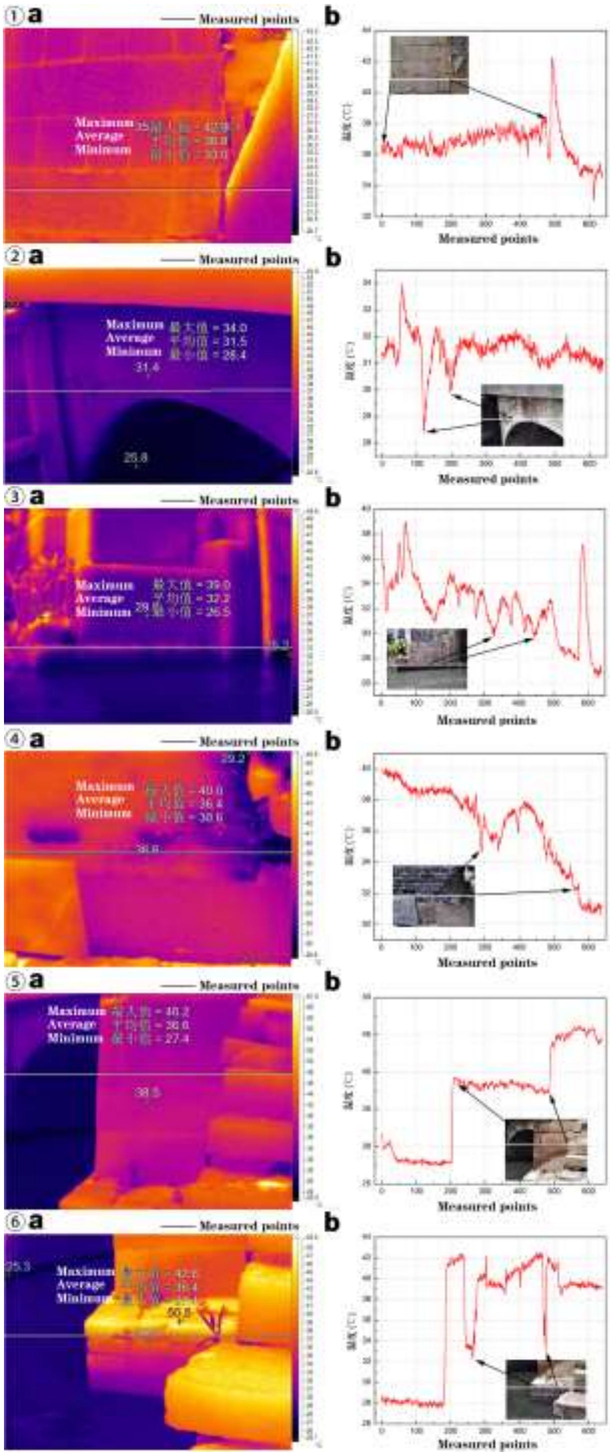

Fig. 6. ① Alveolization; ② Higher plants (grass); ③ Erosion/abrasion; ④ Liverworts; ⑤ Moist spots/areas; ⑥ Spalling: (a) infrared thermal imaging temperature field distribution; (b) 3D iterative reconstruction (3D-IR) images; (c) Temperature curves of test points of damage and weathering areas

Before 2000, Foshan City had always been a heavy acid rain area. After 2000, the pH value and acid rain frequency of precipitation in Foshan City decreased, and the pH value reached 5.38 in 2020, with an annual acid rain frequency of 27.3% [17, 18]. Foshan City has a high temperature all year round, with an average yearly temperature of 23.2°C. According to the standard for dividing the four seasons commonly used in applied climatology, winter is the average climate temperature of less than 10°C, and summer is the average climate temperature greater than or equal to 22°C. Therefore, Foshan City has no winter in the sense of climate, and summer lasts 199 days from April 16 to October 31, which is characterised by a long summer without winter [17]. Therefore, it can be inferred that the damage and weathering of Minledou wharf are not caused by frost damage in winter.

Damage and weathering cause and influencing factors

Through experimental detection and preservation environment analysis, the damage and weathering cause of Minledou wharf are mainly affected by water, acid rain, granite mineral composition, and other significant factors. It is the result of chemical, physical, and biological interactions.

Influence and the physical action of water

Minledou wharf has been influenced by atmospheric precipitation for many years, with condensed water in the air and the effect of capillary water. The water inside the stone rises into the rock stoma very easily, causes internal cementing quality and the loss and rock weathering hydrolysis, and reduces the intensity of the stone material surface, especially under the promoting effects of oxygen and carbon dioxide. It gradually makes the cement in the stone (calcium, mud, etc.) dissolution and the feldspar minerals into loose clay minerals. Under the guidance of water, soluble salt will enter the interior of the rock mass. Under the action of repeated changes in temperature, humidity, and water content, a process of dissolution-crystallisation - re-dissolution - recrystallization occurs. This cyclic crystallisation erosion phenomenon makes the internal alkali powder of stone powdery, flakes off, and seriously affects the overall stability of stone [19]. The enrichment of water also provides an excellent moist environment for the growth of organisms, resulting in a large number of high levels of plant and microbial mildew on the stone surface.

With the materials in the cohesion loss, we can often observe erosion or abrasion phenomena. The stone particles are removed by rain, resulting in gaps and holes, erosion, and abrasive edges into obtuse or rounded corners. Moist spots are mainly due to the infiltration of water (rain, rising moisture, etc.), condensation on the stone surface, and the hygroscopicity of the material itself; this area has a more extensive moisture content. It may be because the existence of hygroscopic salt can absorb the air or surrounding water, resulting in the colour of the stone surface being more profound than the original stone. In general, moist spots coexist with alveolarization.

Acid rain effects and chemical reactions

The climate characteristics of Foshan City promote the transformation of SO_2 to SO_3 in the air, which is conducive to the formation of acid rain. Acid rain will cause severe damage to the stones of Minledou wharf. In the rock erosion process caused by acid rain, corrosive oxidants such as CO_2 and H_2SO_4 can dissolve the architectural heritage of granite. Red sandstone is preserved in the open air, which causes the decomposition and loss of easily weathered minerals in granite and red sandstone. It directly leads to the formation of pits and cavities. Acid rain brings more soluble salts to granite and red sandstone, exacerbates the dissolution and recrystallization of soluble salts in stone, and continuously erodes and destroys the architectural heritage of rocks [20, 21]. The primary sources of soluble salts in the weathering products of granite and red sandstone of Minledou wharf are the mineral composition of granite and red sandstone stone, acid rain, and soluble salts brought by the water surface of the wharf. The soluble salt in the rain and environmental humidity change when the circular erosion phenomenon of dissolved crystallisation occurs. In this process, soluble salt repeatedly crystallising precipitation will produce stress and pressure on the rock pore wall so that it is broken and powdery, eventually leading to erosion, peeling, and a series of damage and weathering of architectural heritage.

Inference of alveolarization is mainly caused by acid rain in the region, especially heavy rain. When the rain hits the stone surface, stone particles are washed out because of long-suffering rains. Acid rain causes the chemical reaction of potash, feldspar, and albite. The mineral components inside the stone, combined with wind and water to take away the dissolved chemical components, will produce a lot of alveolarization. The chemical reaction equation of potash feldspar and albite with hydrogen ions in acid rain is as follows. It is also the reason for the relatively high levels of Al_2O_3, Na_2O, and K_2O in the No. 3 powder sample detected by XRF.

$$K(AlSi_3O_8) + H^+ \rightarrow Al_2O_3 \cdot 2SiO_2 + K^+ \quad (1)$$

$$Na(AlSi_3O_8) + H^+ \rightarrow Al_2O_3 \cdot 2SiO_2 + Na^+ \quad (2)$$

Spalling is the disintegration of materials, mainly the salt crystallization process caused by acid rain. A large amount of rainwater and the water belt under the dock infiltrate the stone with soluble salt from the stone's pores. The cyclic crystallization erosion of soluble salt act on the inside of the rock, causing the surface of the granite and red sandstone to fall off gradually. At the same time, the rock cementation material is gradually lost under the action of water, and its strength decreases. Wharf foundation, wall foundation, and other parts that lead to soluble salt circulation crystallisation are more severe and easily appear powdery and flake peeling. They are under the water surface or very close to the water surface, under the action of large temperature and humidity changes. After the XRF test, the content of calcite $CaCO_3$ is less than expected, and the possibility of salt crystallisation is relatively large. The soluble calcium sulphate generated is very low, and the soluble calcium nitrate is also very good, like all nitrate. The chemical reaction equation is as follows:

$$CaCO_3 + 2H^+ \rightarrow Ca^+ + CO_2 + H_2O \quad (3)$$

Plant and biological effects

Biological and mechanical destruction are mainly manifested in physical activities. High plants can thrive in the presence of large amounts of water; in many places of granite mortar, cracks or voids can see a lot of grass. It is because the wharf building heritage itself is on the water surface, and the stone material has extensive water content. In addition, there is plenty of rain in this area and sufficient sunshine after rain, so tall plants are more likely to grow in the stone material with cracks or disintegrating spaces. Liverworts can thrive in moist conditions, usually in areas where external natural conditions are damp. The cause of damage and weathering of liverworts is similar to that of higher plants (grass) because the stone of the wharf building has substantial water content. Their difference is that liverworts are mainly attached to the stone surface growth, or mildew.

Conclusions

The architectural heritage of Maritime Silk Road is different from other land architectural heritage, especially the wharf architectural heritage located above water, which has unique characteristics of damage and weathering types and formation causes. Through thorough, in-depth research, this paper draws the following conclusions.

(1) Through field mapping and investigation, it is found that there are mainly has six types of damage and weathering in Minledou wharf: alveolarization, higher plants (grass), erosion/abrasion, liverworts, moist areas/spots, and spalling. The six types of damage and weathering have different forms and different locations.

(2) Through various experimental detections and analyses, the granite of Minledou wharf contains a large amount of potash feldspar and albite, a moderate amount of calcite and quartz, and a small amount of pyroxene. The main chemical composition in stone samples is SiO_2, followed by Al_2O_3. The weathering resistance of rock can be judged indirectly by the content of Al_2O_3. After weathering, potash feldspar and albite are relatively loose, lamellar distribution is apparent, and there are many adhesion particles, small aggregates, some large holes, faults, integrity, and stability are decreased.

(3) Through the analysis of the preservation environment, the main factors affecting the damage and weathering of Minledou Wharf are water, acid rain, and the mineral composition of the stone itself. Water and acid rain cause architectural heritage to develop alveolarization, erosion/abrasion, moist areas and spots, spalling, liverworts, higher plants (grass), biological growth, and a series of severe damage and weathering. The cause of damage and weathering is the result of chemical, physical, and biological interactions.

In this paper, the study still has limitations, mainly because the number of experimental samples collected on-site is insufficient. Because the red sandstone inside the dock is not spilling, we can only conduct experimental analysis on the granite samples outside, and relevant research will be supplemented in future studies.

Acknowledgments

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