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Research on the salt disease and deterioration simulation of hui-zhou corridor bridge(an-fu bridge) in China

Qi Liu[1,2], Haoming Yang[1,2]✉ & Decai Gong[1,2]

Rural revitalization strategies, along with the Three-Year Action Plan for the Protection of Corridor Bridges (2023–2025), are important tasks in China. Currently, it is crucial to conduct a detailed investigation and clarify the relevant processes to lay a theoretical and scientific foundation for targeted interventions.In this study, a simulated aging test was conducted on the wall using a saturated salt solution of sodium sulfate and potassium nitrate as the medium. The aim was to investigate the salt disease in the failure mechanism of the wall structure and the strength of the An-fu Bridge, and to explore the impact of different salt solutions on the An-fu bridge. Additionally, the analysis of efflorescence in the An-fu bridge was included. Overall, during the experiment, changes in its apparent characteristics, microstructure, quality, and strength were tested. The results indicated that all experimental samples exhibited weathering and damage. Both sodium sulfate and potassium nitrate caused damage to the internal structure of the masonry. The uniaxial compressive strength of the masonry increased initially and then decreased with the number of cycles. The erosive effect of sodium sulfate on the masonry was significantly stronger than that of potassium nitrate. The findings also suggest that, from the perspective of protecting and maintaining the corridor bridge, it suggested specific protective measures such as line layer maintenance to promote the cultural inheritance and protection of the corridor bridge is not only about enhancing the tourism value and landscape quality of the corridor bridge but also about fostering the economic development and social progress of the area where the corridor bridge is located.

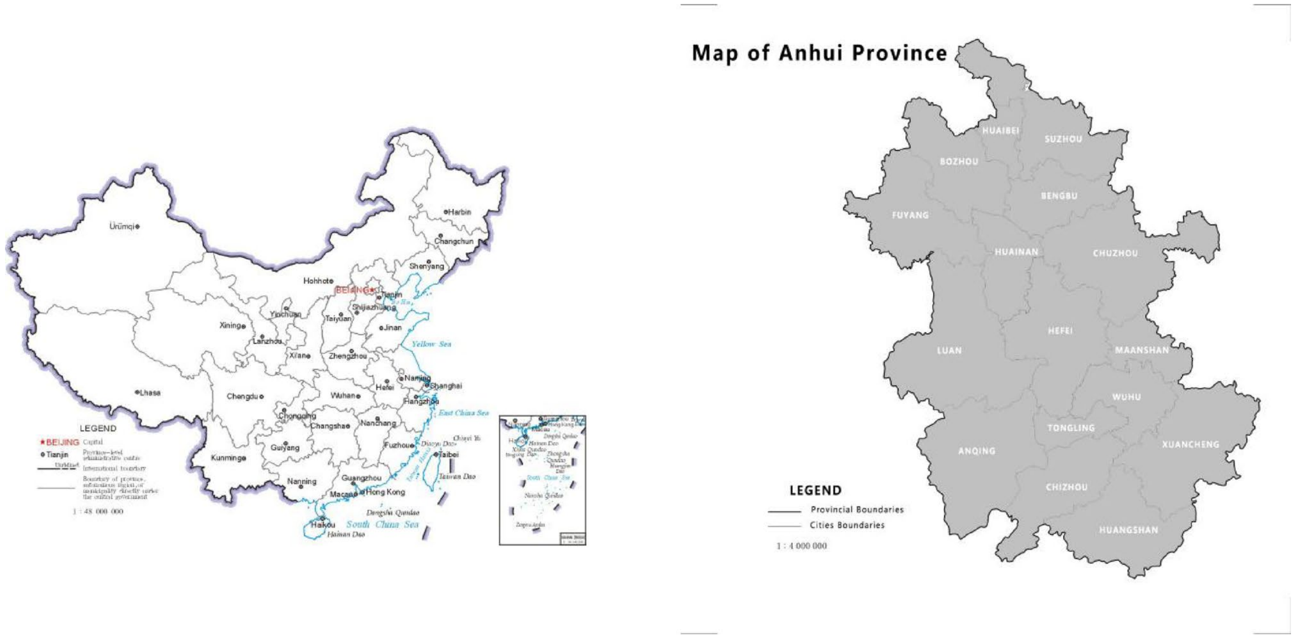
Keywords An-fu bridge, Deterioration simulation, Salt disease

In ancient China, bridges featuring covered galleries or additional buildings were relatively uncommon. In the 1940 s, architectural historian Liu Dunzhen conducted research in the southwest and described a bridge as having a “rainbow-like structure and covered with corridor houses” in his writings[1]. This led the academic community to start paying attention to corridor bridges. Over the past two centuries, the focus of cultural heritage preservation has shifted from a style-centric approach, with early 19th-century restoration efforts, to broader and more contemporary preservation methodologies[2]. The objectives of preservation have expanded, and environmental protection has gradually become more sophisticated. The key challenge in this field remains the development of heritage damage assessment through scientific and technological means[3].

The Hui-Zhou Corridor Bridge holds significant importance in Chinese cultural heritage, with the An-Fu Bridge being one of the most notable corridor bridges in the Hui-Zhou region. It is named Huangshan and is situated in the southern part of Anhui Province(Fig. 1). Huizhou is an ancient name. Huangshan City, formerly known as the Huizhou region, became a prefecture-level city after the dissolution of the Huizhou region in 1987. The distinction between Huizhou and Huangshan City lies in their historical titles and jurisdictions.

The Anfu Bridge stands out among the existing Huizhou corridor bridges due to its unique official bridge functional attributes and distinctive architectural forms as cultural relics(Fig. 2). The protection of corridor bridges not only aligns with the “Three-Year Action Plan for Corridor Bridge Protection (2023–2025)” but also offers a more systematic enhancement for the preservation of corridor bridge cultural relics that embody traditional Chinese characteristics[4].

[1]University of Science and Technology of China, Hefei city, China. [2]Department of History of Science and Scientific Archaeology, Hefei city, China. ✉email: twpqeqr0226@163.com



(**a**) (**b**)

Fig. 1. (**a**) The geographical location of China. Source: Obtained from http://o.southgis.com/news/detail/6028; (**b**) The geographical location of Anhui Province. Source: Obtained from http://zrzyt.ah.gov.cn/ztlm/ahsbzdtfw/index.html.

(**a**) (**b**)

Fig. 2. (**a**) Current situation of weathering of Anfu Bridge wall; (**b**) Current situation of weathering on the facade of Anfu Bridge.

The Anfu Bridge, situated in Qimen County, Huangshan City, Anhui Province, boasts a unique design that distinguishes it from other existing Huizhou covered bridges. Constructed during the Jiajing era of the Ming Dynasty, the bridge's walls have exhibited significant weathering[5].

Recent years have seen increased scholarly attention on the planning, design, and construction of corridor bridges[6].

The literature on corridor bridges is extensive, encompassing ecological considerations, seismic performance, optimization methodologies, and public participation in heritage conservation. This reflects the multidisciplinary approach inherent in the construction and maintenance of bridges. For instance, (Fu et al., 2024) introduced an enhanced optimization method for large-span corridor bridges, showcasing ongoing advancements in the design and construction of these structures[7]. Additionally, (Han et al., 2024) investigated public participation in the conservation of heritage related to corridor bridges[8]. They developed indicators and a framework for public engagement in the preservation of cultural heritage, using the Chinese wooden arch corridor bridge, "Qiansheng Bridge," as a case study.

International experience and scientific studies have shown that Salt weathering not only diminishes the structural integrity of objects, which can lead to safety hazards and damage, but it also erodes the surface features of edifices and heritages that are imbued with significant historical, cultural, and artistic value. Meanwhile, numerous scholars are actively involved in pertinent research endeavors. Efflorescence is a phenomenon that has been extensively studied in various materials, including aerosols and masonry blocks. (Onasch et al., 1999) investigated the deliquescence and efflorescence of ammonium sulfate aerosols as functions of temperature and relative humidity[9]. The study found that the efflorescence transition of ammonium sulfate aerosols increased slightly with a decrease in temperature.(Biskos et al., 2006) Focused on the nanoscale effect on the deliquescence and efflorescence of sodium chloride particles, employing various methods to generate aerosol particles and examine impurity effects on the outcomes[10]. In the field of masonry, (Brocken et al., 2004) conducted research on white efflorescence on brick and concrete masonry blocks, with a special emphasis on sulfate efflorescence on concrete blocks[11]. The study followed a genetic approach, which is predominantly based on the analysis of data. (Freney et al., 2009) provided new insights into the deliquescence and efflorescence of potassium salts pertinent to biomass-burning aerosol particles, utilizing environmental transmission and scanning electron microscopes[12]. (Bertram et al., 2011) The organic-to-sulfate mass ratio and the oxygen-to-carbon elemental ratio of organic components were employed to predict the critical relative humidity for liquid-liquid phase separation, efflorescence, and deliquescence of mixed particles[13]. The control of efflorescence in geopolymers based on natural pozzolan was explored by (Kani et al. 2012)[14]while (Zhang et al. 2014) observed efflorescence in fly ash-based geopolymers and discovered that partial crystallization through curing at high temperatures diminished the efflorescence potential[15]. (Zhang et al. 2018) examined the microstructural and mechanical evolution in fly ash-based geopolymers, induced by efflorescence and subflorescence[16]. (Wang et al., 2020) proposed a test method for the degree of efflorescence in geopolymers and investigated the effects of Si/Al ratio on the efflorescence and characteristics of fly ash-based geopolymers[17]. Collectively, these studies enhance our understanding of efflorescence in various materials and offer valuable insights into controlling and predicting this phenomenon.

However, the primary forms of damage caused by salt to bricks include powdering, flaking, and surface cracking, as well as internal powdering. Salt weathering is a significant process that affects the longevity of construction stones in arid environments. (Cooke,1979) conducted an experiment at Bedford College, London, to simulate salt weathering processes in deserts[18]. The study found that Na_2SO_4 is the most effective salt in weathering rocks, with susceptibility being related to rock properties such as porosity and water absorption capacity.(Doehne,2002) provided a selective review of salt weathering, emphasizing the multidisciplinary nature of studying salt damage to porous building materials[19]. (Ruiz-Agudo et al., 2007) highlighted the critical role of saline solution properties, particularly viscosity, in salt weathering associated with sodium and magnesium sulfate crystallization in porous limestone[20]. (Benavente et al., 2007) evaluated the impact of pore structure, water transport characteristics, and rock strength on salt weatheringthrough thorough rock characterization and statistical analysis[21].

Research aim

The aim of this study is to examine the effects of weathering. In the case of the Anfu Bridge, which exhibits significant weathering, the main cause is the accumulation of readily soluble salts. To explore the damage mechanism of salt degradation on the wall structure and strength of the Anfu Bridge. To compare the effects of different types of salt, a saturated salt solution consisting of sodium sulfate and potassium nitrate was used as the medium. Based on its weathering condition, a simulated aging test was conducted on the wall. To observe changes in its apparent characteristics, microstructure, mass, and strength throughout the experiment.

Analysis of efflorescence in an-fu bridge

International experience and scientific studies have shown that salt weathering compromises not only the structural integrity of objects, raising concerns about safety and potential damage, but also erodes the surface features of edifices and heritages that are rich in historical, cultural, and artistic significance.

To investigate the failure mechanism of the wall structure and strength of the Anfu Bridge and explore the impact of different salt solutions on the An-fu Bridge, this study primarily focuses on the investigation of the An-fu Bridge.

Ion chromatography has proven to be a valuable tool in various scientific disciplines, providing precise and reliable analysis of different substances(Table 1).

Materials and methods

(1) X-ray Fluorescence (XRF) Analysis

Experimental instrument: X-ray fluorescence spectrometer (SHIMADZU, XRF-1800).

Component	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	CaO	TiO_2
Content%	65.775	15.961	9.572	3.101	1.555	1.427	1.27	0.772

Table 1. XRF semi quantitative analysis results of wall tiles (oxide)%.

Component	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	K_2O
Content%	45.996	12.105	3.453	1.963	0.981	0.845

Table 2. XRF semi quantitative analysis of surface hard shell(oxide)%.

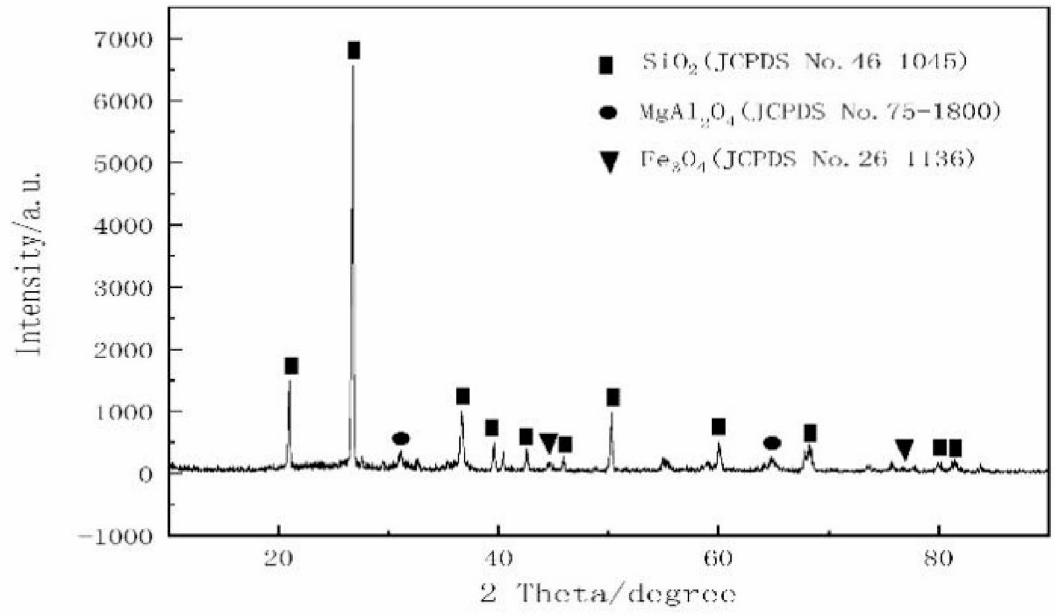


Fig. 3. XRD pattern of the weathered sample of the brick wall.

Experimental method: Brick and stone samples were divided into two parts: the surface weathered area and the deep unweathered fresh area. They were ground into powder form and analyzed for elements and their contents using X-ray fluorescence.

(2) X-ray diffraction (XRD) analysis

Experimental instrument: 18KW target X-ray diffractometer, model: MXPAHF from Japan's Marco Corporation, with a diffraction angle scanning range of 0° to 90°.

Experimental method: Brick and stone samples were divided into two parts: the surface weathered area and the deep unweathered fresh area. After grinding to powder, the phases were analyzed using an X-ray diffractometer.

Results and discussion

The An-fu's brick walls are constructed from bricks and stones bonded with yellow clay, and they are coated with a layer of white ash on the exterior. Semi-quantitative oxidation analysis using XRF was conducted on wall tile samples (Table 2), revealing that the chemical elements' oxides present were SiO_2、Al_2O_3、Fe_2O_3、K_2O、Na_2O、MgO、CaO, and the general requirement range for the chemical composition of modern sintered brick raw materials closely approximates the chemical composition.

Further XRD analysis was conducted on the mineral samples (Fig. 3), and the main phases were identified as: SiO_2 、 $MgAl_2O_4$、 Fe_3O_4,Since the Ca content in the raw material is only 1.27%, wollastonite and plagioclase will not be present in the mineral phase. However, for raw materials with higher Ca content, these calcium-containing minerals will definitely appear in the mineral phase of sintered bricks.

The bulk density of the wall tile sample is 1.75 g/cm^3, the apparent porosity is 31.545%, and the absolute moisture content is 0.16%. The volumetric density value is lower than that of sandstone, resulting in a lighter overall weight of the gallery. Consequently, the load borne by the stone arch is reduced, significantly lowering the risk of deformation due to prolonged static load on the stone arch. Despite the low volume density and degree of compression and wear among the wall tiles, their high apparent porosity and absolute moisture content make them susceptible to air and water erosion, which can lead to a decrease in the compressive strength of the wall tiles. In the future, there is a risk of cracks or even wall collapse in the bricks.

The gallery house's brick wall surface is coated with lime, and some areas are covered with gray-white hard shells. An XRF semi-quantitative oxidation analysis was conducted on the hard shells, and the results indicated that their chemical element oxides were CaO、SiO_2、MgO 、Al_2O_3 (Table 3).

The content of CaO is the highest, constituting 45.996%. Further XRD analysis of the sample (Fig. 4) revealed that its primary crystal form is calcite ($CaCO_3$), with a minor amount of quartz (SiO_2) potentially originating from impurities in the limestone raw material or the external environment. The gray-white hard shell on the

Ion species	Cl^-	SO_4^{2-}	NO_3^-
Concentration(mg/L)	9.7024	77.7668	121.0530

Table 3. Ion chromatography analysis.

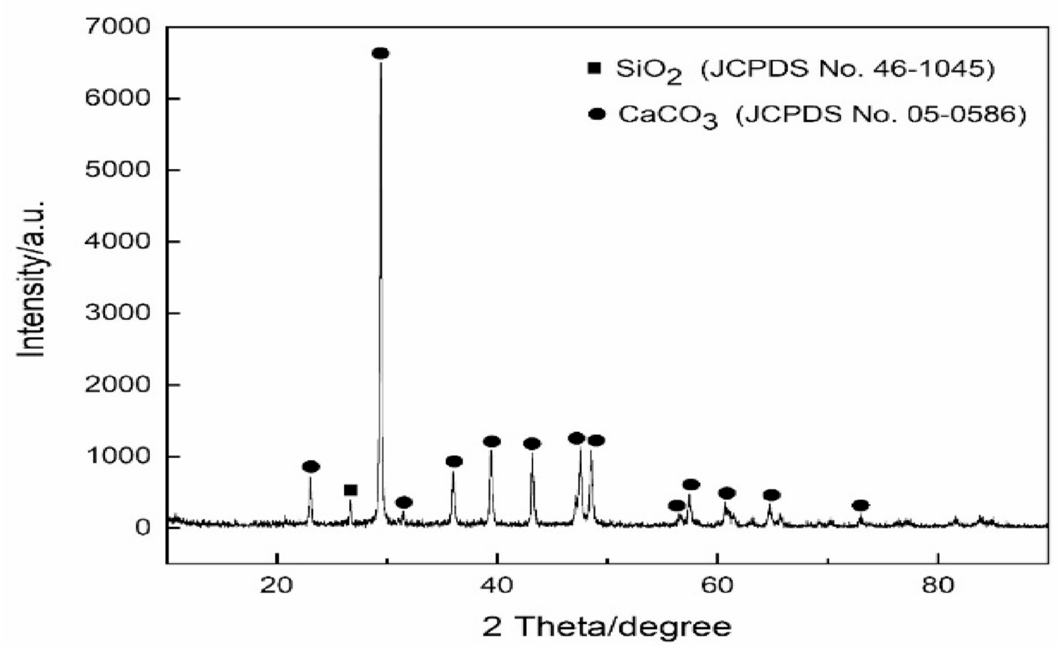


Fig. 4. XRD pattern of the weathered sample of the surface hard shell.

surface of lime is due to the prolonged exposure of dried calcium carbonate to the elements, which reacts with rainwater from the roof and carbon dioxide in the air to form calcium bicarbonate. When the weather turns dry and hot, with the evaporation of water and the reduction in carbon dioxide, calcium carbonate precipitates. The precipitated calcium carbonate acts as a binder, semi-bonding clay minerals, dust, and other substances mixed in the water, slowly settling on the surface to form the gray-white hard shell that we observe.

In summary, the exterior of the brick wall is protected by a layer of lime, and the gray-white hard shell produced by air hardening also contributes to this protection. Consequently, the internal wall tiles are less exposed to environmental factors, leading to a reduced degree of weathering. However, the lime layer has already experienced significant hardening and is detaching from the wall, which is gradually diminishing its protective effect on the wall tiles. Additionally, dust that accumulates in the depressions caused by detachment can gather soluble salts, further accelerating the weathering of the wall tiles(Fig. 3、Figure 4).

Simulation

Upon conducting ion chromatography and XRF analysis on the samples from the stone bridge walls, it was determined that the weathered samples from the Anfu Bridge walls contain soluble sulfates and nitrates.

Materials and sample preparation

Since the brick walls of the Anfu Bridge are cultural relics, it is not feasible to use structural bricks for the numerous samples needed for degradation testing. Considering the irreversible nature of cultural relics, research has shown that the composition of fresh stone samples is essentially identical to that of the Anfu Bridge walls. Consequently, the bricks utilized in this degradation experiment were produced from the same raw materials as those of the Anfu Bridge in terms of mineralogy, and fresh stone samples were chosen as the experimental subjects (Fig. 5).

Instruments and methods

The instruments utilized in this experiment encompass an electronic balance, a constant temperature and humidity chamber, a uniaxial compression testing machine, an X-ray diffractometer, a scanning electron microscope, a super depth of field microscope, a water bath, and others. The temperature and humidity conditions are primarily regulated by the constant temperature and humidity chamber. The uniaxial compression testing machine is employed to perform destructive strength tests on samples in a batch manner throughout the testing process. The X-ray diffractometer serves to ascertain the mineral composition of the specimens.

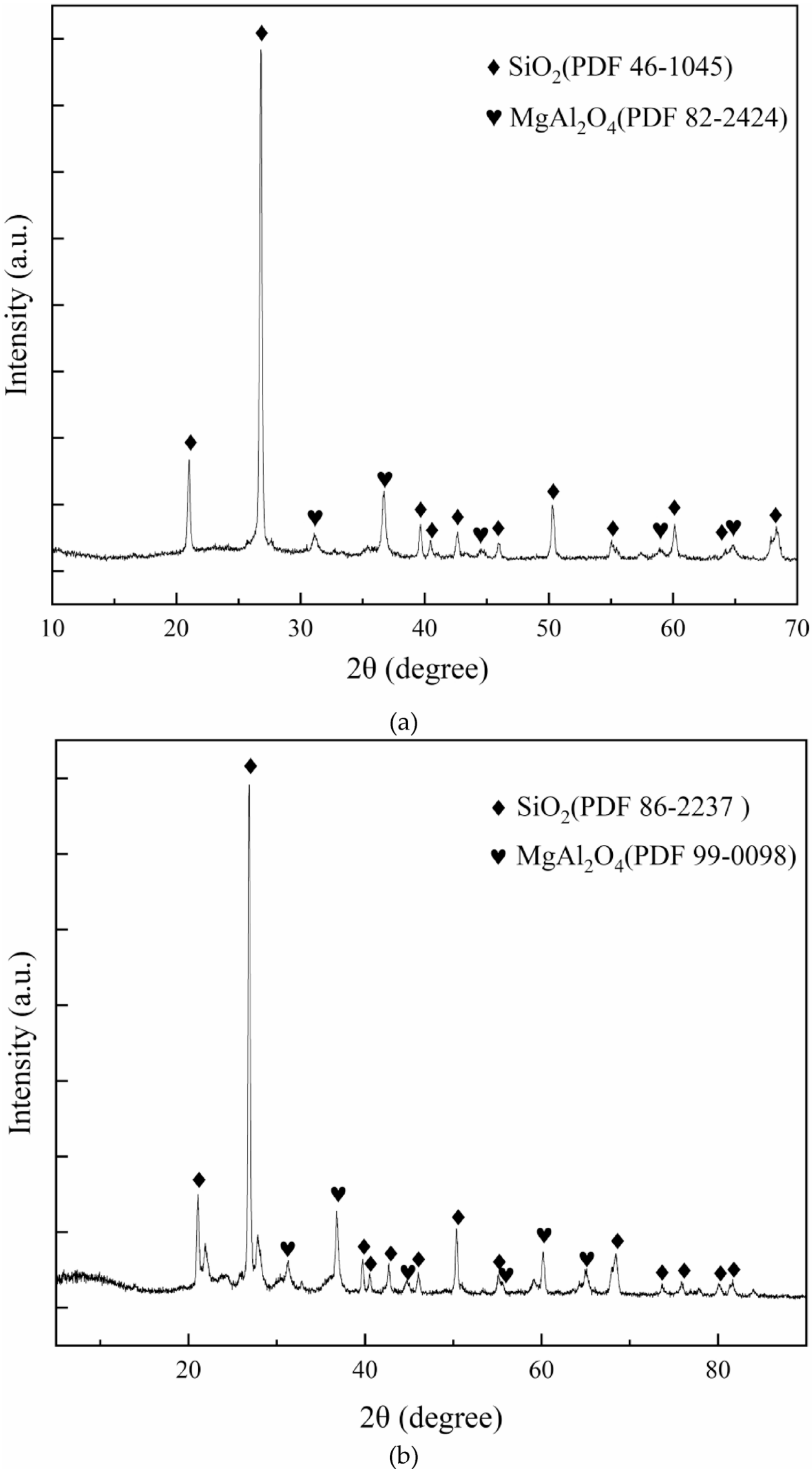


Fig. 5. (**a**) The An-fu bridge samples; (**b**) The fresh stone samples.

Scanning electron microscopy and ultra-depth of field microscopy are utilized to examine the microstructure of the samples(Fig. 5).

Process of experiment

1) Prepare samples by cutting fresh stone samples into cylindrical blocks measuring 20 mm × 40 mm.The experiment comprised ten cycles, with four parallel samples tested per cycle.

2) Measure the samples and place them in a 110 ℃ oven until their quality stabilizes. Upon removal, dry and cool them to room temperature. Record the quality, size, and morphology of each stone sample.

3) Soak the samples in a saturated solution. Prepare saturated solutions of Na_2SO_4 (10%,ω) and KNO_3(10%,ω). heat them in a 35 ℃ water bath for 24 h, then remove and test for quality, size, and morphology.

4) Perform dehydration crystallization by placing the extracted sample in a drying oven at 35 ℃. Continue dehydrating until the sample stabilizes, then test and record its quality, size, and morphology.

5) Repeat steps 3) and 4) until the predetermined number of cycles is completed. Take stone samples from different cycles(0,4,7,10) for compressive strength testing, electron microscopy scanning, XRD mineral composition testing, and microstructure detection.

Results and discussion

Analysis of apparent characteristics of the sample

There are a total of 10 cycles, and during the fourth cycle, the edges and corners start to become granular. As the cycle continues, the top and bottom begin to crumble, and the pulverization phenomenon intensifies. By the end of the 10 cycles, the bottom of the stone sample was fragile and exhibited partial detachment(Fig. 6).

Analysis of micro-structure

Through SEM observation, in the early stage of the experiment, the original particles in both groups of bricks had clear shapes, and there was not much difference compared to the original samples. Salt initially accumulates in small voids and has little effect on the strength of the brick body (Figs. 7 and 9(a), Fig. 9(d)). As the deterioration experiment progresses, salt begins to fill the large voids in the brick body and gradually covers the surface of the cross-section, forming loose fillers (Fig. 9b、c、e、f). This filler exerts a squeezing effect inside the brick body, further expanding cracks and causing significant damage to the brick body. This phenomenon manifests macroscopically as powdery detachment of the stone sample(Fig. 7).

Through XRD detection, it was found that fresh stone samples exhibited salt enrichment internally following cycling experiments. This confirms that the crystals present within the pores of the stone sample are indeed Na_2SO_4 and KNO_3 crystals(Fig. 8、Figure 9).

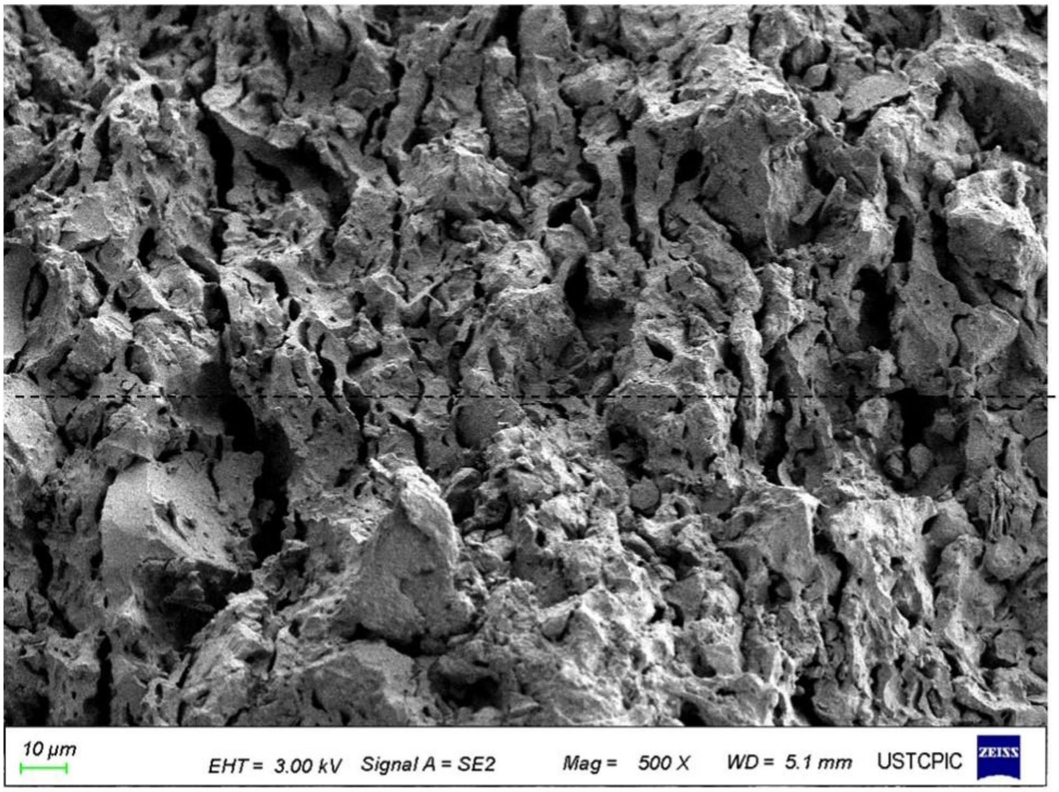
Analysis of quality change

The microstructure analysis of samples during the cyclic process primarily concentrates on the internal structural changes caused by salt entering the voids of bricks and stones. According to the quality change curve and quality change rate curve, it can be observed that the quality of all samples exhibits a process of initial increase followed by a decrease. This occurs because, in the early stages of the cycle, salt accumulates in the voids of the bricks and stones without causing structural damage at this time. As the cycle progresses, the brick sample continuously absorbs water and accumulates salt, and the salt inside the brick sample continuously dehydrates and crystallizes. Due to capillary action, the salt solution will shrink and squeeze into the interior of the stone sample during the dehydration process, further expanding the gaps and making the stone sample fragile. When structural damage occurs in the sample, the macroscopic manifestation is flaky and powdery detachment, and the quality of the sample changes(Fig. 10).

(a)

(b)

Fig. 6. (**a**) KNO3 : Analysis of apparent characteristics of the sample; (**b**) Na2SO4 :Analysis of apparent characteristics of the sample.



(0)

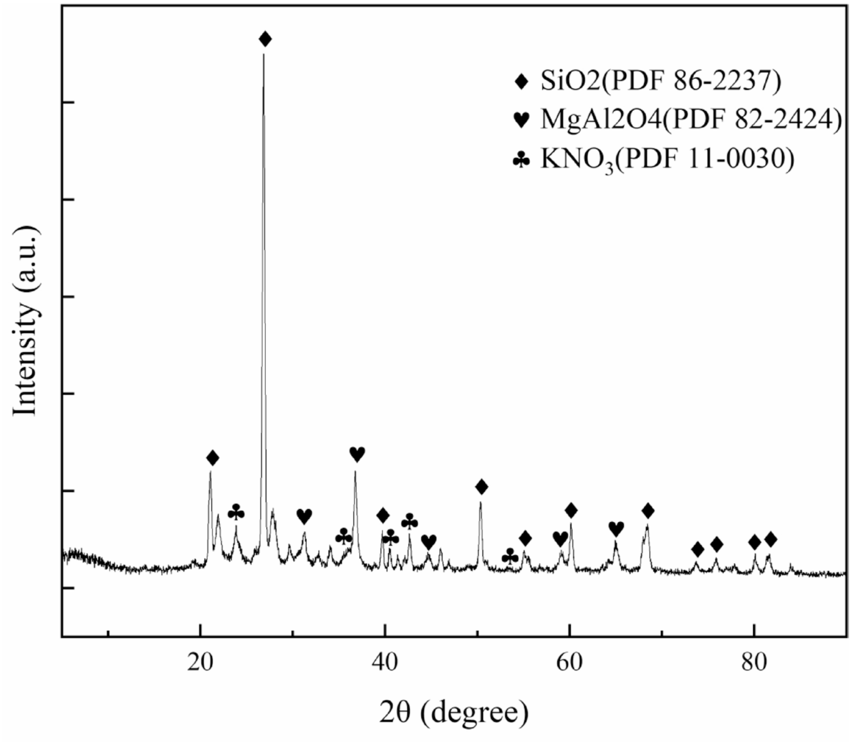
Fig. 7. Original microscopic structure of the samples.

Analysis of intensity variation
Examine the macroscopic mechanical strength alterations of stone samples by performing uniaxial compressive tests after a series of cycles. It is observed that the uniaxial compressive strength of all samples exhibits a pattern of initial increase followed by a decline. The erosive effect of Na_2SO_4 is notably more pronounced than that of KNO_3. At the experiment's onset, both types of salts crystallized and developed within the stone sample's voids, serving a filling function, which enhanced the sample's strength and improved its mechanical properties. As the cyclic experiment continued, the accumulation of salt within the stone sample intensified, the crystalline squeezing effect grew, and the stone sample's strength diminished rapidly(Fig. 11).

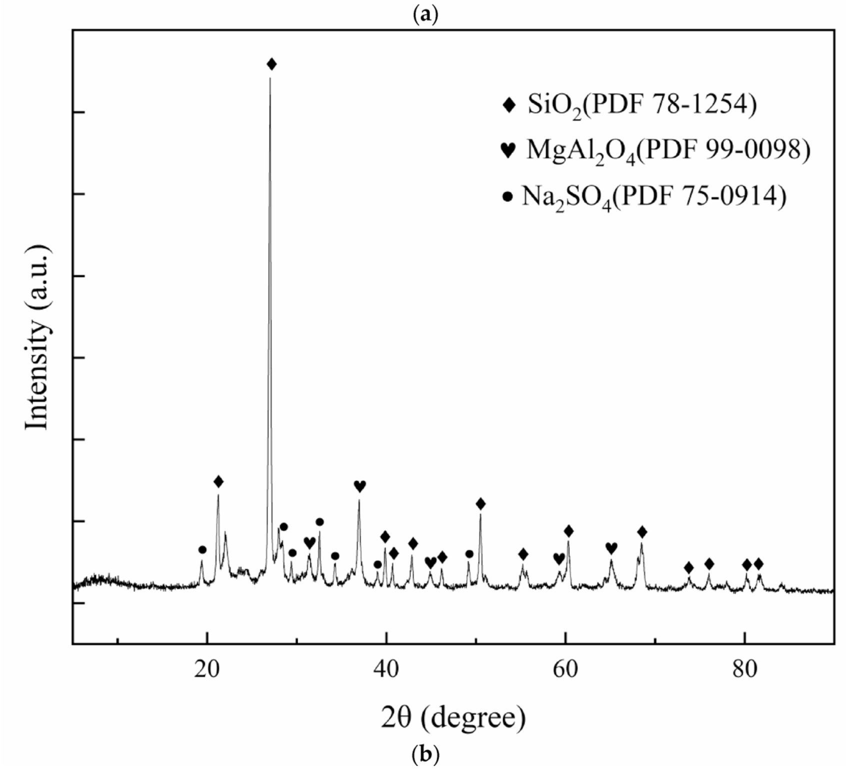
Conclusion
To investigate the damage mechanism of salt damage on the wall structure and strength of the An-fu Bridge, in conjunction with the bridge's weathering status, a simulated aging test was conducted on the wall. A saturated salt solution of sodium sulfate and potassium nitrate was used as the medium to test changes in its apparent characteristics, microstructure, quality, and strength throughout the experiment. The following conclusions were drawn:

The results indicated that all experimental samples exhibited weathering and damage, with salt damage being an important influencing factor on the weathering of stone bricks in the walls of Anfu Bridge. Based on the on-site environmental investigation, it is speculated that the overall cause of weathering of the Anfu Bridge wall is the continuous growth of salt damage inside the brick wall, which squeezes and fills the gaps between bricks and stones, leading to the destruction of rock strength. Soluble salts continuously expand the voids in sintered bricks, causing irreversible damage to the bricks and stones. From the macroscopic and microscopic morphology analysis during the experimental process, salt enrichment should first begin in the sintered micropores with better adsorption properties, and then diffuse to surrounding cracks and large pores. Salt damage in micropores has the characteristic of easy entry but difficult exit. When there are macroscopic salts on the surface and large pores, the internal structure of the brick has already undergone irreversible damage.

Sodium sulfate and potassium nitrate both caused damage to the internal structure of the masonry. Initially, the uniaxial compressive strength of the masonry increased, but then it decreased with the number of cycles. Both quality and strength exhibited a trend of first increasing and then decreasing, and both changes in quality and strength were affected by salt damage. The strength change results of the sample essentially reflect the strength change trend of the brick body during the erosion process by soluble salts. The attenuation of the brick body strength will directly impact the stability of the structure. When the test cycle reaches the predetermined



(**a**)



(**b**)

Fig. 8. XRD detection of fresh stone samples after cyclic experiments.

number of times, destructive uniaxial compressive strength testing is conducted on the sample to analyze the changes in macroscopic mechanical properties. During the enrichment process, there was an initial increase followed by a significant decrease in the later stages. This is mainly because when the salt content is low, salt acts to fill and cement micropores, causing the above indicators to increase. However, when the crystal crushing effect of salt damage becomes dominant in the later stage, the internal structure is compromised, and surface brick powder falls off, resulting in a significant decrease in the above indicators.

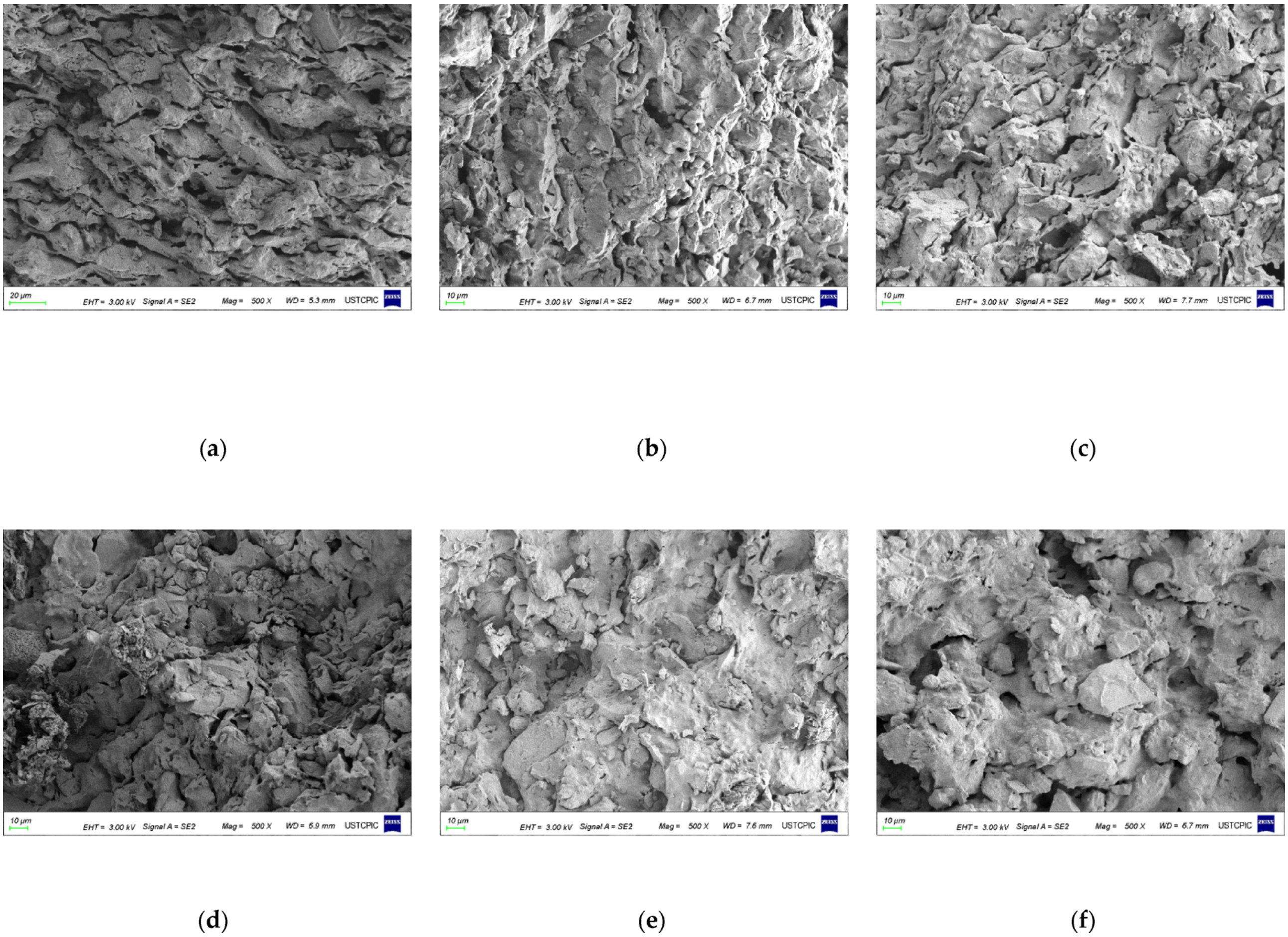


Fig. 9. Microscopic structure of the samples.

The erosive effect of sodium sulfate on masonry is significantly stronger than that of potassium nitrate. Through cyclic experiments involving two different salt solutions, Na_2SO_4 and KNO_3, it was observed that the Na_2SO_4 solution had a more pronounced erosive effect on the An-fu bridge stone samples. As the cycles progressed, the samples continuously absorbed water and accumulated salt, and the salt within the brick samples underwent repeated dehydration and crystallization. Due to capillary action, the salt solution would shrink and be forced into the interior of the stone samples during the dehydration process, further expanding the gaps and making the stone samples fragile. When structural damage occurred in the samples, the macroscopic manifestation was flaky and powdery detachment, altering the quality of the samples.

The majority of covered bridges are situated in rural areas, and there is a scarcity of research on the Huizhou region's covered bridges from the standpoint of employing scientific technology and methodologies. Specifically, there is a need for a comprehensive approach that combines technological verification with historical materials to understand the types and characteristics of these cultural relics and structures. Additionally, it is essential to ascertain the viability of their protection and restoration using scientific methods. Establishing a rational and efficient framework for their preservation is both urgent and imperative. This involves maintaining and uncovering the historical, artistic, and scientific significance of the bridges, ensuring the program's scientific and rational integrity, conducting an in-depth analysis of the cultural relics' characteristics, environment, and deterioration, safeguarding the efficacy and safety of the materials, and evaluating the effectiveness of the protective measures. A comprehensive study on the conservation, development, and repurposing of covered bridges is also required. From the perspective of preventive conservation, this paper suggests an assessment of the current state of preventive measures to devise appropriate preservation strategies and propose effective and sensible development and utilization tactics.

Currently, China is transitioning from poverty alleviation to rural revitalization, the journey towards rural revitalization is a long-term and dynamic process of construction. The rural revitalization strategies are a key initiative in China, complemented by the Three-Year Action Plan for the Protection of Corridor Bridges (2023–2025). This plan suggests focusing not only on the protection and maintenance of corridor bridges but also on promoting the cultural inheritance and protection of these structures. It aims to enhance the tourism value and landscape quality of the corridor bridges, as well as to foster the economic development and social progress of the regions where they are located.

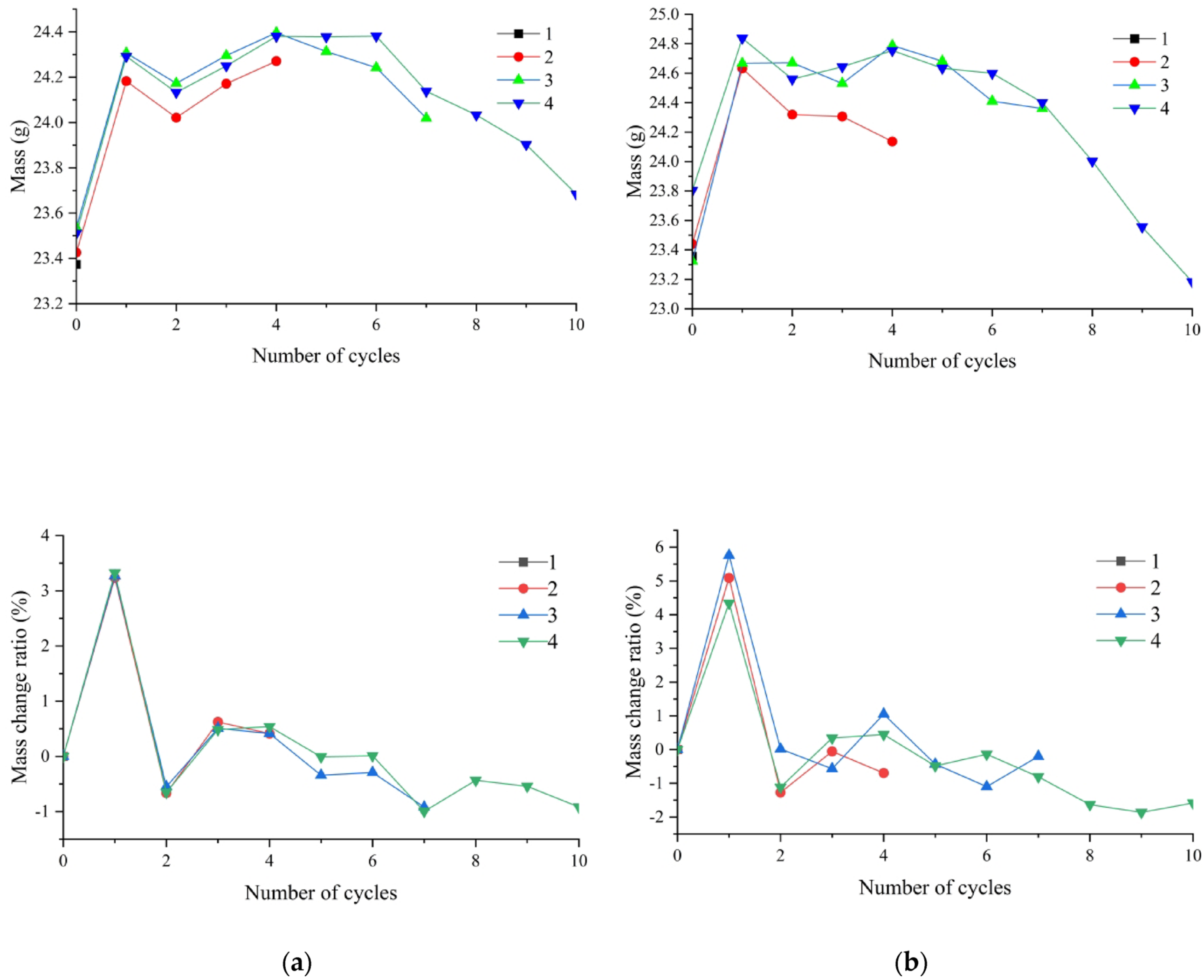


Fig. 10. (**a**) KNO_3:Curves of mass change and The Curves of mass change ratio; (**b**) Na_2SO_4:Curves of mass change and The Curves of mass change ratio.

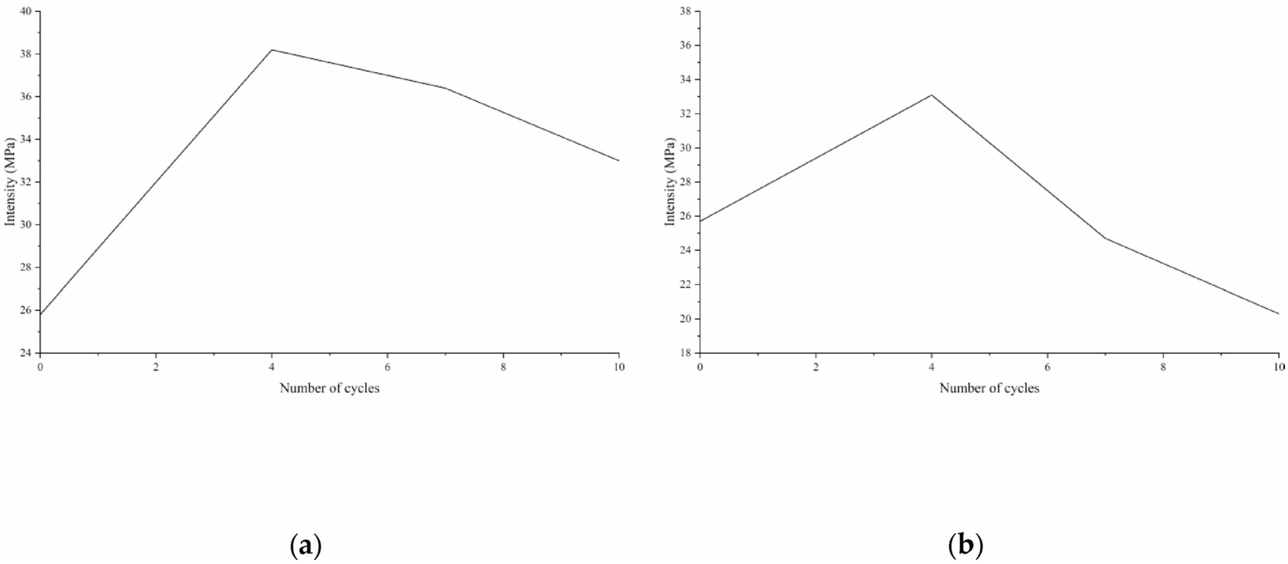


Fig. 11. (**a**) KNO_3:Results of uniaxial compressive strength change; (**b**) Na_2SO_4: Results of uniaxial compressive strength change.

Data availability
All data generated or analysed during this study are included in this published article.

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Author contributions
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Declarations

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Conflict of interest
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Additional information
Correspondence and requests for materials should be addressed to H.Y.