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ORIGINAL ARTICLE

Weathering damage evaluation of rock properties in the Bunhwangsa temple stone pagoda, Gyeongju, Republic of Korea

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Abstract The stone pagoda of the Bunhwangsa temple in Republic of Korea was made of piling small brick-shaped stones. The majority of stone bricks are andesitic rocks with variable geneses. Rock properties of the pagoda roof suffer partial significant deterioration, such as multiple peel-offs, exfoliation, onion-peel-like decomposition, cracks forming round lines and falling-off stone pieces. The stylobates and tabernacles at the four corners are composed of granitic rocks, which are heavily contaminated by lichens and mosses. Some of these contamination marks show dark black or yellowish brown colors by inorganic secondary hydrates. The four tabernacles and northern face of the pagoda body have been exposed to relatively high humidity, which causes light gray efflorescence as stalactites between the northern and western sides of the body. The efflorescences are composed of calcite, gypsum and clay minerals. The stone lion statues at the southeast and northeast corners are made of alkali granite, while the others are lithic tuff. Total rock properties of the pagoda consist of 9,708 stone bricks. Among them, 11.0% are fractured, 6.7% are fallen off, and 7.0% show considerable surface efflorescence, which shows that the pagoda has been highly deteriorated by physical, chemical and biological weathering. The authors strongly suggest long-term monitoring and comprehensive conservation researches.

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Introduction

The stone pagoda of the Bunhwangsa temple in Gyeongju, Republic of Korea is the 30th Korean National Treasure, and is known as the oldest stone pagoda in Korea. It was built around the seventh century during Shilla Kingdom of ancient Korea. The Shilla Kingdom is very famous for its stone cultural heritages. The Dabotap and Seokgatap pagodas in the Bulguksa temple are regarded as the most outstanding works, and thus were listed as World Cultural Heritage sites by UNESCO in 1995 (Lee et al. 2005).

The Bunhwangsa temple stone pagoda is believed to originally be a nine-story pagoda according to the historic documents. However, currently only three stories are left on the top of a very wide stylobate (Fig. 1). This pagoda was constructed mainly of brick-shaped andesitic rocks. However, the stylobate consists mainly of granitic rocks. The stone lion statues at the southeast and northeast corners are made of alkali granite, while the others are lithic tuff (Fig. 2a). The body, which is made of brick-shaped dark gray andesitic rocks, has a sudden change in its size; the first story is very large while the second and third stories are much smaller.

The body in the first story has doors on four sides, each of which has a Buddha relief to protect the law of Buddhism. The roof stone takes the form of step-like layers in both the upper and lower parts with the third story roof stone rises in a round shape in the four corners. There are lotus flowers in quartz porphyry on

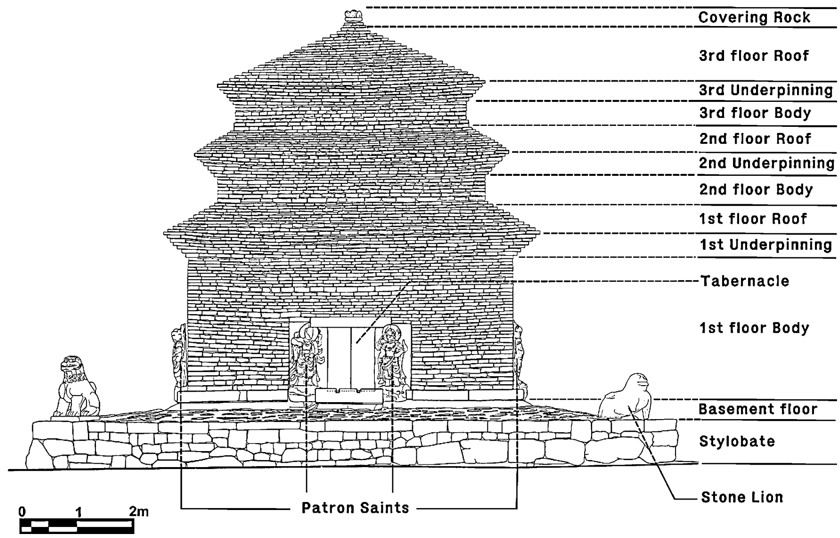

Fig. 1 Southern frontal view of the surveyed map and description names for the stone pagoda in the Bunhwangsa temple

Fig. 2 Field occurrences of the stone pagoda in the Bunhwangsa temple. **a** General view from the southwestern side. **b** Stalactite-like white precipitates collected from northern body rocks of the pagoda. **c** Photograph shows detail survey in the uppermost roof of the third floor

the covered rock on top of it. The pagoda has maintained its appearance since it was repaired in 1915 by the Japanese technicians who also discovered many cultural relics inside the pagoda including the reliquary and beads of Buddhist saints (CHA 2005).

In many cases, physical, chemical and biological weathering characteristics of the stone cultural heritage differ from one another, as the composing rock types are different. Moreover, the weathering characteristics of the same rock types are also widely different depending on the exposure conditions (Fidler 2002; Lee and De Freitas 1989; Lisci et al. 2003). Recently, there have been many researches on the subject (Price 1996; Lee et al. 2003; 2005). In addition, as the Bunhwangsa pagoda is composed of stone bricks, which is an exception in Korean stone cultural heritages, this may be the reason why the weathering state and damages of the Bunhwangsa pagoda are worse than other stone pagodas in Korea.

Though there are many studies on historic, archaeological and artistic aspects of the stone pagodas in Korea (Park 1999; CHA 2005), only a few of them cover construction materials, structural stability, petrological weathering, damage and conservational measures. Thus, a quantitative and careful investigation process was performed by the authors on the Bunhwangsa pagoda. Firstly, the construction rock types and their weathering damages were studied (Fig. 2b, c). Secondly, the physical and chemical changes of those rock types by weathering, and quantitative weathering damages by biological influences were evaluated. Finally, some methods for the conservation of the pagoda were suggested. The results can also be applied to many other conservation researches on stone cultural heritage.

Current state and conditions

The Bunhwangsa stone pagoda currently has three stories. The second and third stories are considerably smaller than the first one. The stylobate is the one-story structure made of piled-up field stone, which is very common for the stylobates of the stone pagodas.

There is an extra story made of granites in the middle to support the first-story body. The body stone extends from 30 to 45 cm in length. The composing rock types of each body and roof are various andesitic rocks 4–9 cm in thickness. Though the Bunhwangsa pagoda appears to be a typical stone brick pagoda, it is very distinguishable (Fig. 2a). As the Shilla Kingdom did not have the technology to manufacture bricks at that time, the bricks were made by trimming the regular-shaped andesitic rocks (Park 1999; CHA 1992).

As the pagoda was reconstructed in 1915, it has three stories. However, the pagoda is believed to have had seven or nine stories according to the historic records and a report by the Cultural Heritage Administration of Korea in 1989. The comparison of the size of each story supports the idea of seven stories according to an estimate by using size proportion between the second and third stories and applying the proportion to the first and third stories. From the amount of rock fragments from brick production, it can also be estimated that the pagoda was nine stories. The perspective size by the Cultural Heritage Administration Projects in Korea would be 41.6 m for seven stories and 48.5 m for nine stories, which is very tall and huge for a stone pagoda (CHA 1992).

The pagoda located in front of the Bogwangjeon (main building of the temple). There are stone fragments around in the northeast area of the pagoda, which were created during brick production and can be used to estimate the amount of rock bricks for the pagoda construction, and eventually to estimate the original size of the pagoda. The overall site environments are good, but the pagoda is completely exposed to tourists without any protection facilities. There is also weathered soil, which can contaminate the pagoda surface by frequent visitors.

There are many trees around the pagoda. They can block the sunlight and cause contamination with fallen leaves. There have been arranged several projects to protect the pagoda and improve the landscape, but there are still problems. The stylobate and foundation of the pagoda are polluted with all kinds of microorganisms and lower plants such as lichens and mosses. The body and roof stones have foliose lichens and higher plants (Fig. 2b, c).

Analytical methods

In this research, a polarizing microscope and a scanning electron microscope (SEM) were used to observe the occurrences, mineral texture, relative content, and mineralogical relationships in the samples. The SEM is a Shimatzu ISI-SX-40 with an attached LINK X-ray analysis (EDXA, PV 9100/60) system. The analytical samples were done with a double coating of carbon and gold. Moreover, for part of the samples X-ray diffraction analysis was used to conduct an accurate identification of the rock-forming minerals, transmutation, and clay minerals. A Rigaku model D/Max-IIB with a Cu-Ka X-ray at 30 kV and 15 mA was used for the diffraction analysis.

The relative proportion of the rock-forming minerals was calculated by using mode analysis targeting thin sections related to each of the samples. The Leitz model Orthoplan (071948) microscope with automatic counter attached was used for both polarizing and reflecting light. Concentrations of major elements were analyzed with XRF. Moreover, ICP-AES, ICP-MS, and INNA were used for minor element and rare earth elements analysis. Measurement of magnetic susceptibility (MS) was conducted using the KT-6 (Pocket Susceptibility Meter) model that is characterized by the measurement limit of 10^{-5} SI unit. The magnitude of MS was marked with 10^{-3} SI unit.

Properties of the rock materials

Petrological characteristics

The geological features of the Gyeongju area near the Bunhwangsa pagoda consist mainly of Cretaceous Bulguksa granitic rocks that intrude the andesitic rocks. The pyroclastic rocks and sedimentary rocks from the early Tertiary covered the granitic rocks. These rocks are distributed in the alluvium as unconformity. The Bulguksa granites are found in Mts. Nam, Toham, and Seondo, and consist of alkali granites, micrographic granites, biotite granites, granodiorites, and porphyritic granites (Lee and Hwang 1999; Jwa et al. 2000). Alkali granites typically lie around Mt. Nam, while granodiorites are around Mt. Toham. Micrographic granites, biotite granites and porphyritic granites are spread around Mts. Seondo, Maseok, and Samtae in the vicinity of the Gyeongju area.

The Bunhwangsa pagoda has a total of 9,708 stone bricks. The stylobate has 377, and the body and roof have a combined 8,823. The four statues of stone lions are made of only one rock, while the tabernacles have 504. The rock types are andesites, granites, and tuffs. The body of the pagoda is mainly andesites with different genetic processes, and the stylobates and tabernacles are comprised of various granites. There are four stone lion statues made of alkali granites and tuff, and the Noban (top covering rock) is made of quartz porphyry (Fig. 3a–c).

The andesites and granites, which are the main components of the pagoda, were observed under a polarizing microscope. The andesites are composed of subhedral plagioclase with irregular grain sizes and fine-grained quartz that was totally rounded. Minor rock-forming minerals are microcrystalline biotite and hornblende. The andesitic tuff has subhedral semi-crystalline plagioclase, quartz and tuffaceous matrix (Fig. 3d, e). Strong alteration and weathering were observed. Feldspars were replaced by clay minerals along the boundary of the grains and twinning planes, while hornblende and biotite were replaced by chlorite along the cleavage planes.

The stylobate, tabernacles, and Buddha relief are mostly made of alkali granites, which have equigranular texture and consist of quartz with wavy extinction, alkali feldspar becoming perthite and biotite. Quartz and feldspar alternate with each other and show a micrographic texture (Fig. 3f). The alkali feldspars were altered into sericite or clay minerals. Hornblendes and biotites are also usually transformed into hydroxide minerals along cleavages.

The whole rock MS is a good method in petrographic study for the stone cultural heritages and is used to distinguish different overall magnetization intensity of igneous rocks. The MS refers to the relative intensity of magnetization to the external magnetic field, and it is expressed as $I = kH$, where I is the magnetization intensity, and H is the external magnetic field, whereas k is the MS. In general, the average MS of granite is 2.512 (10^{-3} SI unit). The authors used 1.256 as the criterion. If the value is higher than that, the sample is classified as the magnetite series. Otherwise, the sample will be classified as the ilmenite series (Ishihara 1998).

Uchida et al. (1999) conducted multi-dimensional interpretation by applying this method at Angkor Wat in Cambodia. The MS was estimated by averaging five measurements of each rock property of the Bunhwangsa pagoda. The MS of granites range from 0.04 to 12.0 ($\times 10^{-3}$ SI unit), which is attributed to the mixed composition of various granites. The ranges of the andesites were from 14.6 to 39.9 ($\times 10^{-3}$ SI unit). These wide ranges of the MS imply that the granites and andesites have various mineral compositions (Fig. 4).

Mineralogical and chemical characteristics

Rock fragments were collected around the pagoda and examined to determine whether the fragments came from the pagoda. X-ray diffraction (Fig. 5) and geochemical analysis were used for these samples (Table 1). The andesitic rocks of the body and roof of the pagoda consist of quartz andesites, andesitic tuff, and

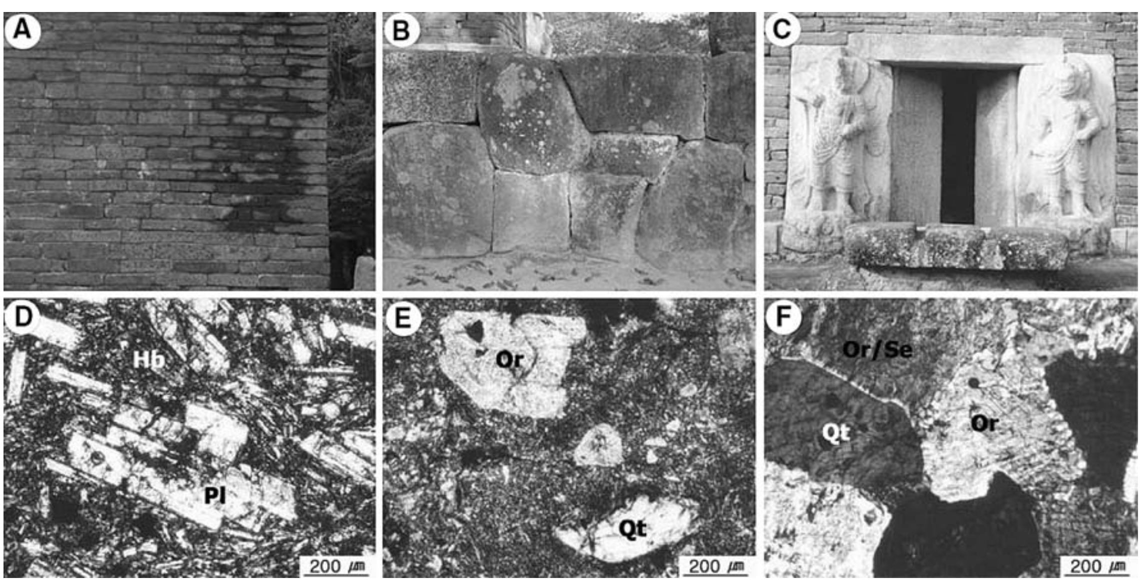

Fig. 3 Constituting rock types and their microphotographs of host rocks of the stone pagoda in the Bunhwangsa temple. **a** Brick-shaped andesitic rocks of pagoda body is highly damaged by leakage of rain along fractures. **b** Basement rock materials are composed mainly of granitic rocks. **c** Stylobate, tabernacles and stone statues are composed of various granitic rocks. **d** Pilotaxitic textures of plagioclase and chloritized hornblende in andesitic rocks from the pagoda body. **e** Andesitic tuff composed of tuffaceous groundmass and subhedral plagioclase of the pagoda body rock. **f** Quartz, alkali feldspar and biotite assemblage of alkali granite in the pagoda basement rock, which alkali feldspars are highly weathered into sericitic clay minerals

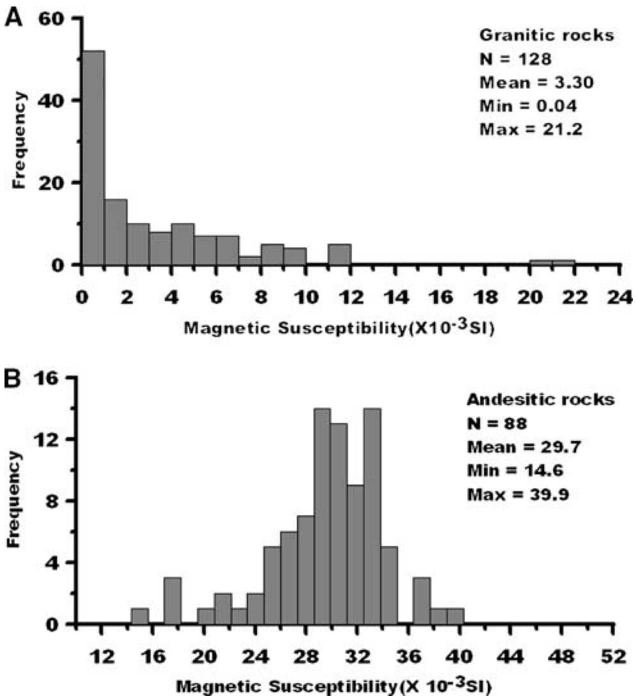

Fig. 4 Magnetic susceptibility of rock properties in granitic rocks (**a**), and andesitic rocks (**b**) of the stone pagoda in the Bunhwangsa temple

basalt. The X-ray diffraction analysis also identified a small amount of quartz and orthoclase along with the major mineral component of plagioclase. There were also traces of minerals such as smectite and chlorite. The alkali and micrographic granites usually were composed of quartz, orthoclase, plagioclase, and biotite, with traces of hornblende and chlorite (Fig. 5). The rhyolite tuff of the stone lion statues contains quartz, plagioclase, and chlorite. The concretes using materials for emergency treatment in 1915 were formed of calcite, quartz, plagioclase, and orthoclase added to cement.

Chemical weathering index (CIA) and weathering potential index (WPI) were used to determine the weathering degree of the major geochemical elements (Table 1). The CIA shows the changes to the alkali elements compared to Al_2O_3 that have small fluidity. As weathering progresses, calk-alkali elements are dissolved in the solution and easily lost, while Al_2O_3 remains in the same samples, which increases CIA. The bigger the index is, the further the weathering progresses (Nesbitt and Young 1984). The results from the Bunhwangsa pagoda are as follows; the CIA of basalt is 50.38; andesite 52.38; andesitic tuff 51.19; and micrographic granite 53.23. The chemical weathering indices are high for all types of rocks of the Bunhwangsa pagoda.

The WPI represents the ratio of alkali to calc-alkali elements. The higher number means that the weathering potential will be high. The WPIs of basalt, andesite, andesitic tuff, rhyolite tuff, micrographic granite, and alkali granite were 8.28, 8.14, 5.35, 6.07, 4.06, and 5.57, respectively. All materials show very active potential for chemical weathering. Among them, the most sensitive weathering materials are basaltic and andesitic rocks.

Evaluation of weathering damages

Structural instability

The structural instability of stone cultural heritage is mainly influenced by the ground condition. As pagodas with brick or brick-shaped rocks, the main problems in surface damage come from discoloration, cracks, and losses in the stylobate, which can affect the entire structure of the pagoda. One of the reasons why the stone pagodas fail to be intact over the years is that these surface damages can easily cause the collapse of the pagoda. In particular, as most pagodas were built on the top of the stylobate, the instability of the ground has serious impacts (Lee and Suh 2002; Lee et al. 2005).

The Bunhwangsa pagoda was built by piling up brick-shaped stones. The stylobate has cement and concrete for reinforcement purposes. The tabernacles are made of brick-shaped granites. The body on the tabernacles seems to be unbalanced, and the tabernacle on the eastern side has cracks. The center of the first-story body leans toward the west, and there is a fracture zone in the direction. The Buddha relief sculpture on the northern face of the first-story body has been partly destroyed and distorted.

The structural instability of the pagoda was evaluated by detailed surveyed maps. The plane figure of the third roof stone, which is seriously distorted (Fig. 6), shows that the center point of the roof stone does not coincide with that of the Noban (top covering rock). When comparing the horizontal line to the vertical line at each direction, they are not at the right angle. The angle at the northeast side is off 1.8°, which is 127.38 mm in length. That at the southeast is off by 1.0°, which is a 94.08 mm horizontal offset. The authors believe that the uneven settlement of the pagoda caused this structural distortion.

Physical weathering damages

The pagoda does not show serious damage or crack on its overall appearance. However, on a closer look, there are surface exfoliation and peel-off on the stylobate and tabernacles, as well as wear and tear on the

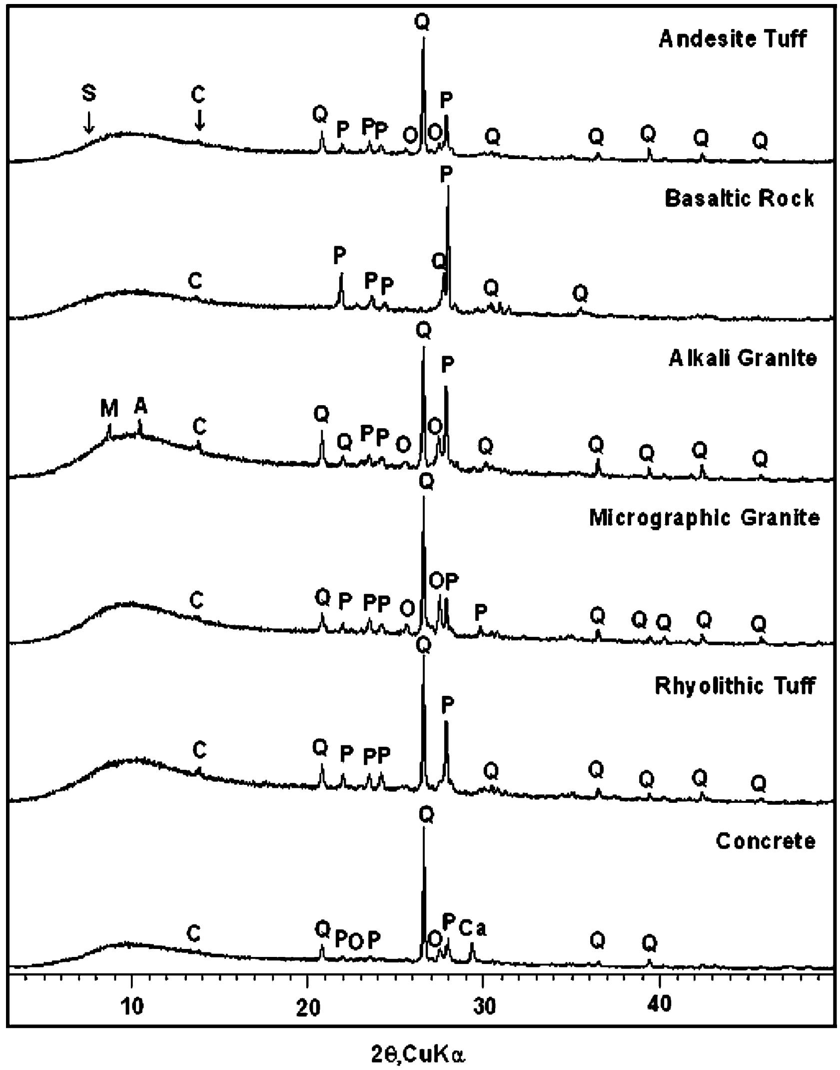

Fig. 5 X-ray powder diffraction patterns showing host rocks of the stone pagoda in the Bunhwangsa.temple. (*C* chlorite, *A* amphibole, *Q* quartz, *P* plagioclase, *M* mica, *O* orthoclase, *S* smectite, *Ca* calcite)

Table 1 Major element contents (wt%) for rock types of the stone pagoda in the Bunhwangsa temple

No. Rock names	BH-1 Basaltic rock	BH-7 Andesitic rock	BH-10 Andesitic tuff	BH-11 Rhyolitic tuff	BH-5 Graphic granite	BH-12 Alkali granite	BH-14 Concrete
SiO_2	57.92	67.79	70.34	76.23	76.76	76.06	59.32
Al_2O_3	18.16	15.59	14.4	12.98	12.57	11.65	9.90
Fe_2O_3	7.28	3.64	2.83	1.58	1.15	2.66	2.20
MnO	0.13	0.12	0.15	0.03	0.02	0.07	0.06
MgO	2.11	0.64	0.63	0.10	0.09	0.02	0.63
CaO	5.30	3.09	2.01	0.65	0.16	0.29	11.04
Na_2O	3.91	2.87	4.54	4.20	3.57	4.28	2.30
K_2O	1.68	3.54	2.41	3.64	4.51	4.32	2.88
TiO_2	0.76	0.73	0.47	0.15	0.16	0.12	0.28
P_2O_5	0.31	0.18	0.16	0.04	0.08	0.03	0.08
LOI	1.99	0.65	1.28	0.50	0.88	0.65	11.04
Total	99.55	98.84	99.21	100.1	99.96	100.15	99.74
CIA[a]	50.38	52.38	51.19	51.90	53.23	48.76	26.85
WPI[b]	8.28	8.14	5.35	6.07	4.06	5.57	–24.17

Fe_2O_3 total FeO, *LOI* loss-on-ignition, *CIA*[a] chemical index of alteration, *WPI*[b] weathering potential index

corners (Fig. 7). Especially, the andesitic rocks have many fragmental losses and cracks. The roof stones are in a serious condition due to weathering damages (Fig. 7a, b), which are surface exfoliation, peel-off, and fragmental losses along the cracks (Fig. 7c, d). The four stone lion statues at the corners on the stylobate also

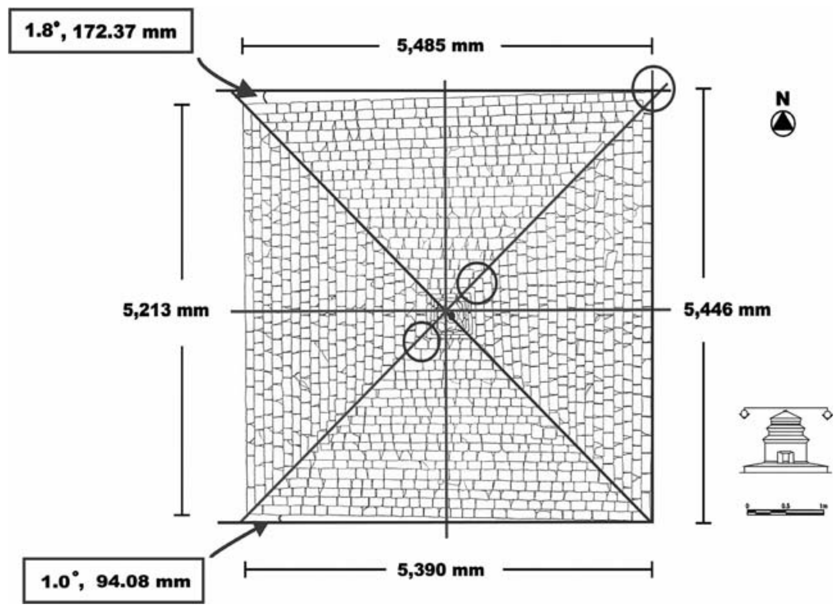

Fig. 6 Detailed measurements of structural instability in the uppermost third roof floor of the stone pagoda in the Bunhwangsa temple

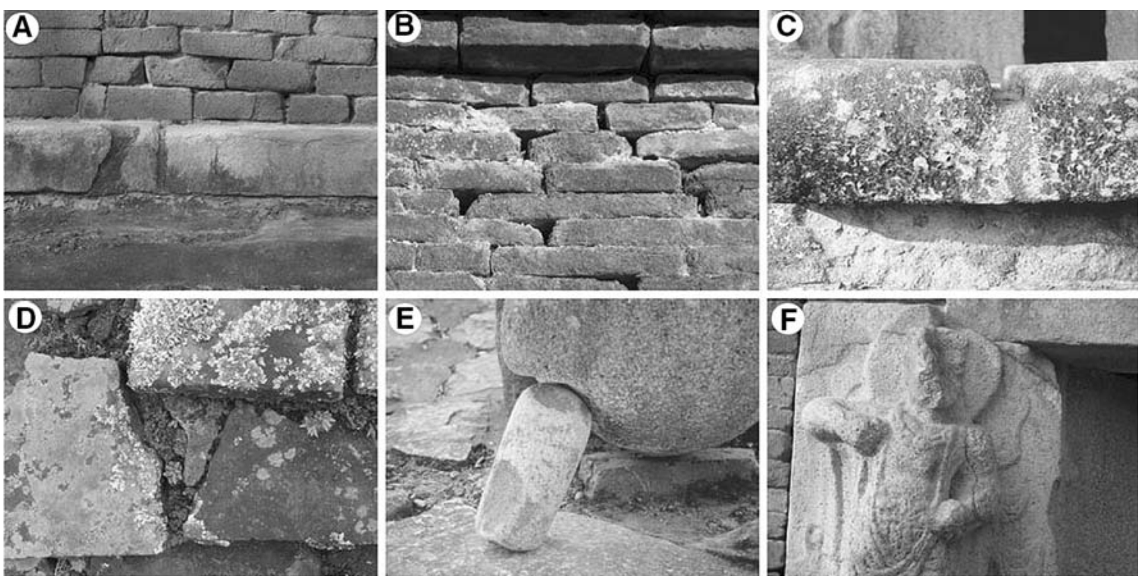

Fig. 7 Fractures and cracks showing host rocks of the stone pagoda in the Bunhwangsa temple. **a** Sheeting exfoliations in the basement rocks. **b** Highly weathered surface of andesitic rock coated with white gray crusts due to the dust and air pollutants. **c** Stylobates and tabernacles altered with discolorations and exfoliations. **d** Andesitic rocks on the uppermost third roof are severely deteriorated by weathering processes. **e** Stone lion statue with a broken leg. **f** Stone tutelary and beast statues show partly falling off and fractures along the marginal boundary

suffer from serious weathering damages (Fig. 7e). The Buddha relief sculptures standing at the gate of the tabernacles show losses, fall-off, and surface weathering along the marginal boundary (Fig. 7f).

Tables 2 and 3 show the visible occupancy rates of fractures and fall-offs. The criteria for the damages are as follows: a crack should be visible with naked eyes; and fall-off should have the size of one-fourth of the original piece. The analysis shows that the pagoda has the total numbers of 9,708 pieces. There were 2,216, 2,086, 2,230 and 2,291 pieces at the east, west, south, and north directions, respectively. The western face has the least pieces. Table 2 shows that the third-story roof has the most fractures along the rain pathway, and that there are many cracks at the eastern, western, and northern faces of the pagoda. The western faces of the

Table 2 Visual assessment of total numbers and percentages of fractured rock properties of the stone pagoda in the Bunhwangsa temple

Division	Conditions	Counts of construction materials (%)				Total (%)
		East	West	South	North	
Third roof rocks	Fractured	72 (23.7)	120 (41.8)	61 (19.7)	75 (24.2)	328 (27.1)
	Total blocks	304 (100)	287 (100)	309 (100)	310 (100)	1,210 (100)
Third underpinning	Fractured	11 (12.4)	7 (7.8)	15 (14.9)	8 (8.6)	41 (11.0)
	Total blocks	89 (100)	90 (100)	101 (100)	93 (100)	373 (100)
Third body rocks	Fractured	14 (12.0)	12 (8.2)	19 (12.8)	11 (7.0)	56 (9.8)
	Total blocks	117 (100)	146 (100)	148 (100)	158 (100)	569 (100)
Second roof rocks	Fractured	25 (8.3)	12 (4.2)	26 (8.8)	20 (6.6)	83 (7.0)
	Total blocks	302 (100)	284 (100)	293 (100)	305 (100)	1,184 (100)
Second underpinning	Fractured	12 (7.8)	22 (17.6)	14 (9.1)	20 (13.3)	68 (11.7)
	Total blocks	153 (100)	125 (100)	154 (100)	150 (100)	582 (100)
Second body rocks	Fractured	20 (13.2)	19 (13.0)	28 (19.6)	14 (8.5)	81 (13.4)
	Total blocks	151 (100)	147 (100)	143 (100)	165 (100)	606 (100)
First roof rocks	Fractured	24 (7.3)	16 (5.4)	39 (13.3)	19 (6.8)	98 (8.2)
	Total blocks	331 (100)	299 (100)	293 (100)	279 (100)	1,202 (100)
First underpinning	Fractured	13 (7.8)	14 (10.2)	29 (20.1)	8 (4.8)	64 (10.4)
	Total blocks	167 (100)	137 (100)	144 (100)	167 (100)	615 (100)
First body rocks	Fractured	63 (10.5)	72 (12.6)	68 (10.5)	30 (4.5)	233 (9.4)
	Total blocks	602 (100)	571 (100)	645 (100)	664 (100)	2,482 (100)
Tabernacle	Fractured	1 (16.7)	2 (33.3)	3 (50)	1 (16.7)	7 (29.2)
	Total blocks	6 (100)	6 (100)	6 (100)	6 (100)	24 (100)
Basement floor	Fractured	1 (1.0)	0 (0)	0 (0)	0 (0)	1 (0.3)
	Total blocks	99 (100)	77 (100)	102 (100)	99 (100)	377 (100)
Stylobate	Fractured	2 (1.3)	3 (3.0)	4 (3.7)	2 (1.7)	11 (2.3)
	Total blocks	154 (100)	102 (100)	109 (100)	115 (100)	480 (100)
Stone lion	Fractured	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	1 (100)	1 (100)	1 (100)	1 (100)	4 (100)
Total (%)	Fractured	258 (11.6)	299 (14.3)	306 (13.7)	208 (9.1)	1,071 (11.0)
	Total blocks	2,476 (100)	2,272 (100)	2,448 (100)	2,512 (100)	9,708 (100)

second-story and first-story roof have a lot of cracks with occupancy rates of 19.6 and 20.1%, respectively.

Table 3 shows the visible occupancy rates of fall-off pieces. The third-story roof has the most fall-offs along rain pathways. The occupancy rates at the east, west, south, and north directions are 18.1, 16.4, 17.5, and 21.0%, respectively. These fractures and fall-offs can cause serious structural instability near the future, and fall-offs can be dangerous to visitors. The gaps from fractures and fall-offs suffer from dust invasion, which will accelerate weathering. It is suggested that various clinical experiments be performed on deteriorating functions, losses, fall-offs, and surface weathering to develop effective conservation techniques for cementing, replacement, and reinforcement.

Damages by inorganic pollutants

The chemical weathering process in stone usually involve resolution, solution, hydration, hydrolysis, oxidation, reduction, carbonation, and chelation, most of which work together to destroy the rocks (Nagano and Nakashima 1989; Sharma and Rajamani 2000). There are stalactites, which are grayish precipitates and/or efflorescence between the brick-shaped stones of the Bunhwangsa pagoda. The stalactites are widely distributed on the surfaces of the pagoda stone (Fig. 8a). The major mineral is calcite from the hydrochloric acid reactions and also other white efflorescence, such as gypsum or brucite can easily be found.

There are other kinds of white precipitates in crusts, which should be clay minerals from the weathering of the pagoda. The precipitates also combined with the dust by visitors. There are whitening events and yellowish brown precipitates of carbonates along the rain pathways inside the tabernacles (Fig. 8b). The grayish white precipitates dominated in the northern face of the pagoda, while the dark gray precipitates are common at the eastern and western faces, praying stone in the south and stylobates at all four faces. There are also secondary precipitates by chemical reactions between the vegetation and the stone (Fig. 8c, d). The yellowish brown discoloration inside the tabernacles and on the surface of the Buddha relief sculptures is also observed along rain-flowing paths with dust, soil, and grayish white precipitates (Fig. 8e, f).

Table 4 shows the numbers and occupancy rates of the surface contamination by efflorescences. The criterion for surface contamination is that the coverage of

Table 3 Visual assessment of total numbers and percentages of fall-off rock properties of the stone pagoda in the Bunhwangsa temple

Division	Conditions	Counts of construction materials (%)				Total (%)
		East	West	South	North	
Third roof rocks	Fall out	55 (18.1)	47 (16.4)	54 (17.5)	65 (21.0)	221 (18.3)
	Total blocks	304 (100)	287 (100)	309 (100)	310 (100)	1,210 (100)
Third underpinning	Fall out	5 (5.6)	3 (3.3)	10 (9.9)	8 (8.6)	26 (7.0)
	Total blocks	89 (100)	90 (100)	101 (100)	93 (100)	373 (100)
Third body rocks	Fall out	16 (13.7)	14 (9.6)	4 (2.7)	7 (4.4)	41 (7.2)
	Total blocks	117 (100)	146 (100)	148 (100)	158 (100)	569 (100)
Second roof rocks	Fall out	14 (4.6)	14 (5.0)	8 (2.7)	9 (3.0)	45 (3.8)
	Total blocks	302 (100)	284 (100)	293 (100)	305 (100)	1,184 (100)
Second underpinning	Fall out	10 (6.5)	10 (8)	6 (3.9)	14 (9.3)	40 (6.9)
	Total blocks	153 (100)	125 (100)	154 (100)	150 (100)	582 (100)
Second body rocks	Fall out	12 (8.0)	14 (9.5)	9 (6.3)	10 (6.1)	45 (7.4)
	Total blocks	151 (100)	147 (100)	143 (100)	165 (100)	606 (100)
First roof rocks	Fall out	16 (4.8)	17 (5.7)	16 (5.5)	23 (8.2)	72 (6.0)
	Total blocks	331 (100)	299 (100)	293 (100)	279 (100)	1,202 (100)
First underpinning	Fall out	14 (8.4)	9 (6.6)	19 (13.2)	5 (3.0)	37 (6.0)
	Total blocks	167 (100)	137 (100)	144 (100)	167 (100)	615 (100)
First body rocks	Fall out	35 (5.8)	15 (2.6)	30 (4.7)	22 (3.3)	102 (4.1)
	Total blocks	602 (100)	571 (100)	645 (100)	664 (100)	2,482 (100)
Tabernacle	Fall out	0 (0)	2 (33.3)	1 (16.7)	0 (0)	3 (12.5)
	Total blocks	6 (100)	6 (100)	6 (100)	6 (100)	24 (100)
Basement floor	Fall out	0 (0)	1 (1.3)	0 (0)	0 (0)	1 (0.3)
	Total blocks	99 (100)	77 (100)	102 (100)	99 (100)	377 (100)
Stylobate	Fall out	5 (3.2)	3 (3.0)	4 (3.7)	2 (1.7)	14 (3.0)
	Total blocks	154 (100)	102 (100)	109 (100)	115 (100)	480 (100)
Stone lion	Fall out	2 (200)	1 (100)	0 (0)	2 (200)	5 (125)
	Total blocks	1 (100)	1 (100)	1 (100)	1 (100)	4 (100)
Total (%)	Fall out	184 (8.3)	150 (7.2)	151 (6.8)	167 (7.3)	652 (6.7)
	Total blocks	2,476 (100)	2,272 (100)	2,448 (100)	2,512 (100)	9,708 (100)

grayish white precipitates is at least one-third of the surface area. The most serious whitening events were observed on the second-story and third-story roof supporting stones, whose occupancy rates are 26.7 and 25.6%, respectively. The rates of the second-story body were 33.3%, which is the highest.

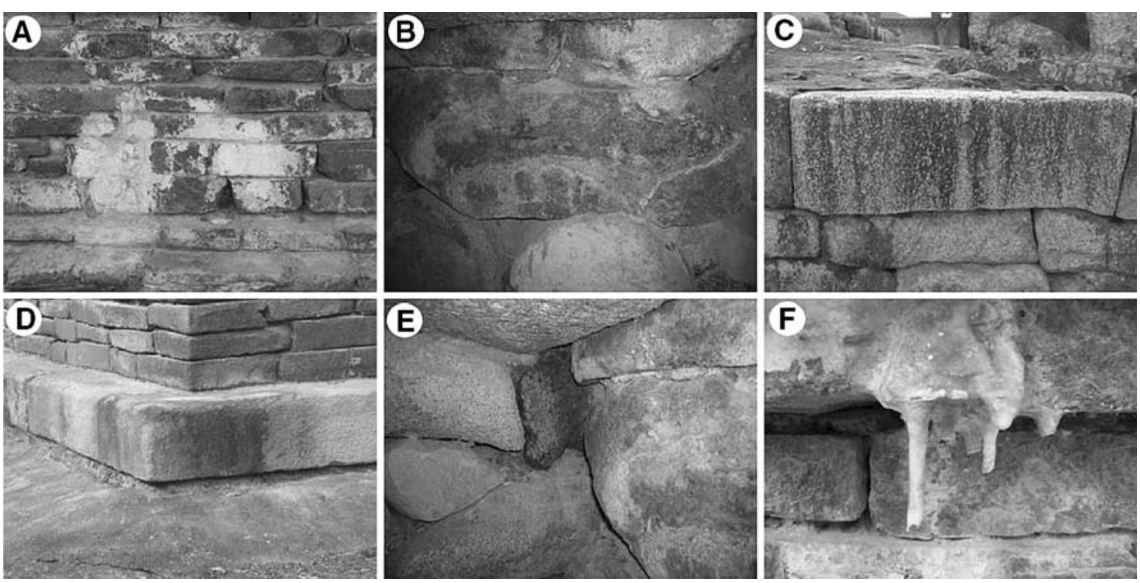

Fig. 8 Secondary contaminants of the stone pagoda in the Bunhwangsa temple. **a** Gray precipitates composed of calcite, gypsum and clay minerals. **b** Reddish brown precipitates by iron hydroxides occurred with the basement and inside of the tabernacle. **c** Dark brown contaminants coated basement rocks. **d** Black contaminants and reddish brown precipitates occurred the basement of body rocks. **e** Reddish brown precipitates by iron hydroxides occurred with the basement and inside of the tabernacle. **f** Stalactite-like white gray precipitates formed boundary between the rock materials

Table 4 Visual assessment of total numbers and percentages of rock properties by efflorescence of the stone pagoda in the Bunhwangsa temple

Division	Conditions	Counts of construction materials (%)				Total (%)
		East	West	South	North	
Third roof rocks	Efflorescences	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	304 (100)	287 (100)	309 (100)	310 (100)	1,210 (100)
Third underpinning	Efflorescences	9 (10.1)	15 (16.7)	27 (26.7)	11 (11.8)	62 (16.6)
	Total blocks	89 (100)	90 (100)	101 (100)	93 (100)	373 (100)
Third body rocks	Efflorescences	10 (8.5)	22 (15.0)	15 (10.1)	15 (9.5)	62 (10.9)
	Total blocks	117 (100)	146 (100)	148 (100)	158 (100)	569 (100)
Second roof rocks	Efflorescences	2 (0.7)	5 (1.8)	2 (0.7)	4 (1.3)	13 (1.1)
	Total blocks	302 (100)	284 (100)	293 (100)	305 (100)	1,184 (100)
Second underpinning	Efflorescences	18 (11.8)	32 (25.6)	25 (16.2)	5 (3.3)	80 (13.7)
	Total blocks	153 (100)	125 (100)	154 (100)	150 (100)	582 (100)
Second body rocks	Efflorescences	45 (30.0)	21 (14.3)	22 (15.4)	55 (33.3)	143 (23.6)
	Total blocks	151 (100)	147 (100)	143 (100)	165 (100)	606 (100)
First roof rocks	Efflorescences	4 (1.2)	3 (1.0)	3 (1.0)	5 (1.7)	15 (1.2)
	Total blocks	331 (100)	299 (100)	293 (100)	279 (100)	1,202 (100)
First underpinning	Efflorescences	12 (7.2)	8 (5.8)	35 (24.3)	44 (26.3)	99 (16.1)
	Total blocks	167 (100)	137 (100)	144 (100)	167 (100)	615 (100)
First body rocks	Efflorescences	50 (8.30)	42 (7.4)	33 (5.1)	75 (11.3)	200 (8.1)
	Total blocks	602 (100)	571 (100)	645 (100)	664 (100)	2,482 (100)
Tabernacle	Efflorescences	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	6 (100)	6 (100)	6 (100)	6 (100)	24 (100)
Basement floor	Efflorescences	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	99 (100)	77 (100)	102 (100)	99 (100)	377 (100)
Stylobate	Efflorescences	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	154 (100)	102 (100)	109 (100)	115 (100)	480 (100)
Stone lion	Efflorescences	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Total blocks	1 (100)	1 (100)	1 (100)	1 (100)	4 (100)
Total (%)	Efflorescences	150 (6.8)	148 (7.1)	162 (7.3)	214 (9.3)	674 (7.0)
	Total blocks	2,476 (100)	2,272 (100)	2,448 (100)	2,512 (100)	9,708 (100)

The whitening event was serious at the west and southwest direction in the second- and third-story roofs. The northern parts of the first-story roof and of the second-story are also in a very serious condition. For eastern faces, the body of the second-story has the worst whitening event about 30%. In summary, the whitening events are dominant on eastern and northern faces where the water leakage is wide.

X-ray powder diffraction analysis was conducted for the mineral assemblages of the grayish white precipitates. As a result, the major mineral was calcite with trace of gypsum regardless of different peaks (Fig. 9), which was also confirmed by SEM. The authors observed authigenic kaolinite inside alkali granites formed during weathering processes (Fig. 10a). Clay minerals were also observed, which were created from plagioclase and biotite within the weathered andesites (Fig. 10b).

It can be easily observed that precipitates are on the surface and grayish white precipitates like stalactites are on the body surfaces and the lower parts of the roof stones. They SEM images suggest that calcite and gypsum were combined with clay minerals (Fig. 10c, d). The SEM images of the tuff, which was fallen off from the stone lion statues, are shown in Fig. 10e and f. The column- or needle-shaped minerals in the figures were created in the open cavities of grain boundaries with euhedral patterns.

Contamination by organic pollutants

Organic matters play a critical role in the surface decomposition and biodegradation of stone cultural heritages. Micro-organisms can change inorganic rock into organic compounds, when they thrive on the surface of the rocks. In these processes, they can cause diverse environmental changes depending on different energy sources and inorganic nutritive salts (Eckhart 1978; Young and Urquhart 1998; Lisci et al. 2003).

The brick-shaped stones in the rain pathway on the roof of the Bunhwangsa pagoda have been invaded by lichens, bryophyta, and herbaceous plants. In particular, the herbaceous plants thrived at the boundary of cement filling between the stone bricks. There were scattered spider webs and ant nests. The dust and other inorganic pollutants were also serious. The stylobate was seriously contaminated by lichens and bryophyta. Higher plants and bryophyta can also be found on the concrete filling and on the stone surfaces along the rain pathways. The algae seriously contaminated the Bud-

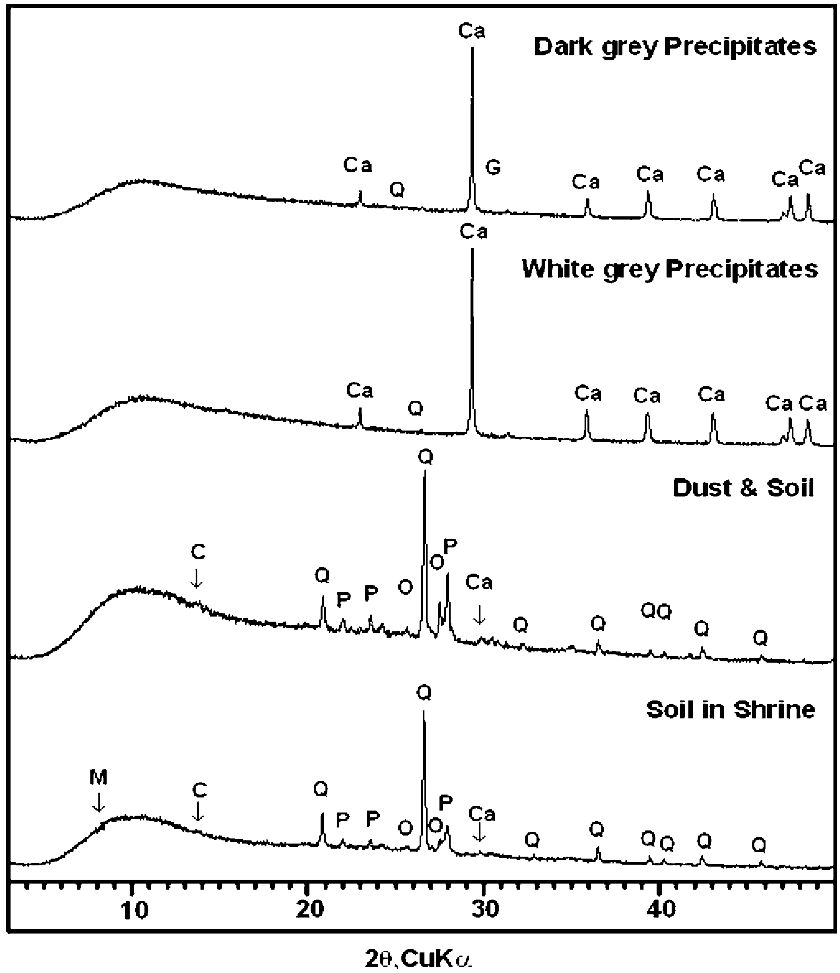

Fig. 9 X-ray powder diffraction patterns showing secondary contaminants of the stone pagoda in the Bunhwangsa temple. *M* mica, *C* chlorite, *Q* quartz, *Ca* calcite, *G* gypsum, *P* plagioclase, *O* orthoclase

dha relief sculptures with colonies of green, yellowish brown, and dark algae.

The parts most damaged by lichens were the four stone lion statues, contaminated by crustose and foliose lichens, bryophyta, algae, and fungi. Herbaceous plants grow around the pagoda, which can be a potential biological damage. Discolorations to green, dark and yellowish brown inside the tabernacles were observed with naked eyes, which imply humid environments by frequently rainfall. Secondary organic contamination, coverage of creatures and the review on the conservation aspects will be covered in detail in the near future.

Discussion on conservation sciences

The stone cultural properties are favorable for their endurance compared to other cultural assets. However, they often fall victim to weathering and collapse by long-term exposure to heat, water, atmosphere and living creatures. It is very important to investigate the cause of damages and material changes before conservation planning. This investigation should include diverse factors of physical, chemical, biological, and environmental impacts.

For stone or brick-shaped stone pagoda, the construction materials are diverse and therefore, structural imbalance can occur due to differential weathering degrees of these diverse materials. The pollutants, precipitates, and living creatures can accelerate the weathering processes. The investigation results on the Bunhwangsa pagoda are summarized as follows. The occupancy rates of the cracks are very similar at the faces to the east, west, and south direction, and the northern face has the smallest as 9.1%. The fragmental fall-offs are very similar in all directions, so are the whitening events. However, the northern face suffers from a little more whitening (Table 5). In summary, the northern face has less cracks, fall-off and more whitening event, as it is less exposed to the sunlight and holds water longer, which provides favorable conditions for secondary pollutants.

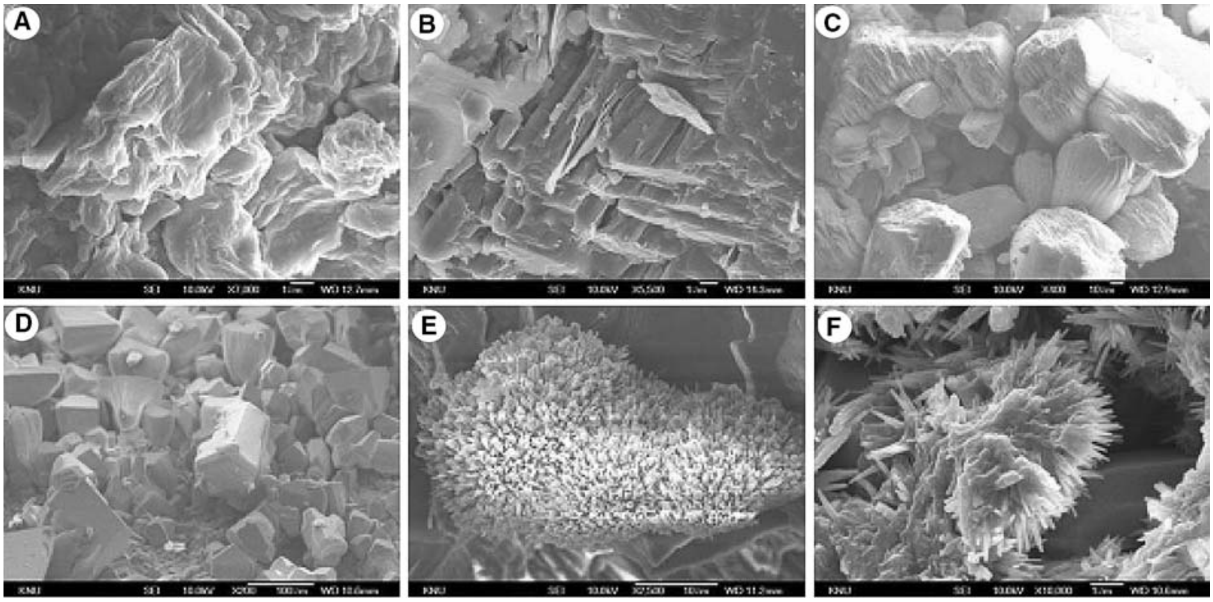

Fig. 10 Scanning electron microphotographs showing secondary minerals and precipitates of the stone pagoda in the Bunhwangsa temple. **a** Kaolinitic clay minerals formed with alkali feldspar of granitic rock. **b** Highly eroded biotite and plagiocalse of the andesitic rock. **c**, **d** Euhedral calcite and gypsum in the white gray precipitates formed rock surface. **e**, **f** Fibrous to acicular zeolitic clay minerals from the rhyolitic lithic tuff within the stone lion

Table 5 Summary on visual deterioration degree of each side of the stone pagoda in the Bunhwangsa temple

	Fractured blocks (%)	Fall out blocks (%)	Efflorescences blocks (%)	Total blocks (%)
East	258 (11.6)	184 (8.3)	150 (6.8)	2,476 (100)
West	299 (14.3)	150 (7.2)	148 (7.1)	2,272 (100)
South	306 (13.7)	151 (6.8)	162 (7.3)	2,448 (100)
North	208 (9.1)	167 (7.3)	214 (9.3)	2,512 (100)
Mean	267.8 (12.2)	163 (7.4)	168.5 (7.6)	2,427 (25)
Total	1,071	652	674	9,708

The most important cause for weathering processes in the pagoda is the structural instability, as it can create cracks, which can accelerate other deterioration processes, such as chemical and biological weathering. Chemical weathering caused by rainfall, snow, and fog can create decomposition of minerals, differential weathering, and wear on the corners. The sources of biological weathering are algae, lichens, and herbaceous plants. The secondary contamination includes precipitates by rainfall, the erosion of the cement mortar from the reconstruction project, and white precipitates on the surface.

The most urgent conservational measures are to cement the cracks, exfoliation, peel-offs, and fragmental loss, to lessen the structural instability, and to remove the secondary precipitates and vegetations on the surface. These recommendations can be applied to conservation researches on stone cultural heritage, however, it should be emphasized that quantitative and diagnosis of characteristics of materials and weathering aspects should be performed beforehand.

Conclusions

1. The pagoda consists of many kinds of rocks. The overall site environments are favorable, but the site is directly exposed to visitors without any protecting facilities. The northeastern parts suffer from serious whitening, while the major damages of southeastern parts are cracks. The total number of rock components of the pagoda is 9,708. Among them, 11.0% are fractured, 6.7% are fallen off, and 7.0% show considerable efflorescences, which shows that the pagoda has been highly deteriorated by physical and chemical weathering.
2. The stones of the pagoda consist mainly of andesitic and granitic rocks. The body and roof of the pagoda appear to be safe from weathering and other kinds of damages except cracks or partial wear at the corners. The roof rocks, however, suffer from multiple exfoliation and peel-offs, onion-peel-like decomposition, radial cracks and fragmental fall-offs.
3. There are stalactites of grayish white precipitates between stone bricks. They consist mainly of cal-

cite with traces of gypsum and clay minerals. The precipitates are dominant on the face of the northeastern direction. The most serious damages are on the eastern faces of the first- and second-story, and the northern faces. Dust contamination by visitors can also be observed.

4. The stylobate consists of mostly granites, and is seriously contaminated by lichens and mosses. Some parts are in dark black or yellowish brown colors from the inorganic pollutants by secondary oxidation. The invasion of higher plants is serious on the fillings and the rain pathway of the stylobate. In addition, the stylobate suffers from wear at the corners with peel-offs and granular decomposition with minor exfoliation and cracks.
5. The authors suggest that clinical experiments be conducted to replace and reinforce some stone bricks or the entire pagoda materials. Among them, the tabernacles show serious separation and distortion causing the structural instability. All of those damage factors should be diagnosed accurately for successful conservation planning.

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