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Review

Water is a critical factor in evaluating and assessing microbial colonization and destruction of Angkor sandstone monuments

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ABSTRACT

Sandstone monuments/temples of the Angkor Empire in the Southeast Asia are important UNESCO World Cultural Heritage of the Khmer Civilization and recorded history for the people today. Majority of these monuments suffer severe deterioration from weathering caused by a combination of physical, chemical and biological forces, including natural and anthropogenic influences. Current knowledge on deterioration of sandstone is not only scattered, but also isolated and restricted by the specialized disciplines/fields of the investigators, resulting in a lack of comprehensive understanding or integrated information on the causes and mechanisms to the damage of these temples/monuments. It is clear that water is the most critical factor, if not the utmost important one over time, affecting the integrity of the sandstone constituents of the overall architecture and also the carvings of bas-relief at many of these temples. Water is important to life and promotes the mobility of solutes, and both microbial and plant growth accelerates the destabilization of the stone structural integrity. Colonization by plants and microbes alters the local environmental conditions allowing dissolution of sandstone and mobility of solutes from and out of the sandstone. When water is not drained effectively from these temples/monuments for an extended period of time, stagnation of water forms a small pool, providing moist and water into sandstone nearby and below for an extended longer period of time. Under evaporation condition, the accumulated solutes in water can be concentrated and also transported into sandstone through initiation of capillary phenomenon to lead to salting effect and attack of the sandstone. Soluble salts in sandstone can be crystallized under further drying conditions to result in defoliation of the outer surface layer from the sandstone structure. With the supply of water, microorganisms can also contribute in a number of ways to the physical and chemical destruction processes involved. Therefore, a holistic approach with water considered must be formulated in investigation of the mechanisms involved and protection measures of Angkor sandstone temples and architecture.

1. Introduction

Cultural heritages are important evidences and recorded history of civilization. Khmer culture of the Angkor Empire was thriving at its peak between 9th and 12th centuries with a vast expanse of territories covering today's Southeast Asia, including today's Cambodia, Viet Nam, Laos and Thailand. The Khmer Kings built a large number of temples/monuments for religious purpose, and also cities and palaces. The well-engineered water transportation and drainage systems were built to support population and agriculture through connections of cities and territories, including the East Baray (reservoir) by Rajendravarman before 968 (Freeman and Jacques, 1999). King Suryavarman I built the Royal Palace inside Angkor Thom and also probably the West Baray at a dimension of 8 km by 2 km, which is still in use today. Suryavarman II ruled from 1112 to about 1150 s at the peak of the Angkor Empire with construction of the best-known Angkor Wat (Fig. 1a) and also several successful military campaigns to expand his territories. The last king Jayavarman VII was responsible for building hundreds of temples, hospitals and others with the Angkor Thom (Fig. 1b) and the Bayon temple surviving as the most significant ones today. Unfortunately, the empire collapsed suddenly, believed due to severe environmental disaster (Day et al., 2012), but the true cause is still unknown.

The main structural material of these temples/monuments is mostly sandstone taken from Kulen Mountains and the quarry is still in

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Fig. 1. Angkor Wat (a) and the south gate to Angkor thom (b) in siem reap of Cambodia.

operation today. Actually, current maintenance and repair use the stone from this quarry. Other materials used for construction and decoration, particularly wood, could not persist longer enough under the tropical climate and only traces of them can be recovered from archaeological excavations. In 1992, these remaining architectures of sandstone became UNESCO World Heritage sites, not only for the local people to generate a significant economic income, but also for visitors around the world. Over the past long history, many of these architectures suffered from severe damage from wars, deterioration from the tropical climate and invasion by plants, and colonization by different microflora (Meng et al., 2016, 2017), restoration and protection are parts of the current efforts taken to protect and preserve these architectures by many countries' experts working at different sites in Cambodia.

Southeast Asia has a very comfortable climate to life, warm and hot most of the year, with plenty of rainfall and sunshine to support the active growth of microflora, flora and fauna. Even without the microflora, rocks and minerals are decomposing slowly over time and Angkor temples show clear sign of damage from both abiotic and biological processes. Such tropical climatic conditions promote a quick establishment of natural flora of plants and microorganisms on surfaces of these temple sandstones visibly shown in different colors at different stages of the development and seasons (Kusumi et al., 2011; Lan et al., 2010; Li et al., 2008; Meng et al., 2016, 2017). Temples under good management for tourists are well maintained by clearing plants frequently. As a result, majority of these monuments and temples are now covered with different types of organisms showing a range of colors. Most of the known ones on surfaces of stone include lichens (Warscheid and Leisen, 2011), bacteria (Lan et al., 2010; Li et al., 2010), archaea (Gu and Katayama, 2017; Meng et al., 2016, 2017) and fungi (Hu et al., 2011; Li et al., 2008, 2010), which are known for their roles and abilities to dissolve rocks and minerals (Gu et al., 1998) by producing inorganic acids through oxidation of sulfur (Li et al., 2008, 2010) and ammonia (Meng et al., 2016, 2017). Others indicate the potential effects of Fe oxidizing bacteria in destruction of stone (Warscheid and Leisen, 2011) and they do not consider biological contribution as important as physical processes to the overall damage of sandstone