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Determination of weathering degree of the Persepolis stone under laboratory and natural conditions using fuzzy inference system

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HIGHLIGHTS

- A new approach was presented to qualitatively predict the stone weathering degree.
- Fuzzy models were employed to determine the weathering degrees of the stone.
- The predicted weathering degree was modified based on local climatic information.
- The modified weathering degree was compared with actual weathering in Persepolis.
- Based on the comparison the approach is reliable to quantify weathering degree.

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ABSTRACT

Weathering imposes vital effects on stony monuments. Mostly, the degree of weathering is determined by simple test results, ignoring simultaneous effects of various weathering factors. Hence, the main purpose of this study is to develop prediction models with fuzzy inference systems to determine the weathering degree of the Persepolis stone, using various accelerated ageing tests in laboratory condition and to extrapolate the results to the natural condition, considering climatic information. The results suggest reliable conformity between the prediction of the weathering degree of the stone and the weathering degree observed in the Persepolis complex in natural condition.

1. Introduction

Weathering has been considered a natural destructive factor in the deterioration of monument stones. This process has several adverse effects on chemical, physical, and mechanical characteristics of stones, of which freeze-thaw, salt crystallization, thermal shock and dissolution are the most important. Depending on their local climatic condition, stones may be affected by one or more of these processes. Hence, determination of the weathering degree of stones, taking into consideration of all the weathering factors is a complicated task.

Another challenge is providing a quantitative approach for assessing the quality of weathered stones. Most of the early research presented qualitative approaches to determine stone weathering degree [1–6]. Besides, attempts were made to shift to quantitative approaches. It is believed that quantitative approaches provide more consistent and objective material descriptions than merely qualitative description, particularly by non-specialist users. Hence, chemical indices are being utilized to determine weathering degree (e.g. [7–14]). As chemical indices may change due to other processes (e.g. tellogenic diagenetic factors such as mineral transformation and/or replacement), regardless of weathering, they are not reliable indicators to assess stone weathering degree [15]. Weathering of stone building materials is mainly a physical phenomenon. Chemical weathering usually requires a geologic time scale not compatible with the historical time of the ancient constructions, set aside sulphation of stone surfaces or acid dissolution of carbonate materials due to industrial pollution. The oldest cultural heritage was built at least in Neolithic Age. Ludovico-Marques (2008), referred in [21], reported Paleolithic stone bases of wood shelters found in Côa Valley, in

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Portugal, more than 20,000 years old, but even these have not enough time to allow the general chemical weathering phenomena to occur.

As weathering proceeds, gradational changes occur in physical and mechanical properties of rocks, which could be used as a quantitative approach to determine the weathering degree [16]. Thereby various accelerated ageing tests are being utilized to assess weathering rate of rocks (e.g. freeze-thaw [17–19], salt crystallization [20–22], thermal shock [23] and wetting-drying [19]). The composition of an artificial weathering cycle does not need to encompass the different possibilities of natural weathering inside itself. Authors as Bortz and Wonneberger [24] consider equivalence based on the stone effects caused by a number of accelerated artificial weathering cycles per year of natural weathering and not per number of natural weathering cycles. Bortz and Wonneberger (2000) [24] carried out an empirical process of comparing mechanical data of artificial weathered stone with mechanical data of natural weathered stone on New York building marbles. They reached at most 10 years and established a simple equivalence between several cycles of Freeze–Thaw artificial weathering per year of natural weathering occurring in New York environment. According to the authors, these works generally compare artificial weathering cycles and natural weathering periods up to 30 years.

In most researches, quantitative classifications mainly used the values of physical and mechanical index properties (i.e. Schmidt hammer rebound value, P-wave velocity, porosity, uniaxial compressive strength, point load strength index and Brazilian tensile strength) obtained from accelerated ageing tests. Several authors advise non-destructive methods to determine weathering data of stone (e.g. [25–31]) as well. Mechanical behaviour of rocks can be assessed from physical behaviour [32] even after consolidation treatments of weathered rocks [33]. These index properties obtained from accelerated ageing tests are necessary to determine the weathering degree (e.g. [34–38]). Recently, a combination of properties is being used as components of simple classification systems in order to evaluate the weathering degree [see 15, 38]. However, the classifications raised from these authors still suffer from a sharp boundary problem. In these models (based on simple interface algorithms), either ignoring or overemphasizing those elements which may fall near the boundary of intervals, the sharp boundary problem is predictable. Data sets which show signs of sharp boundary problems can be easily mined with fuzzy sets, as they soften the effect of sharp boundaries [39]. Some researchers used fuzzy inference system to determine stone weathering degree [15,40,41]. Exclusively in these approaches, a number of stone samples with different qualitative weathering degrees and similar lithology are selected. Then predictive fuzzy models are developed based on data collected from physical and mechanical tests to evaluate quantitative weathering degree.

Hence, the present study follows two main purposes. First, the development of a predictive model for reliable estimation of weathering degree of the Persepolis stone under various accelerated ageing tests (freeze-thaw, salt crystallization, thermal shock, wetting-drying and dissolution) using fuzzy inference system. Second, simultaneous evaluation of effects of the weathering factors in the deterioration of the stone in natural condition. To achieve these purposes, stone blocks were collected from Majd Abad quarry, as the main site supplying stone for the construction of Persepolis, and weathering level of Persepolis monument was carefully evaluated. Based on the data obtained from the accelerated ageing tests, prediction models are developed using a fuzzy inference system for each test. Subsequently, outputs of the developed models (calculated weathering degrees for individual tests) being weighted regarding the climatic condition of each location to characterize weathering degree of the Persepolis stone.

2. Study area

Persepolis or Takht-e Jamshid was the ceremonial capital of the Achaemenid Empire (550–330 BCE), which, in contemporary Persian language is known as Parseh, while ancient Persians called it Parsa, meaning the city of Persians. Persepolis was built in the proximity of Marvdasht city (northeast of Shiraz, Fars Province) (Fig. 1) and has been declared as a World Heritage Site by UNESCO [42]. The construction of Persepolis began during the reign of Darius I (552–486 B.C) about 518 B.C, and was finished by his son, Xerxes I (486-465 B.C). The great city of Persepolis was built in terraces rised above the Pulwar River, erected on a larger terrace of over 125,000 square feet, partly cut out of the Mount. Kuh-e Rahmat ("the Mountain of Mercy"). To create the level terrace, large depressions were filled with soil as landfill. Large column bases and capitals of the palaces were made of limestone of various colors and monolithic blocks of stone were used to make the porticos, stairs, corridors and many of the window frames. No mortar was used between the stone blocks and many of them were joined by iron clamps and molten lead. More than 3000 designs adorn the buildings and mausoleums of Persepolis [43]. Stones used for the construction of Persepolis are of two types. The first type is black limestone from the Majd Abad quarry (25 Km south of Persepolis), the major site wherefrom the Persepolis complex stones were exploited (Fig. 2). The stone excavated from Majd Abad quarry belongs to the Ilam Formation which is being dated as Santonian to Campanian (late Cretaceous) in age [44]. The second type is grey limestone which was exploited from another quarry located at Kuh-e Rahmat in the proximity of the site with Aptian age (early Cretaceous). As the major materials were derived from the first site, the last type was excluded in our experiments.

The Marvdasht city with an altitude of 1620 m above sea level, has cold weather in hilly areas (location of Persepolis complex) and a moderate climate in lowlands. A typical continental climate with cold, snowy winters and hot, dry summers prevails in the Marvdasht region. Meteorological data of Marvdasht city are presented in Fig. 3.

As temperature frequently drops below 0 °C in the region during winter (see Fig. 3a), evidently freeze-thaw cycles may operate between November and March in the region (Fig. 3a). Also, assessment of number of days with maximum temperature equal to 30 °C and higher (Fig. 3a) shows that thermal effect cycles can drastically affect the weathering of Persepolis stone. Thereby, freeze-thaw and thermal shock are probably the main natural destructive factors as well (Fig. 3b). Also, efflorescences are observable on some pillars of the site, where salts were crystallized in pores near the surface of the stones (Fig. 3c). Furthermore, air pollution has increased in recent years in the Marvdasht city due to industrial activities such as petrochemicals and small units producing PVC pipes. Potentially they could increase concerns about the durability of Persepolis stone against acid rains and salt crystallization weathering.

3. Experimental procedure

In coordination with domestic authorities, some blocks (with approximate dimensions of 30 × 30 × 40 cm) were collected from the Majd Abad quarry using geological hammer and chisel in order to obtain rock cores for experimental tests. Two series of cylindrical cores were prepared to identify some of the stone properties (porosity, P-wave velocity, and Brazilian tensile strength) before and after artificial accelerated ageing tests (freeze-thaw, salt crystallization, thermal shock, dissolution and wetting-drying). Numbers and dimensions of the samples used for physical and mechanical laboratory tests are presented in Table 1. To determine