COMPARISON OF VULNERABILITY CONDITIONS OF ADOBES' STRUCTURE – THE STUDY OF HISTORICAL AND RESTORED ADOBES OF KOOH-E KHAJEH ANCIENT SITE (KOHAN DEZH CASTLE) IN SISTAN, IRAN

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Keywords: *Adobe, restoration, Kohan Dezh Castle, vulnerability, gradation, Kooh-e Khajeh site, Sistan*

Abstract: *Adobe constructions are very frequent in dry, hot and desert regions. Due to weather conditions and the availability of suitable resources and earth to make adobes, Kohan Dezh castle, at the foot of Kooh-e Khajeh hill (Sistan region) is among the first places where such constructions were made. Owing to the particular properties of the adobe, the constructions have always been vulnerable to weather conditions, especially moisture. Before restoring such monuments and altering their structure, sufficient research on their morphology and scientific-based restoration experiments need to be carried out; the results are integrated in planning the restoration project and the related scientific research. In Kohan Dezh Castle Restoration Workshop Project, restoration adobes produced in a previous restoration project were compared to the original adobes in order to understand the differences in their structure and constituent components. In the next stage, results were used to carry out necessary experiments to examine the vulnerability conditions for each of these samples against moisture. Finally, the strengths and weaknesses of restoration adobes were also studied. The analyses included gradation of the soil comprising the adobes, determination of density and porosity percentage, capillary tension test, water immersion test, abrasion resistance test, compressive strength test, and artificial rain which proved that the adobes produced for restoration were more vulnerable to moisture-induced damage then the historical ones. In order to optimize the structure of restoration adobes and increase their resistance against moisture-induced damage, their structure and gradation of their compounds and particles were modified so as to resemble those of the historical ones.*

Cuvinte cheie*: Chirpic, restaurare, castelul Kohan Dezh, vulnerabilitate, granulometrie, Kooh-e Khajeh, Sistan*

Rezumat*: Construcțiile din chirpici sunt foarte frecvente în zonele calde, aride și deșertice.Ca urmare a condițiilor climatice și a disponibilității materiei prime pentru realizarea chirpiciului, castelul Kohan Dezh, de la poalele dealului Kooh-e Khajeh (regiunea Sistan) este printre cele mai vechi construcții realizate din chirpici. Prin natura lor, construcțiile din chirpici sunt vulnerabile la condițiile de mediu, în principal la umiditate. Înainte de a restaura astfel de construcții și a le modifica structura trebuie cercetată morfologia acestora științific și experimental, iar rezultatele trebuie integrate proiectele de cercetare și restaurare. În cadrul Dezh Castle Restoration Workshop Project a fost analizat chirpici folosit la restaurarea castelului și apoi a fost comparat cu chirpiciul original, pentru a evidenția diferențele de structură și compoziție. Rezultatele au fost apoi folosite în experimente care investigau vulnerabilitatea acestora la umiditate. În final, au fost studiate punctele tari și cele slabe ale chirpiciului folosit la restaurare. Analizele au constat în studierea granulometriei, densității, porozității, tensiunii capilare, impactului la imersiunea în apă, rezistenței la abraziune, la compresie și la ploaie a chirpiciului folosit la restaurare; testele au demonstrat că acesta este mai vulnerabil la influența apei decât chirpiciul antic. Pentru optimizarea calității și rezistenței chirpiciului modern la apă se impune modificarea structurii și granulometriei acestuia astfel încât să fie cât mai asemănător cu cel antic.*

INTRODUCTION

Sistan is located in a vast territory in the southeastern Iran, a large part of it being today part of Afghanistan. The Sistan region, along with Baluchestan, make the Sistan and Baluchestan Province of Iran (see Moradi *et alii* 2013; 2014; Mutin 2017; Sarhaddi-Dadian 2015a; 2015b; 2017a; 2017b; 2020). Kooh-e Khajeh is the only elevated feature in the Sistan plains, located 30 kilometres away from the city of Zabol (See Fig. 1). The complex consists of Islamic and pre-Islamic structures, which are considered to be Iran's most prominent adobe monuments (Sarhaddi-Dadian 2013).

Adobe has been one of the oldest and most important construction materials used for building both houses and giant and stately structures, from the pre-historic period up to the present day. The monuments located at Kooh-e Khajeh in Sistan are unique adobe structures with special value. On this mountain are located special architectural structures, including Kohan Dezh Castle, Kok Kohzad Castle, Chehel Dokhtaran Castle and other scattered structures and tombstones. The most important of these structures is an imposing castle called by the locals Kohan Dezh. The extraordinary value of this construction, residence for local rulers of the Parthian-Sasanian periods, comes from the best preserved Parthian wall paintings discovered inside Iranian Plateau, early Parthian plasterworks, and unique flower reliefs. Adobe makes the major building material of this structure, although stone and brick were also sometimes used. The coatings mainly consist of clay, but other features are present in these constructions: cob, plaster, wall painted ornaments of wall paintings and embossed flower designs (Tabasi 2005, p. 55). The building has suffered damages through time and is now in critical conditions: numerous parts have been destroyed by environmental elements and human interference. The most severe damages, according to their impact, are the following: fractures, decomposition, hydrodynamic scour, flaking and pulverizing of adobes, and damages resulting from termite attacks etc. (Tabasi 2005, p. 56).

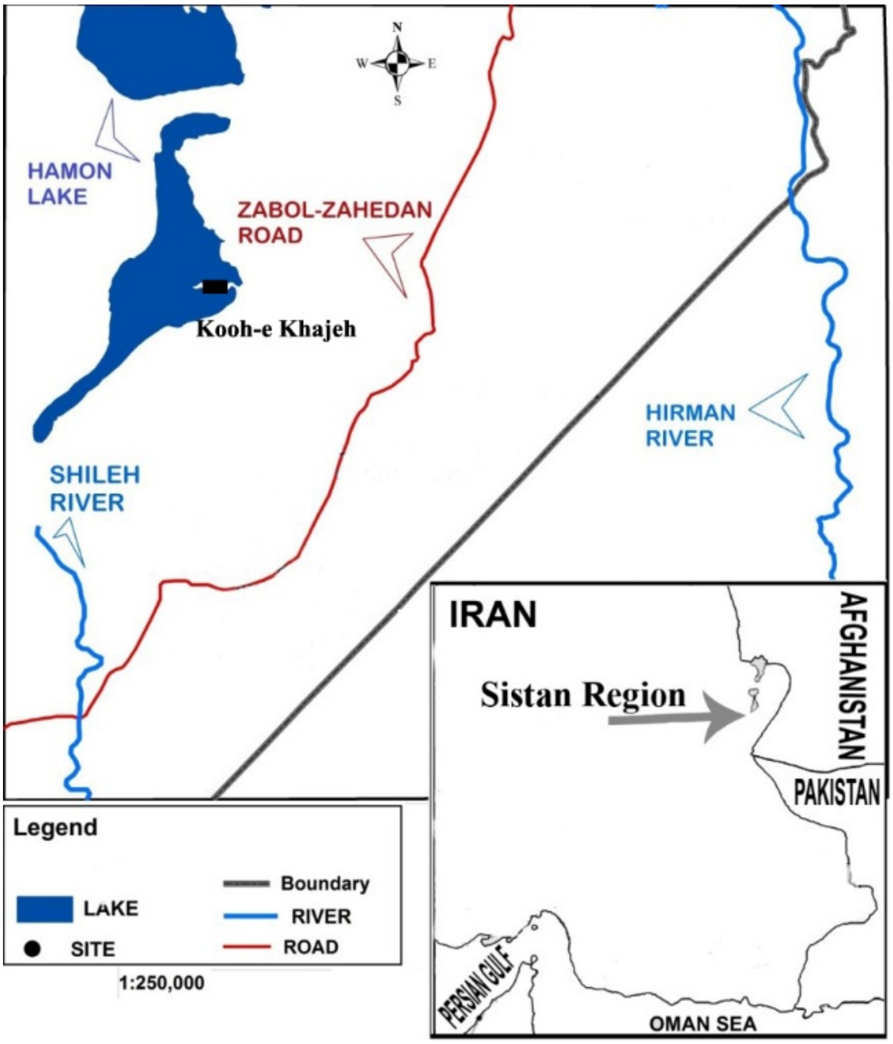

Figure 1. *Location of Kooh-e Khajeh in Sistan Region (Sarhaddi-Dadian 2017b).*

The Kohan Dezh Castle in Kooh-e Khajeh has seen special restoration measures in recent years, which have been aimed merely at repairing damaged parts by applying protective cob and can be considered as somehow useful emergency interventions. Apparently, the restoration building materials, especially adobes used in the repairing this construction do not differ much from the original (historical) adobes in terms of protection against damaging conditions and elements, but there might be differences in their structure which could impact their long-term endurance. The present study seeks to primarily identify the differences in structure and key components of the original and restoration adobes, and then to use these observations as a touchstone in evaluating the vulnerability of each of these adobes to moisture. Finally, the pros and cons of restoration adobes are presented in order to suggest directions for future research and for using our results in restoring and renovating this castle and similar structures.

Given that the same clay from Sistan region was used to produce both historical and restoration adobes, the question is if there will be any significant difference in their structure. Specifically, will both types of adobes (historical and restoration) have the same amount of resistance against simulated damaging elements? Apparently both types of adobes should have a similar structure and display identical reaction towards damaging elements, provided the same source of clay has been used for both of them. In this research the structural properties of adobes were first studied and then they were examined under simulated damaging elements, and finally their resistance was analysed and discussed.

THEORETICAL FRAMEWORK AND THE REVIEW OF RELATED LITERATURE

As the homogeneity of the restorative materials with the original materials of the construction is a regulation registered in the charter for the protection of monuments, using natural and traditional protective and restoration materials is standard procedure. Thus, using modern technology in compliance with the historical and traditional properties of the construction and its materials, in a non-destructive way, is also permitted according to the same protective charters and regulations, as their proper application might even lead to an improved protection level (Bahramzadeh *et alii* 2018, p. 116). In order to make restoration adobes which are compatible with the environmental conditions and type of construction, there are numerous methods and additives to choose from, but what is regarded as important by the curators and restorers is the use of traditional and local materials and preservation of the authenticity in making restoration materials (Warren 2008, p. 233).

Before a construction or historical building is about to be protected and restored, the restoration team must decide they use restoration materials or not; the materials must be examined and evaluated, their structural properties must be studied, and they should be tested in environmental conditions similar to those of the construction, and finally they must correspond to the original materials. Numerous studies have been conducted on the evaluation and examination of clay and adobe materials which have yielded considerably important results, and thus a review will contribute to the goals of the present study. Most of the research refers to the key components, gradation and vulnerability conditions of the materials; the landmarks are presented below.

Varjavand (1973) talks about the classification of different soils and various materials used in producing adobes used for the structure of ancient and historical constructions in Iran and Mesopotamia. He refers to additives such as hay, rock fragments, ash, goat hair, camel fur, animal dung, husk and date tree fibres which were mixed with the clay to make adobes.

In his book, Hadiyan-Dehkordi (2007) points out that among soil elements, clay ores have a high absorption capability, which increases their mass when they absorb water and once they lose it, they get back to their original size, leaving cracks in the construction. Therefore, a series of cracks and fractures appear on the clay surface due to this wet and dry cycle, which finally lead to the weakening of the structure.

Hami (2009) points out that adobe is like a sandy skeletal soil where the dry clay has bound the sand grains together and filled the vacancies in the skeletal structure. The compressive strength of the adobe depends on its soil gradation and the method used to produce it. The compressive strength of the adobe increases with consistent gradation of adobe clay, optimal use of water and pressure moulding.

In his MA thesis, Bahramzadeh (2012) argues that improper gradation and composition of adobe soils result in the damage and corrosion of clay building materials. An amount of clay below 3% or over 20% in the composition of soil will cause problems in the structure of the building materials. Too little clay will reduce the soil's flexibility and too much clay will increase the contraction, leading to internal cracks which impact the strength of the building. Generally, a suitable gradation includes one-third to two third of sand, one fourth of silt and one fifth to one tenth of clay.

In an article published in 2016, Hadian-Dehkordi argues that adobe erodibility is influenced by the gradation and degree of the cohesion of the soil used, on the clay ores and their content of soluble and insoluble salts. Therefore, the particles, which can get closer to each other when they dry up, will have a stronger bond and better strength. The presence of tiny and flat grains like those in clay ores is one of the most important factors in increasing dry strength of the adobe.

Madahi and colleagues (2017), refer to the shortcomings of adobe as follows: it is very heavy, has low dryness and wetness resistance (contracts in dry conditions, weak against water, has low durability during transportation, is heterogeneous in size, it flakes, pulverizes and decomposes under temperature fluctuations, develops efflorescence in the presence of soluble salts, and corrodes from the activity of termites if the adobe comprises plant fibre.

METHODOLOGY AND DATA COLLECTION TOOLS

The methodology used in this research is descriptive-analytical; in order to collect scientific data and information on both historical and restoration adobes, we used publications (books, articles, theses, journals, etc.), and conducted instrumental and non-instrumental tests. The results were analysed individually and then comparatively. The final results proved to be very useful for future research. These tests included the adobe samples' soil gradation test (hydrometer and wet sieving method), density and porosity tests of adobe samples, capillary tension analysis test, water immersion resistance test of sample adobes, abrasion resistance test of dry and post-saturation adobe samples, compressive strength test of dry and post-saturation adobes and artificial rain test (rain simulation test), respectively. All protocols for the above-mentioned tests were derived from relevant scientific publications.

Laboratory studies method

The first step was sampling. Three historical samples were randomly taken from three points of the Saam Castle in Kooh-e Khajeh, and other three restoration adobes were taken from the southern gate. These samples were coded during collection. Letter S is for Saam, A for adobe, H for historical adobes and R for restoration adobes. In order to standardize the tests and also for better accuracy of the results, the sample adobes were cut into smaller pieces of 5 × 5 × 5 cm. The following tests were conducted: capillary tension test, water immersion test, abrasion resistance test and compressive strength test. For each of the above tests, two samples of each code were examined and the mean results of both samples were taken as the final result for that sample.

Restoration samples		Historical samples	
Sample Picture	Sample Code	Sample Picture	Sample Code
	S-A-R^1		S-A-H^1
	S-A-R^2		S-A-H^2
	S-A-R^3		S-A-H^3

Table 1. *Classification of tested samples with their codes.*

The first test was gradation or measuring the weight proportion of different grains of the soil, and the physical classification of each sample adobes, as the results were supposed to play a major role in examining other properties of the sample adobes.

For this test, 500 grams of soil were dried in an oven at 60° centigrade for 24 hours, then they were weighed and wet sieved through a stacked column of sieves ranging from size 4 (largest mesh, 4.75 mm, on top) to size 200 (smallest mesh, 0.075 mm, at the bottom). A tray was placed under the lowest sieve (size 200) to collect the finest particles for the hydrometer analysis. The particles from each sieve were collected separately, dried again in the oven at 60° centigrade for another 24 hours, and then weighed again. In order to calculate the weight ratio for each particle fraction, their weight was divided by the total weight and was presented as percentage (Heydarian 2011, p. 35). This test is mainly used for soils, where 90% of grains are larger than the mesh of sieve number 200; in the case of about 10% of the grains which are smaller than the mesh of sieve number 200, a hydrometer analysis is also conducted. Some hay and animal dung were also spotted in the historical samples, and were taken into account and calculated in the gradation test.

The hydrometer analysis is based on the principle of the sedimentation of soil grains in water. When the sample soil is completely mixed with the water, the floating grains, based on their form, size and weight, deposit at different speeds. To make testing easier, it was assumed that all grains were spherical in shape, and their sedimentation speed was defined based on the Stokes law. In order to conduct the hydrometer analysis, 40 grams of soil were dried in the oven, then pounded and diluted to the desired volume in water in a sedimentation cylinder flask. The ingredients were mixed in order to obtain a homogeneous mixture and then a hydrometer was inserted into the flask and the density data were read at time intervals of 30 seconds, 1, 2, 5, 10, 20, 40, 80 and 240 minutes. The results of the soil gradation for the sample historical and restoration adobes are presented in Table 2 (Mesbah *et alii* 2000, p. 21).

Density and porosity tests, which were conducted on the sample historical and restoration adobes later during this research, were an addition to the results of the other tests. Generally, the purpose of this study was to determine the density and porosity of historical and restoration adobes; by using the results of other tests and by comparing the samples, proper conclusions regarding the structure, physical properties and vulnerability of the samples can be drawn. The degree of porosity of the adobe is related to the degree of the particles' cohesion and to the diversity of that soil. This test also shows the size of the particles of the adobes. The bigger the particles are, the greater the space between them is and hence the adobe has a greater porosity.

For density and porosity tests, small inform pieces of adobe were selected. These pieces were then put inside an oven at 60° Centigrade for 24 hours to dry up. After that, the pieces were put inside a desiccator to cool down and then weighed. The sample was immersed inside the beaker of carbon tetrachloride (via a thread which was already weighed and the weight was deducted after it was saturated to avoid any mistakes) and kept there till bubbles from the sample stopped. The carbon tetrachloride-saturated sample was immediately taken out of the beaker and weighed again (Fig. 2). In the next step, the sample was put inside a graded cylinder flask of 250 ml carbon tetrachloride (Fig. 3) and the difference in the liquid level was recorded. Then considering the obtained data, the below formula and steps, which are applied to A-H1-S sample (Teutonico 1988, p. 53), were used to calculate the percent of porosity and density of other samples. The results are presented in Table 3.

Figure 2. *Weighing the tested sample adobe.*

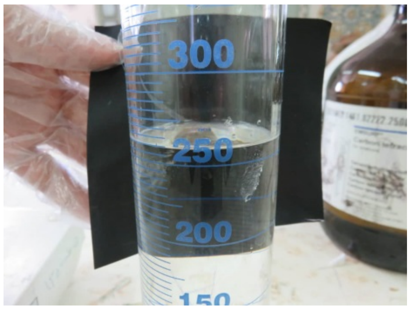

Figure 3. *Putting the sample adobe inside the graded cylinder flask containing carbon tetrachloride.*

Dry weight: $W_1 = 26.16$ gr
Saturation Weight: $W_2 = 32.398$ gr
Initial Volume: $V_1 = 250\ cm^3$
Secondary Volume: $V_2 = 270\ cm^3$
$W_2 – W_1 = 32.398 – 26.16 = 6.238$ gr

Sample's Porosity Volume = $\frac{\text{carbon tetrachloride's weight}}{\text{density}} = \frac{6.238\text{gr}}{1.59\frac{\text{gr}}{\text{cm3}}} = 3.923\ cm^3$

Apparent Volume = $V_2 – V_1 = 270\ cm^3 – 250\ cm^3 = 20\ cm^3$

True Volume of the Sample = Apparent Volume – Porosity Volume = $20\ cm^3 – 3.923\ cm^3 = 16.077\ cm^3$

Apparent Density = $\frac{\text{dry weight}}{\text{apparent Volume}} = \frac{26.16\text{ gr}}{20\text{ cm3}} = 1.308\frac{\text{gr}}{\text{cm3}}$

True Density = $\frac{\text{dry weight}}{\text{true volume}} = \frac{26.16\text{ gr}}{16.077\text{ cm3}} = 1.62\ \frac{\text{gr}}{\text{cm3}}$

Porosity Percentage = $\frac{\text{porosity volume}}{\text{apparent Volume}} \times 100 = \frac{3.923\text{ cm3}}{20\text{ cm}} \times 100 = 19.615\%$

The next test was capillary water absorption, which shows the degree of attraction between similar and dissimilar molecules, resulting in a liquid (in this case water) to rise in the tubes or small fibrils, thus wetting the solid (Teutonico 1988, p. 43). To do this test, the sample adobes which were cut into 5 × 5 × 5 cm pieces were dried in an oven at 60° centigrade after 24 hours. Then the adobes were cooled down in a desiccator (for 30 to 60 minutes). In the next step a sponge with a diameter of 1 cm was placed at the bottom of the tray and the same amount of distilled water was added to the tray. Six samples of adobes were put inside the tray on the sponge, one after another at an interval of 10 seconds (the reason for choosing this time interval was to have enough time to record the data obtained from each sample) and the rise in water level due to the adobes were measured at regular intervals by a ruler (Fig. 4). This was continued until the water reached the top of the adobe cube, then the complete saturation time was recorded. It was necessary to add some distilled water to the tray in order to compensate for the water absorbed by the adobes (Bahramzadeh 2012, p. 52). The results of this test are presented in Table 4. Water has always played a major role in the erosion of porous materials. Water movement depends on the physical properties of the materials such as structure, porosity, capillarity and penetrability of them. This simple test evaluates the water rise via capillarity (Hadiyan-Dehkordi 2007, p. 239). The purpose of this test was to measure the amount of capillary tension in historical and restoration adobes and then to compare the results.

Figure 4. *Measuring the water rise in adobe structure in capillary test.*

In order to calculate the resistance against saturation conditions (water resistance test), the already cut samples were submerged in beakers containing 800 ml of distilled water; the degree of destruction of samples were checked at regular intervals, and the results are presented in Table 5. Similarity of test conditions for all samples was a key requirement for the test accuracy. It's recommended for the sample to be completely submerged in water and the amount of water to be equal for all samples (Fig. 5). This test was carried out for measuring the complete destruction time of sample adobes in water saturation mode. It was, in fact, a test meant to determine the resistance of adobes against immersion in water so that we could evaluate their degree of vulnerability and correlate it to their texture (Değirmenci 2008, p. 28).

Figure 5. *Sample adobes' water immersion test.*

The next test was the resistance to abrasion, carried out in order to evaluate the resistance of adobes against abrasive forces such as wind, dust and moving sands in nature. The protocol followed here was taken from the executive instructions in Hosseini Seir's article published in the Proceedings of the Ninth International Conference of Study and Preservation of Adobe Architecture (Hosseini Sir 2003).

In the abrasion resistance test, the cut sample adobes were dried in an oven at 60° centigrade for 24 hours so that all their moisture would completely evaporate. Then these samples were cooled down in a desiccator (for 30 to 60 minutes) and weighed by a digital scale and their weight was recorded. Next, these adobes were put inside a wooden vice and received 90 abrasion strokes with a P80 sandpaper. The same amount of weight was put on the device in order to avoid using hand force for vertical pressure (Fig. 6). When this step was finished, the adobes were dried one more time in an over at 60° centigrade for 24 hours so that their moisture would completely dry up, and after that they were cooled down in a desiccator (for 30 to 60 minutes) and finally weighed with a digital scale. The weight difference in each adobe before and after the test shows their degree of destruction against the abrasive force. For instance, the destruction percentage of the sample adobe A-H1-S is determined as follows (Hosseini Sir 2003, p. 99).

$$\frac{\text{degree of destruction}}{\textit{before the test}} = \frac{x}{100} \rightarrow \frac{2.67\text{gr}}{209.342} = \frac{x}{100} \rightarrow x = \frac{100 \times 2.67}{209.342} = 1.27$$

The abrasion resistance test was performed again on the sample adobes after their were saturated in water for evaluating their resistance against abrasive force in post-saturation conditions, as clay materials, depending on their type of ore in their composition, swell after they absorb moisture and water penetrates into their constituent layers. The swelling causes the adhered particles to separate irreversibly after the absorbed water dries up, which consequently leads to weakening of the original cohesion of clay materials. This is why the abrasion resistance test was conducted on the sample adobes after they were saturated and dried up.

In this test, the sample adobes were exposed to conditions where they would completely soak in water and become saturated (like capillary test), they dried up in open air for 24 hours and their moisture was removed by keeping them in an oven at 60° for 24 hours. The remaining steps in this test were similar to those of compressive strength test of dry sample adobes; the results of this test for all adobe samples are defined for both conditions and presented in Table 6.

Figure 6. *Performing abrasion test on sample adobes.*

Another test performed on the adobes was the compressive strength test which sought to reveal the approximate resistance of adobes against compression force. The amount of adobes' compression strength is affected by their gradation and the composition and also by the adhesive substance in their structure. By resistance we refer to the amount of compression stress enough to crack the cube-shaped sample under similar conditions of simple loading (Hejazi *et alii* 2014, p. 67).

In this test, adobes of 5 × 5 × 5 centimetres were put under a single-axis mechanical jack specially designed to measure the compression strength and the compression force was gradually increased until the first fractures appeared in the adobe. The initial fracture time and the force applied were recorded (Eslami 2010, p. 58).

Like abrasion resistance test, this test was conducted on sample water-saturated adobes, so that when the water touches the adobes, it penetrates into their structure and occupies the space between constituent particles. These particles then absorb the water and swell. The swelling of particles causes an increase in the space between particles, a decrease in cohesion properties and also reduces adobe's resistance against force. Thus, the purpose of this test was to study the effect of water on the compression strength of saturated sample adobes and to compare them with other non-saturated samples. This test was conducted after the saturated adobes were completely dry again. The results of these two tests are presented in Table 7.

The rain-wash resistance test was the last test to be done on adobes. The purpose of this test was to measure the resistance of sample adobes against rain-wash phenomenon in a laboratory environment. Although the analysis of the results of this test is done qualitatively and through comparing each sample's vulnerability, the results obtained are quite practical and valid. In this test, the cut sample adobes were put inside a tray under a cold-water shower installed at a height of 2 meters above the adobes. The sample adobes were exposed to the cold-water shower for 1 minute with a flow rate of 4 litres/minute. At the end of the test, the amounts of the destruction of samples were qualitatively checked (Fig. 7 and 8) and the results were recorded in Table 8. Similar test conditions for all samples were a key requirement for the test accuracy.

Figure 7. *Sample A-H1-S before the artificial rain test.*

Figure 8. *Sample A-H1-S after the artificial rain test.*

RESULTS

The gradation results in Table 2 shows that the soil used for the historical adobes have approximately the same gradation and the same amount of clay, silt and sand exists in the composition of all historical samples. But this is not the case for the restoration samples, as each of these samples has a particular gradation. What is important in the results of this test is that the amount of clay and silt in the composition of restoration adobes is much higher than in the historical adobes; at the same time, the historical adobes are richer in sand. In brief, the soil in the restoration samples is more finely grained than that of the historical adobes.

Porosity in solid building materials refers to the void spaces and pores in them, which are filled by water or air. In other words, porosity is a fraction of the volume of voids over the total volume. Having said that, the results of the density and porosity percentage test (Table 3) showed that the historical samples had a higher porosity than the restoration ones, due to the difference in their gradation; this means that the amount of fine grains in the restoration sample is higher (situation already confirmed by the results of gradation test). This difference in porosity percentage comes from different building conditions for each type of adobes. These conditions, impacting the adobe's density and porosity include: compression and pressure applied to the adobe by the builder while molding the soil, the proportion of soluble salts in the composition of sample adobes' clay, clay fermentation at the time of their production, and even the drying conditions of the samples.

According to the results of capillary test, the historical adobes showed similar absorption rate and had approximately same saturation time but the restoration samples became saturated at quite different times. The difference in saturation time and rate of samples can be caused by the difference in the diameter and number of spaces (capillary tubes) in the adobes' volume. The bigger the diameter of spaces is the slower is the flow of water through capillary tubes, and thus saturation takes longer. Also, if there are many voids with larger diameters, the flow of water through capillary tubes will experience a sharp drop and adobes will show a higher resistance against moisture rise. The difference in the number and diameter of capillary tubes can be both a result of difference in gradation of adobe structure and of the conditions and the method used in the making of adobes. The greater is the amount of clay grains (smaller in size) in an adobe composition, the smaller the size of voids in an adobe becomes (Bahramzadeh 2012, p. 54). The results of the gradation test showed that the historical adobes had a similar gradation which gave them roughly the same capillary speed; the variance in the gradation of restorative adobes results in differences in their capillary speed. The results from the gradation and porosity tests show high capillary speed in the restorative adobes, except for A-R2-S sample, whose low capillary speed might be explained by a low amount of clay in its structure and by the higher degree of compression of the particles during molding, which produced a smaller number of voids and capillary tubes.

Sample Code	Clay Percentage	Silt Percentage	Sand Percentage
S-A-H_1	10.44	14.08	75.48
S-A-H_2	8.52	14	77.48
S-A-H_3	10.11	14.25	75.64
S-A-R_1	26.56	21.96	51.48
S-A-R_2	16.52	36.04	47.44
S-A-R_3	24.37	23.25	52.38

Table 2. *Gradation test results.*

Sample Code	S-A-H^1	S-A-H^2	S-A-H^3	S-A-R^1	S-A-R^2	S-A-R^3
Density	1.645	1.95	1.62	1.756	1.781	1.733
Porosity Percentage	19.096	17.685	19.615	13.42	11.97	13.79

Table 3. Results of density and porosity test of sample adobes.

Sample	S-A-H_1	S-A-H_2	S-A-H_3	S-A-R_1	S-A-R_2	S-A-R_3
Complete Saturation Time (Minute)	420	520	510	330	More than 600	120

Table 4. *Results of capillary tension test of sample adobes.*

Degree of Destruction	Effect
10%	
20%	
35%	
70%	
Complete Destruction	

120	90	60	30	Sample / Time (Minute)
				S-A-H_1
				S-A-H_2
				S-A-H_3
				S-A-R_1
				S-A-R_2
				S-A-R_3
Descriptions: The H2 sample was destroyed in 60 hours.				

Table 5. *Results of water immersion test of adobes.*

The results of water immersion test are presented in Table 5. The longer duration before destruction for historical adobes can be explained through the difference in the diameter and number of voids in the adobes volume, which directly impacts on the water absorption rate, the consequent swelling and the decomposition. Particle collapse occurs when enough water fills the voids in the adobe structure and exertion of pressure reduces adobe's cohesion, thus overcoming the surface tension and mutual attraction between the particles, resulting in their separation (Warren 2008, p. 138). Having that said, the premature and simultaneous destruction of restorative adobes can also occur (according to the results of gradation test in Table 2) because of the high number of fine clay particles in their composition, as too much clay significantly increases water absorption which expedites the destruction of clay building materials.

Adobe erodibility is dependent upon the gradation and degree of cohesion of the soil used, on the type of clay ores, and on soluble and insoluble salts (Hadiyan-Dehkordi 2016). As the results of abrasion resistance test in Table 6 showed, the degree of destruction in restoration sample adobes was higher than that for historical ones. But because the amount of clay is higher in the historical samples, they must have better particle bondage and coherence. Therefore, they must have better resistance against abrasion than the historical samples. After observing the opposite, we argue that it is possible that differences between the gradation of restorative and historical adobes as well as the sand grains in the structure of historical adobes act like a shield against abrasive forces. This is the reason which explains the difference in destruction between the two types of adobe against abrasion. The results of this test proved similar for both dry and post-saturation dried samples, but it seems that the erodibility of adobes saturated with water has significantly increased compared to the dry or non-wetting samples. The lesser is the swelling of constituent particles during water absorption and the more binding points they have, the better is their cohesion during drying process and stronger the bondage against external destructive forces.

The results of the compressive strength test in Table 7 show that the restoration samples have better resistance against compression than the historical samples. These results are influenced by the soil gradation (a high amount of clay in each of the samples impacts on its resistance), as well as by the wear and tear induced by the great antiquity of the historical adobes.

The results of the same test for the adobes which were dried after being water-saturated show that the restoration adobes have a better compressive resistance than the historical ones, and that this difference is bigger between dry and post-saturation restoration adobes than between dry and post-saturation historical adobes. In other words, the compressive strength of restoration adobes experiences a sharp drop after they become saturated in water. The compressive strength of the adobe depends on its soil gradation and the method used to make it. The compressive strength of the adobe increases with consistent gradation of the clay, pressure moulding, and optimized use of water (Hami 2009, p. 142).

The materials combined in the structure of restoration adobes are in such a proportion that once they absorb water, they swell and fracture so much that the structural unity in these adobes is largely undermined. But both restorative and historical sample adobes demonstrate an acceptable resistance against compression.

According to the results of the artificial rain test in Table 8, the A-H2-S experienced the lowest destruction while the A-R3-S sample experienced the most damage during the specified time. The results of this test are somehow similar to the results of water immersion and capillary tests, as the historical samples displayed a better resistance against water and moisture than the restoration samples. The results of this test show the vulnerability of each of adobes to rain. When rain is accompanied by wind, it makes raindrops hit harder on the surface of clay building materials, especially adobes, thus apart from fracturing the adobe, the mechanical impact makes the grains loose (Rezazadeh Ardebili 2011, p. 119).

Sample Code	S-A-H_1	S-A-H_2	S-A-H_3	S-A-R_3	S-A-R_2	S-A-R_1
Destruction percentage of dry samples	1.27	0.68	0.41	2.31	1.27	0.76
Destruction percentage of sample after saturation	3.342	1.91	2.499	3.362	2.85	2.097

Table 6. *The results of abrasion resistance test for sample in dry and post-saturation mode.*

Sample Code	S-A-H_1	S-A-H_2	S-A-H_3	S-A-R_2	S-A-R_1	S-A-R_2	S-A-R_3
Amount of Resistance (Kg/Cm2) In Dry Mode	17.09	26.03	20.07	27.71	37.43	27.71	38.85
Amount of Resistance (Kg/Cm2) In Post-Saturation Mode	13.96	11.81	19.04	14.96	19.79	14.96	30.16

Table 7. *Results of compression strength test on dry adobes.*

Sample Code	S-A-H^1	S-A-H^2	S-A-H^3	S-A-R^1	S-A-R^2	S-A-R^3
Destruction Percentage	5	2	5	7	10	20

Table 8. *Results of artificial rain test.*

DISCUSSION

Particle size distribution and soil grain stability are among the most important features of soil structure which, due to their dynamic nature, experience spatial and temporal changes. The size of soil particles and their stability have significant effect on the physical properties of soil such as permeability, ventilation, soil resistance and transfer of liquid, minerals and gases, and are considered as an important index in evaluating the properties of the soil (Bardsirizadeh *et alii* 2017, p. 534). A soil can also be described as well grained or badly-grained. A well-grained soil possesses a proper range of coarse to fine grains and any soil which is poorly-grained can be defined as a badly-grained soil (Eftekharian, Titidezh 2001, p. 63). In terms of cohesion, soils are divided into cohesive and non-cohesive types. A cohesive soil is a type of soil whose particles have good cohesion and unity due to the particularities of the clay ores. A non-cohesive soil consists of separate particles with no binding between them (Ibn Jalal, Shafai Bajestani 1991, p. 14).

Gradation studies of soils of all historical and restorative samples were first conducted, and they represented the background in analysing the results of other tests. The gradation test showed that the amount of clay and silt in restoration adobes was higher than in historical adobes and the latter had a more homogeneous and similar gradation than the former. It must be noted that the restoration samples have a finer-grained structure, with less coarse grains and particles than the historical samples. Following that, the results of the porosity and density tests showed that because the restorative adobes have more clay and silt particle (fine-grained particle), they have higher compression and lower porosity rates.

Considering the results of these two tests, we now set out to evaluate the vulnerability conditions of adobes against damaging elements simulated in a laboratory environment. Based on the capillary test, it must be noted that water rise pace, time and complete saturation in historical adobes were the same as they have similar gradation and porosity but the results of the same test proved opposite for the restoration adobes because they have completely different gradation. High capillary speed in the restoration adobes is explicable, provided their gradation and porosity percentage. But in A-R2-S sample the capillary speed dropped sharply, in a way that it took more than 600 minutes for the sample to become fully saturated. The reasons behind this might be the low amount of clay particles in its structure compared to other restoration samples, the high compression and density rate (low porosity) of constituent particles which resulted in a reduction in its voids and capillary tubes.

In the water immersion test, which was somehow similar to the capillary test, the restoration adobes experienced speedy destruction and decomposition and the reason for this, like the capillary test, is the gradation and the porosity of the samples. A high amount of clay in the structure of an adobe means more water absorption and consequently significant swelling of the adobe. The dry samples showed acceptable cohesion and resistance in the abrasion resistance and compression strength tests. The same test on the adobes sample which were first water-saturated and then dried showed their resistance was greatly reduced. This is because when moisture is absorbed by the clay building materials (adobe), it penetrates into the pores and holes of these materials and leads to their swelling; once the water evaporates, the swelling is irreversible, thus leading to the decomposition of their original unity and to the separation of their cohesive particles. The rain-wash test which was conducted through the artificial rain in order to determine the resistance of adobes against precipitation, showed that the historical samples had a better resistance against the rain-wash element that the restoration samples; the latter showed high absorption of water over the one minute interval of the test and consequently showed quick decomposition of their surface layers. The presence of hay and animal dung in the structure of the historical adobes must also be investigated in order to determine its role in the overall resistance of the adobe.

CONCLUSION

Every study or research conducted in the protection and restoration of historical buildings can be useful for that monument and serve as a paving ground for future research. The present study was a research project which was based on the laboratory sciences standards in the field of restoration and research in building materials, and will serve as a foundation for future research and studies in the building materials of Saam Castle and similar monuments. One of the main objectives of this research was to get results on the influence of environmental and weather conditions on restoration adobes and to reduce their vulnerability.

Based on the results of the tests conducted, although the same source for the soil of adobes was used, the restoration and historical adobes showed quite different structure and gradation which explained their different reactions towards damaging elements. Despite featuring a better unity and higher density due to their high-clay and fine-grained structure, the restoration adobes proved more vulnerable to moisture induced damage than the historical adobes. However, the soil's quality used in future projects can be improved through modifying their constituent components and gradation, in order to both minimize their vulnerability and to reproduce their original structure. Variable amounts of hay and animal dung can also be added to gain better results in their resistance against moisture induced damage.

We emphasize once more that any future restoration projects need to be based on scientific research and experiments.

ACKNOWLEDGEMENTS
A part of this research was conducted using the UOZ-GR-9618-13 grants and researchers would like to express their gratitude to the University of Zabol for the research grants awarded. E-mail address: hsarhaddi@uoz.ac.ir.

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ABREVIERI / ABRÉVIATIONS / ABBREVIATIONS

AAC – Acta Archaeologica Carpatica, Kraków
ACMI – Anuarul Comisiunii Monumentelor Istorice, Bucureşti
ACSS – Ancient Civilisations from Scythia to Siberia, Leiden
ActaArch – Acta Archaeologica. København
ActaArchHung – Acta Archaeologica Academiae Scientiarum Hungaricae, Budapest
AJA – American Journal of Archaeology, Boston
Alba Regia – Alba Regia. Annales Musei Stephani regis, Székesferhérvár
Altertum – Das Altertum, Deutsche Akademie der Wissenschaften zu Berlin Sektion für Altertumswissenschaft Akademie der Wissenschaften der DDR Zentralinstitut für Alte Geschichte und Archäologie, Berlin
Aluta – Aluta. Revista Muzeului Național Secuiesc Sfântu Gheorghe
AM – Mitteilungen des Deutschen Archäologischen Instituts, Athenische Abteilung, Berlin
AMI(T) – Archäologische Mitteilungen aus Iran (und Turan)
ANRW – *Aufstieg und Niedergang der römischen Welt. Geschichte und Kultur Roms im Spiegel der neueren Forschung*, Berlin – New York, 1972–1998
Antaeus – Antaeus. Communicationes ex Instituto Archaeologico Academiae Scientiarum Hungaricae, Budapest
Antiquity – Antiquity. A Review of World Archaeology, Durham, UK
Anuarul MJIAP– Anuarul Muzeului Județean de Istorie și Arheologie Prahova, Ploiești
AnUCraiova – Analele Universităţii din Craiova
AnUVT – Annales d'Université "Valahia" Târgoviște, Section d'Archéologie et d'Histoire
Apulum – Acta Musei Apulensis. Muzeul Naţional al Unirii, Alba Iulia
ARA – Annuaire Roumain d'Anthropologie
ArchBulg – Archaeologia Bulgarica, Sofia
ArchÉrt – Archaelogiai Értesítő. A Magyar Régészeti és Művészettörténeti Társulat tudományos folyóirata, Budapest
ArchHist – Archeologia Historica, Brno
ArchKorr – Archäologisches Korrespondenzblatt, Mainz
ArchRozhledy – Archeologické Rozhledy, Praha
Area – Area, Royal Geographical Society, London
ArheologijaSofia – Arheologija. Organ na Archeologičeskija Institut i Muzej, Sofia
ArhMold – Arheologia Moldovei, Iași
ArhVestLjubljana – Arheološki vestnik. Inštitut za arheologijo ZRC SAZU, Ljubljana
ASC – Archeologica Slovaca Catalogi, Bratislava
AVANS – Archeologické Vyskumy a Nálezy na Slovensku, Nitra
BARIntSer – British Archaeological Reports. International Series, Oxford
BARSupSer – British Archaeological Reports. Supplementum Series, Oxford
BASOR – Bulletin of the American Schools of Oriental Research, University of Chicago
BCH – Bulletin de Correspondance Hellénique, Athènes-Paris
BiblIstrPont-SA - Biblioteca Istro-Pontică. Seria Arheologie. Institutul de Cercetări Eco-Muzeale „Gavrilă Simion”, Tulcea
BiblMemAnt – Bibliotheca Memoriae Antiquitatis, Piatra-Neamţ
BiblMusNap – Bibliotheca Musei Napocensis, Cluj-Napoca
BiblMuzNaț-SCP – Biblioteca Muzeului Naţional – Seria Cercetări Pluridisciplinare, Bucureşti
BiblThrac – Bibliotheca Thracologica, Bucureşti
BiEtud IFAO –Bibliothèque d'étude, Institut français d'archéologie orientale, le Caire
BMJT – Buletinul Muzeului Judeţean Teleorman, Alexandria
Bonner Jarbücher – Bonner Jahrbücher des Rheinischen Landesmuseums in Bonn, Bonn
BSA – British School at Athens, Athens
BSNR – Buletinul Societăţii Numismatice Române, Bucureşti
CA – Cercetări arheologice, București
Caiete ARA – Caietele ARA, Revistă de Arhitectură, Restaurare şi Arheologie, Asociaţia ARA, Bucureşti
CAPH – Cemeteries of the Avar Period (567–829) in Hungary, Budapest
Carpica – Carpica. Complexul Muzeal „Iulian Antonescu” Bacău, Bacău

CCA – Cronica Cercetărilor Arheologice din România, Bucureşti
CCDJ – Cultură şi Civilizaţie la Dunărea de Jos, Călăraşi
ClAnt – Classical Antiquity, University of California, Berkeley
Collegium Antropologicum – Collegium Antropologicum. Journal of the Croatian Antropological Society
Crisia – Crisia. Muzeului Ţării Crişurilor, Oradea
Dacia – Dacia (Nouvelle Série). Revue d'archéologie et d'histoire ancienne. Académie Roumaine. Institut d'archéologie « V. Pârvan », Bucarest
DMÉ – A Debreceni Déri Múzeum Évkönyve, Debrecen
Documenta Praehistorica – Documenta Praehistorica, University of Ljubljana, Faculty of Arts, Department of Archaeology, Ljubljana
Drobeta – Drobeta. Muzeul Regiunii Porților de Fier, Drobeta-Turnu Severin
EphemNap – Ephemeris Napocensis. Academia Română, Institutul de Arheologie şi Istoria Artei, Cluj-Napoca
ERAUL – Études et Recherches archéologiques de l'Université de Liège
eTopoi – Journal for Ancient Studies, Berlin
EurAnt – Eurasia Antiqua. Deutsche Archäologisches Institut, Berlin
Expedition – Expedition. The Magazine of Archaeology, Anthropology
FAH – Fontes archaeologici Hungariae, Budapest
FolArch – Folia Archaeologica. A Magyar Nemzeti Múzeum Évkönyve. Annales Musei Nationalis Hungarici, Budapest
Gallia – Gallia. Archéologie de la France antique
Germania – Germania. Anzeiger der Römisch-Germanischen Kommission des Deutschen Archäologischen Instituts, Frankfurt
Gladius – Gladius. Estudios sobre armas antiguas, armamento, arte militar y vida cultural en Oriente y Occidente, España
GNMP – Glasnik Narodnog muzeja Pančevo, Pančevo
GSAD – Glasnik Srpskog arheološkog društva, Beograd
Gymnasium – Gymnasium. Zeitschrift für Kultur der Antike und humanistische Bildung
Habis – Habis. Arqueología, filología clásica, Universidad de Sevilla
Hesperia – Hesperia. Journal of the American School of Classical Studies at Athens, Cambridge
Historia – Historia. Zeitschrift für Alte Geschichte, Franz Steiner Verlag, Stuttgart
Histria archaeologica – Histria archaeologica. Časopis Arheološkog muzeja Istre, Pula, Croatia
HMÉ – A Hajdúsági Múzeum Évkönyve, Hajdúböszörmény
IAA Reports – Israel Antiquities Authority Publications, Israel
Ialomița – Ialomița. Studii de cercetări de arheologie, istorie, etnografie și muzeologie, Slobozia
IARPotHP – International Association for Research on Pottery of the Hellenistic Period e. V.
IJA – International Journal of Archaeology
IJO – International Journal of Osteoarchaeology, Journal online
Iran – Journal of the British Institute of Persian Studies
Istros – Istros, Muzeul Brăilei, Brăila
IzvestijaSofia – Izvestija na Nacionalnija Arheologičeski Institut, Sofia
JAMÉ – A nyíregyházi Jósa András Múzeum Évkönyve, Nyíregyháza
JAS – Journal of Archaeological Science
JDAI – Jahrbuch des Deutschen Archäologischen Instituts, Deutsches Archäologisches Institut, Berlin
JEMAHS – Journal of Eastern Mediterranean Archaeology and Heritage Studies, Pennsylvania State University
JFA – Journal of Field Archaeology
JHRE – Journal of Housing and Rural Environment, Iran
JNES – Journal of Near Eastern Studies
JPMÉ – A Janus Pannonius Múzeum Évkönyve, Pécs
JRGZM – Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz, Mainz
Klio – Klio. Beiträge zur Alten Geschichte, Berlin
Kühn-Archiv – Kuhn-Archiv. Arbeiten aus dem Landwirtschaftlichen Institut der Universität Halle
MAIASK – Materialy po arheologii i istorii antichnogo i srednevekovogo Kryma, Moskva – Tyumen – Nizhnevartovsk
MAInstUngAK – Mitteilungen des Archäologischen Instituts der Ungarischen Akademie der Wissenschaften, Budapest
MAN – MAN. Journal of the Royal Anthropological Institut, London
Marisia – Marisia. Studii şi materiale. Arheologie – Istorie – Etnografie. Târgu Mureş
MCA – Materiale şi Cercetări Arheologice, Bucureşti
MEFRA – Mélanges de l'Ecole française de Rome. Antiquité, Roma

MFMÉ-SA – A Móra Ferenc Múzeum Évkönyve – Studia Archaelogica, Szeged
MHÁS – Magyarország honfoglalás kori és kora Árpád-kori sírleletei, Miskolc–Budapest–Szeged–Szombathely
Minerva – Minerva. Revista de filología clásica, Universidad de Valladolid
Monographie du CRA – Monographie du Centre de Recherches archéologiques, Valbonne
MŐTK – Magyar Őstörténeti Témacsoport Kiadványok. Magyar Tudományos Akadémia Bölcsészettudományi Kutatóközpont, Budapest
Mousaios – Mousaios. Buletinul Ştiinţific al Muzeului Judeţean Buzău
MR – Magyar Régészet. Online Magazin (Archaeolingua)
NM – Natura Montenegrina, Podgorica
Oltenia – Oltenia. Studii și Comunicări, Craiova
Padusa – Padusa. Bolletino del Centro polesano di studi storici, archeologi et etnografici, Rovigo
PamArch – Památky Archeologické, Praha
Peuce – Peuce, Studii şi cercetări de istorie şi arheologie, Institutul de Cercetări Eco-Muzeale, Tulcea
Phoenix – Phoenix. The Journal of the Classical Association of Canada
Pontica – Pontica. Studii şi materiale de istorie, arheologie şi muzeografie, Muzeul de Istorie Naţională şi Arheologie Constanţa
PZ – Präehistorische Zeitschrift, Berlin-Mainz
Quaternary International – Quaternary International. The Journal of the International Union for Quaternary Research
RA – Revue Archéologique, Paris
Radiocarbon – An International Journal of Cosmogenic Isotope Research, Cambridge
RÉL – Revue des études latines
RMM.MIA – Revista Muzeelor şi Monumentelor, seria Monumente Istorice şi de Artă, Bucureşti
RMV – Rad muzeja Vojvodine, Novi Sad
RT – Régészeti Tanulmányok. A Közép-Duna-medence honfoglalás- és kora Árpád-kori sírleletei, Budapest
RVM – Rad vojvođanskih muzeja, Novi Sad
SAM – Studia Archaeologica et Mediaevalia, Bratislava
Sargetia – Sargetia. Acta Musei Devensis, Buletinul Muzeului judeţean Hunedoara, Deva
SAP – Studia ad Archaeologiam Pazmaniensia. A PPKE BTK Régészeti Tanszékének kiadványai, Budapest
SCA – Studii și Cercetări de Antropologie, București
SCIV(A) – Studii şi Cercetări de Istorie Veche (şi Arheologie), Bucureşti
SCN – Studii şi Cercetări de Numismatică, Bucureşti
SlovArch – Slovenská Archeológia, Nitra
SP – Studii de Preistorie, Bucureşti
Starinar – Starinar. Arheološki institut Beograd
StCl – Studii Clasice, București
Studia Hercynia – Studia Hercynia, Univerzita Karlova
Studia praehistorica – Studia praehistorica, National Institute of Archaeology with Museum, Sofia
Študnijné zvesti – Študijné zvesti. Archeologického ústavu Slovenskej akadémie vied, Nitra
Syria – Syria. Revue d'art oriental et d'archéologie
Th-D – Thraco-Dacica, București
Tisicum – A Jász – Nagykun – Szolnok Megyei Múzeumok Évkönyve, Szolnok
TNYSc – Transactions of the New York Academy of Sciences, New York
Transilvania – Transilvania. Centrul Cultural Interetnic Transilvania, Sibiu
TRW – Transformation of the Roman World, Leiden
TYCHE – TYCHE. Beiträge zur Alten Geschichte, Papyrologie und Epigraphik
Tyragetia – Tyragetia. Anuarul Muzeului Naţional de Istorie a Moldovei, Chişinău
VAH – Varia Archaeologica Hungarica V. Redigit Csanád Bálint. Publicationes Instituti Archaeologici Academiae Scientiarum Hungaricae, Budapest
Valachica – Valachica. Studii şi cercetări de istorie şi istoria culturii, Complexul Muzeal Naţional Curtea Domnească Târgovişte
VAMZ – Vjesnik Arheološkog muzeja u Zagrebu, Zagreb
ŽA – Živa Antika / Antiquité Vivante. Društvo za antički studii na SRM, Seminar na klasična filologija, Filozofski fakultet, Skopje
ZAM – Zeitschrift für Archäologie des Mittelalters, Bonn
ZfA – Zeitschrift für Archäologie, Berlin
Ziridava – Ziridava. Studia Archaeologica. Complexul Muzeal Arad

ZMS – Zbornik muzeja Srema, Sremska Mitrovica
ZNM Beograd – Zbornik Narodnog Muzeja, Beograd