J. Agr. Sci. Tech. (2010) Vol. 12: 91-98

Soil Data Comparison in the Old *vs.* Restored Sections of the Bam Citadel Archeological Site in Kerman, Iran

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ABSTRACT

Soil data can be very significantly informative in archeological and anthropological studies. Bam Citadel (BC), as the largest and oldest earthen (non baked brick) monument of the world has been restored for several times, but no data have yet been available surrounding the materials employed in the restoration work. Bam Citadel (BC) was almost totally destroyed by the severe earthquake of December 26th, 2003. A detailed knowledge concerning the old sun-dried cobs and the architecture of the exposed parts could be essential for a better ongoing as well as future restoration. Some old parts of the citadel have been exposed following the devastating earthquake. A micromorphological, physico-chemical, mineralogical and sulfur isotope geochemistry study was carried out to compare the characteristics of the soil samples obtained from the previously restored *vs.* those of the exposed old parts of the BC. The results indicated that the electrical conductivity differs widely between the samples obtained from the exposed old parts and those obtained from the restored parts (6.4 dS m^{-1} and 42.4 dS m^{-1} respectively). This indicates that a saline soil (EC 42.4 dS m^{-1}) has been used in the recent restoration work, while the old non saline cobs' building material, used by original builders, are thought to have been brought from other non saline areas. Smectite, illite, kaolinite and palygorskite were determined as the predominant clay minerals. Massive microstructure was found as dominant in all the samples, but igneous microlites and gypsum crystals were observed only in the repaired parts. The soil matrix from the old parts was found to be high in organic matter.

Keywords: Bam Citadel, Central Iran, Kerman, Micromorphology, Soil mineralogy, Sulfur geochemistry.

INTRODUCTION

Bam Citadel (BC), as one of the most outstanding cultural and historical monuments, is the largest and the oldest non baked brick example of earthen architecture and constructions in the world. No exact date of construction has been reported, but the citadel seems to date back to 2,500 years ago (Pirnia, 1983). Bam Citadel is located 193 km southeast of the city of Kerman in central Iran. The area under the citadel is reported as about 20 ha (Ayatollah Zadeh Shirazi, 1994). BC has been a living place of people for most of its life time, but about 150 years ago the ruling government encouraged the people to leave the site in order to protect it as a historical monument.

BC was almost totally destroyed by the earthquake recording 6.3 on Richter scale of a duration of 12 seconds that occurred on December 26th, 2003. Devastation of this historic monument revealed that it has been repeatedly destroyed and rebuilt through time. Ten important restoration processes have been reported by Poorbehzadi (1991) on BC starting from Achaemenian (500 B.C.) to Safavid period (400 AD).

BC is built up by use of two distinct types of construction materials, namely: adobe (non baked brick) masonry, known in Persian as "*Khesht*" and built up earth or cob constructions, known as "*Chineh*". Most of

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[DOR: 20.1001.1.16807073.2010.12.1.2.8]

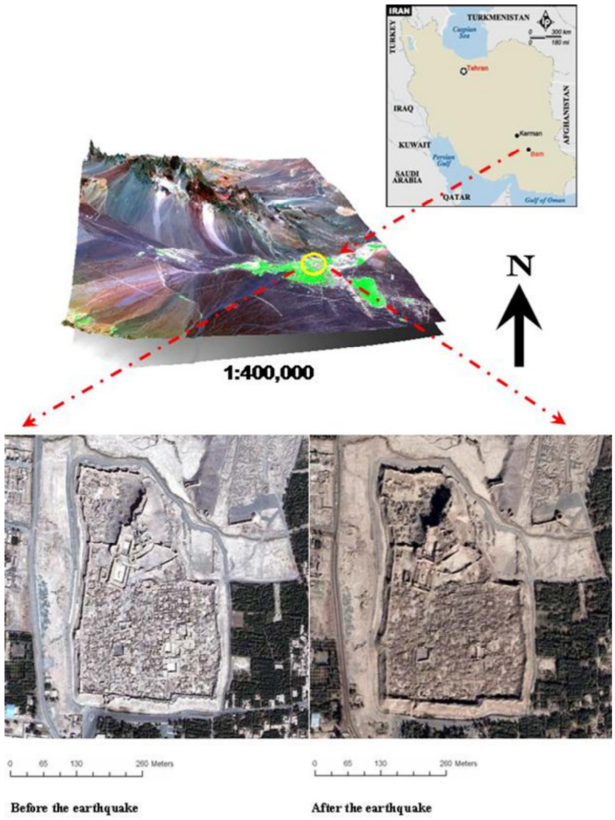

Figure 1. Location of the study area in Southeast Iran**.**

the restoration work has been carried out over the past 25 years. The final step in this restoration process was to plaster the exterior surfaces of Chineh with a layer of straw-reinforced mud plaster. Most of the modern-day restoration work appears to have been done with square sun-dried bricks (Khesht), rather than with Chineh (Langenbach, 2004).

Those structures that had been either maintained, or repeatedly modified and strengthened as well as restored during the late 20th century were more seriously damaged as a result of the 2003 earthquake than did those ancient structures that had not been somehow worked on. The reason for this difference was probably due to the fact that the newer Khesht covering often failed as a result of the internal collapse of the older Chineh on which the covering was founded. If the inner layers shift and settle in response to earthquake vibrations, the outwardly directed pressure could lead to a blowing out of the walls at their bases, causing collapse of the whole structures (Langenbach, 2004).

Due to the historical significance of BC as well as BC's importance in the tourist industry of Iran, it is recommended to obtain the needed information concerning the history and mechanisms involved in BC restoration undertakings. The present research was conducted to make a comparison between the old (Chineh) and the new restoring mud bricks (Khesht) employed in BC, and to find out if soil data can play any substantial role in furthering the fruitfulness of archeological studies in the area.

MATERIALS AND METHODS

Figure 1 depicts the location of Bam Citadel (BC), 193 km southeast of the provincial city of Kerman. Ten building material soil samples from old parts exposed

[DOR: 20.1001.1.16807073.2010.12.1.2.8]

due to the recent earthquake (Chineh) and from the previously restored parts (Khesht) of the citadel were collected. Both old cobs exposed by earthquake and the previously restored adobes underwent mineralogical, micromorphological, sulfur isotope, and physico-chemical analysis.

Air-dried samples were crushed and ground before being passed through a 2-mm sieve. Such routine physico-chemical properties as particle size distribution (pipette method), calcium carbonate equivalent content (back titration), organic carbon percentage, pH, and EC were determined (Page *et al.,* 1992).

For mineralogical study, selected samples were first repeatedly washed to have gypsum and soluble salts removed. Carbonates and Fe-oxides were then removed by use of 1M sodium acetate buffer solution (pH 5) and dithionate citrate bicarbonate (DCB), respectively (Jackson, 1979). The clay fraction of the samples was separated through centrifuging as described by Jackson (1979). Five treatments were done on each sample, namely Mg-saturated, Mg-saturated and ethylene glycol, K-saturated, K-saturated and heated at 350^{o}C, as well as K-saturated and heated at 550^{o}C. Slides were analyzed using a Siemens X-ray diffractometer with Cu kα radiation operated at 40 kV and 40 mA.

Several samples related to old as well as to restored parts were mounted on Al stubs and coated with gold for Energy Dispersive X-ray spectrometry (EDX) and SEM observations using XL 30 ESEM Philips microscope.

To perform Transmission Electron Microscopy (TEM) studies, diluted suspensions of selected clay samples were transferred to Cu grids coated with Formwar and studied by a TECNAI, F20, Philips TEM at an accelerating voltage of 60 kV.

Undisturbed samples were saturated and hardened by a vestapol resin and the prepared thin sections observed through an Olympus BH1 petrographic microscope for micromorphological studies.

All forms of sulfates (soluble as well as mineral forms) were converted to pure $BaSO_4$ for $\delta^{34}S$ analysis according to the method described by Dowuouna *et al*. (1992). An elemental analyzer coupled with a mass spectrometer was used as an on-line sulfur isotope determination technique (Giesemann *et al.,* 1994). NBS-127 with $\delta^{34}S$ value of $+21.1^{0}/_{00}$ was used as standard.

RESULTS AND DISCUSSION

Table 1 shows some of the physico-chemical properties as well as sulfur isotope composition of the previously restored (adobe) *vs.* old exposed (cob) samples. The old parts contain more clay (about twice) than the restored parts. Due to higher stickiness and plasticity of clay particles as compared to sand and silt, it seems that the original builders of Bam Citadel (BC) were completely aware of the constructive and beneficial clay properties as demonstrated by their old cobs carrying more clay content than the restored bricks of the later times, and thus resisting more against earthquakes. On the other hand, the electrical conductivity of the building materials of the restored parts is seven times that of the building materials of the old parts (about 42 dS m^{-1} in restored parts as compared with 6.4 in the untouched old parts). Although mean annual precipitation of the area is about 60 mm which is very low, but due to high electrical conductivity of the restored bricks and high solubility of salts, the restored bricks may not be resistant enough to external effects through a lapse of time. This conclusion is supported by similar findings by Langenbach (2004). He has reported that those structures of the Bam Citadel that had been restored during the late 20th century were more seriously damaged by earthquake than the ancient structures that had not been put to restoration.

Table 1. Comparison of some of the Physico-chemical properties and δ ^{34}S values between the old and restored parts.

	δ^{34}S (%)	$CaCO_3$ (%)	Sand (%)	Silt (%)	Clay (%)	EC (dS m^{-1})	pH	Organic matter (%)
Restored parts	14.7±1.2	14.8±0.85	37±2.5	47±3.2	16±1.2	42.4±2.1	7.4±0.98	0.4±0.02
Old parts	7.7±0.44	15.8±0.91	30±2.61	37±3.4	33±1.52	6.4±0.5	8.1±1.1	0.7±0.05

Data are means of five samples±standard deviation.

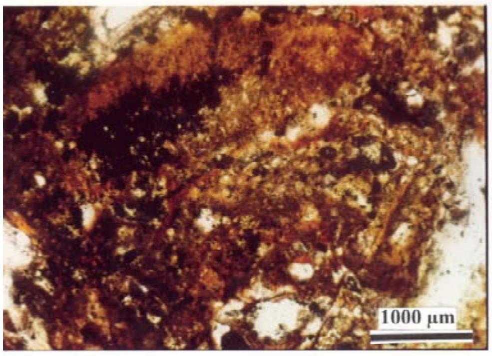

Figure 2. Organic matrix of the old parts (Plain Polarized Light).

Soils of the area around BC are highly saline and gypsiferous (Moghiseh *et al.,* 2007). As the archeologists have picked up the saline soils of the surrounding area for recent restorations, it can verifiable be concluded that the original founders of BC may have carried in non-saline soils (of a higher clay content) to the area from other regions for building up of BC.

The restored bricks (adobes) were reinforced by straw, while shredded date palm tree was used for reinforcement of the old cobs. The timbers were placed in the wall not to provide a frame, but to resist the propagation of cracks and the lateral spreading movement of the masonry. Palm timber is more resistant than straw, as observed through an increased termite population in the modern bricks reinforced by straw. The insects had succeeded in separating the different vertical segments apart from each other and reducing the cohesion of the inner core of the walls (Langenbach, 2004). Moreover, the straw ends up at the joints between adobes, leaving no substantial coherence across joints between individual adobes in restored parts. The role of date palm segments used in the old cobs is like steel in the fortified concrete structures of the present day.

The results of this research (Table 1) show that organic carbon content in the old parts of the citadel is about twice that in the repaired parts. A substantial amount of straw was found in the restored parts as additive to make the bricks more coherent. The date palm logs inserted in the old walls have been decomposed through time not being visible in the present samples now. Comparing micromorphological thin sections of the old *vs.* the restored parts, it can easily be seen that the

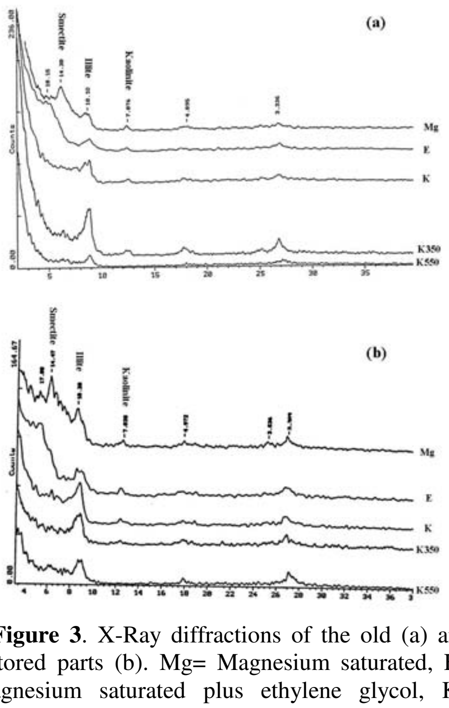

Figure 3. X-Ray diffractions of the old (a) and restored parts (b). Mg= Magnesium saturated, E= Magnesium saturated plus ethylene glycol, K= Potassium saturated, K350= Heated up to 350 degrees and K550= Heated up to 550 degrees.

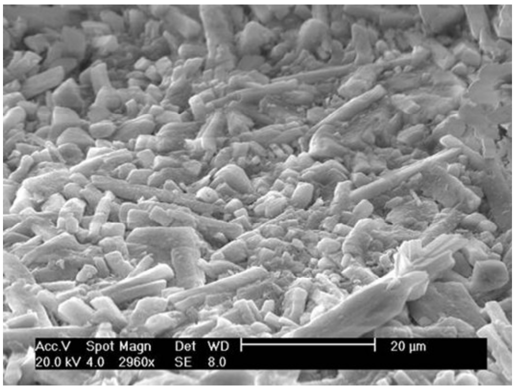

Figure 4. Scanning electron micrograph of restored parts showing different forms of gypsum crystals.

matrix of the old parts contains a higher level of organic matter as well as some papule-like organic materials (Figure 2). On the other hand, the organic material plays a reinforcing role in making cobs coherent. The straw used in the restored parts is rapidly used up by insects and could not act as reinforcing material. Besides, cracks may also appear in the newly repaired parts which may further decrease the cohesion of the new restored parts, also reported by Langenbach (2004). Few differences in $CaCO_3$ content and pH among the samples were observed which are not of much significance to be further discussed.

Illite, kaolinite, and low crystalline smectite were detected in either one of the samples (old *vs.* restored) in XRD studies (Figure 3). Smectite and illite have been reported as pedogenic clay minerals in soils of Iran (Abtahi, 1980; Khademi and Mermut, 1998; Farpoor *et al.,* 2002a). Kaolinite seems to be a mineral inherited from the parent material in Bam arid area as also reported in Kerman soils with an almost similar climate (Farpoor *et al.,* 2002a).

An examination of the restored parts through SEM, revealed many rod-like, columnar, and prismatic gypsum crystals (Figure 4) with palygorskite bundles also observed surrounding the gypsum crystals (Figure 5a). Mg/Si ratio obtained through EDX analyses also proves the presence of palygorskite in the restored brick samples (Figure 5b). TEM studies also show some palygorskite crystals in

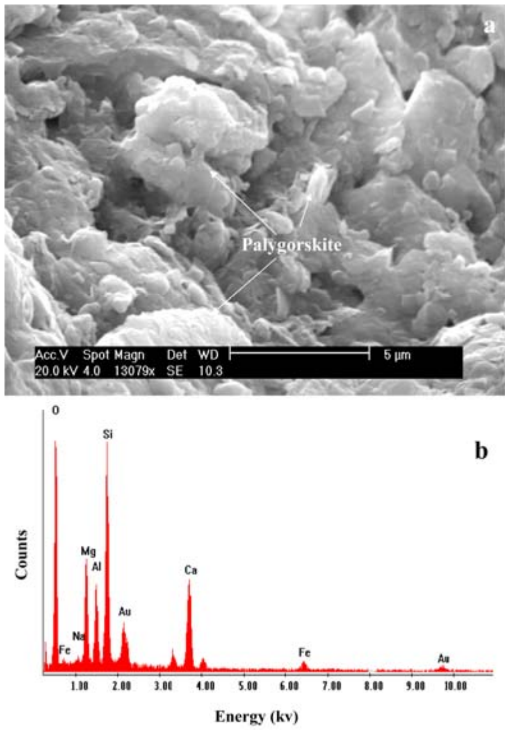

Figure 5. (a) Scanning electron micrograph of restored parts showing palygorskite bundles around gypsum crystals, (b) EDX plot showing Mg/Si ratio of palygorskite.

the clay suspensions of the restored parts (Figure 6a). The presence of palygorskite around gypsum crystals in central parts of Iran is reported by Khademi and Mermut (1998) as well as by Farpoor *et al.* (2002a).

Palygorskite formation is due to an increase of Mg/Ca ratio following gypsum crystallization in the closed water bodies of central Iran. Very few palygorskite crystals were observed using SEM and TEM in the old parts of the citadel (Figure 6b). This suggests that old soils likely came from an area with less palygorskite but more smectite. This may also suggest a different environment under which the soils had been formed.

Micromorphological observations showed a massive microstructure in either one of the old or restored thin sections as they both are related to coherent sun-dried earthen materials. Some gypsum crystals were only found in the restored parts (Figure 7a). Since the restored bricks (similar to soils of the area) are saline

[DOR: 20.1001.1.16807073.2010.12.1.2.8]

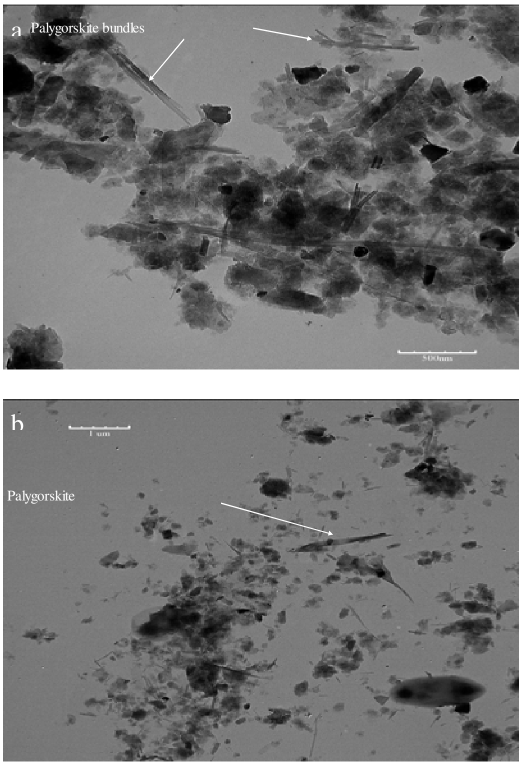

Figure 6. Transmission electron micrographs showing palygorskite crystals in restored (a) and old parts (b).

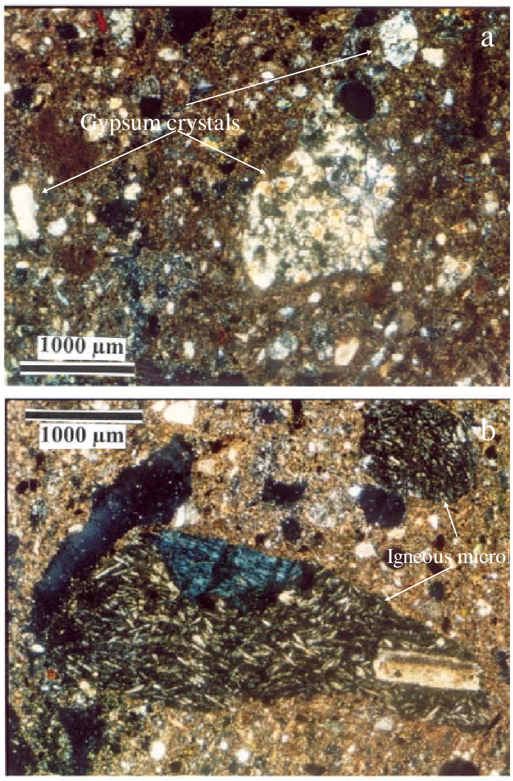

Figure 7. Thin sections of the restored parts showing gypsum nodules (a) and igneous microlites (b), both sections in Crossed Polarized Light.

and gypsiferous while no gypsum found in thin sections of the old bricks, this may lead one to the conclusion that soil needed for the construction of old cobs was carried into the area from elsewhere. This supports the before mentioned idea concerning the difference in clay content of the old and restored samples. Some igneous microlites were observed only in restored parts (Figure 7b) which might be further evidence for a different origin of bricks and that soils of the old cobs have a different source.

The $\delta^{34}S$ values of sulfates in the samples related to the old and restored parts are $7.7^0/_{00}$ and $14.7^0/_{00}$, respectively. Since precipitation during cooler temperatures is depleted in heavy isotopes (Craig, 1961; Fontes, 1980; Gat, 1980; Khademi *et al.,* 1997; Farpoor *et al.,* 2004), it seems that the old parts with lighter sulfur isotopes were formed during a climate of lower temperature and/or higher precipitation. This is also another support for a lower EC, higher organic matter and less palygorskite content of the old parts as they have experienced a higher available moisture of the past. The soils used to make old structures were not subject to later isotopic fractionation since they have been changed into massive cobs. On the other hand, no climatic change is reported to have taken place during this period of time. So, the idea that the building soils of the old cobs have been brought over from elsewhere with a different climate is hereby further supported. If the sulfur isotopic composition of the soils near the area were available, it could probably shed more light on the source of soils used for the construction of old cobs by the original founders. However, the $\delta^{34}S$ value of 14.7 for the restored samples is quite close to isotopic values of the soil sulfates of the recently analyzed samples (Khademi *et al.,* 1997; Farpoor *et al.,* 2002b). The reason is probably that a saline soil containing sulfates and gypsum mixed with straw were used to put the

BC damaged parts into restoration. One of the most important parameters in making sun-dried earthen constructions is believed to be the low cost, as they are made up of building materials readily available in the close vicinity. It becomes evident that the original builders have obtained non saline soils from other areas despite the rising expenses to construct BC. This may further be due to the higher shear strength and better mechanical properties of such soils. To investigate the reasons, in more detail other studies seem indispensable.

CONCLUSIONS

Saline soil containing soluble salts and gypsum mixed with straw has been chosen as building material in the restoration of BC. Soils used in the restored parts are much more saline than those of the old parts. The building materials of the old parts also contain more organic matter than those in the new restored sections. Smectite, illite and kaolinite are the dominant clay minerals found in both the restored as well as in the old building materials' samples.

Following the 2003 earthquake, the citadel has been under restoration. A fully thorough knowledge of the old sun-dried cobs and of the architecture of the exposed parts is very essential for better and longer lasting restoration operations. The study's results confirm the fact that the information obtained from soil science data could be highly and significantly helpful in archeological as well as in anthropogenic studies.

ACKNOWLEDGEMENTS

Physico-chemical analyses of the samples were financially supported by the Department of Soil Science, Faculty of Agriculture, Shahid Bahonar University of Kerman, Iran, for which the author is thankful. Support from Natural Sciences and Engineering Research Council of Canada (NSERC) given to Prof. H. Roy Krouse along with his further financial assistance in carrying out the electron microscopy and stable isotope geochemistry analyses are gratefully acknowledged and appreciated.

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مقایسه نتایج خاکشناسی بخشهای قدیمی و مرمت شده ارگ تاریخی بم در منطقه کرمان، ایران

م. ه. فرپور

چکیده

اطلاعات خاکشناسی می توانند در مطالعات باستان شناسی و انسان شناسی بسیار مهم باشند. ارگ بم به عنوان بزرگ ترین و قدیمی ترین بنای خشت و گلی جهان بدفعات زیاد مرمت شده اما اطلاعی درباره موادی که جهت مرمت بکار رفته گزارش نگردیده است. ارگ بم در اثر زلزله شدید ۲۶ دسامبر ۲۰۰۳ تقریبا تخریب گردید. اطلاعات تفصیلی در مورد خشتهای حرارت ندیده قدیمی و معماری بخشهای رخنمون شده می تواند به مرمت بهتر این بنا کمک نماید. برخی از قسمتهای قدیمی ارگ پس از زلزله رخنمون شد. خصوصیات میکرومرفولوژیکی، فیزیکی-شیمیایی، کانی شناسی و ژئوشیمی ایزوتوپ گوگرد بین نمونه های جمع آوری شده از بخشهای قبلا مرمت شده ارگ و بخش های رخنمون شده در اثر زلزله مقایسه گردید. نتایج نشان داد که هدایت الکتریکی در نمونه های قدیمی رخنمون شده و بخشهای مرمت شده کاملا متفاوت است (به ترتیب ۶/۴ و ۴۲/۴ دسی زیمنس بر متر). این نتایج نشان می دهند که اخیرا یک خاک شور (هدایت الکتریکی ۴۲/۴ دسی زیمنس بر متر) جهت مرمت بکار رفته است درحالیکه خاک غیر شوربکار رفته برای ساخت خشتهای قدیمی احتمالا توسط سازندگان اولیه ارگ از جای دیگری به منطقه آورده شده است.کانی های رسی اسمکتیت، ایلیت، کائولینیت و پالیگورسکیت از جمله کانی های رسی غالب بودند. در کلیه نمونه ها، ریز ساختمان توده ای مشاهده گردید اما بلورهای گچ و میکرولیت های آذرین تنها در بخشهای مرمت شده یافت شدند. میزان مواد آلی در زمینه (ماتریکس) خاک مربوط به بخش های قدیمی زیاد بود.

[DOR: 20.1001.1.16807073.2010.12.1.2.8]