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Original article

AN EVALUATION STUDY ON THE REASSEMBLY OF INSCRIBED STONE PIECES IN THE GRAND EGYPTIAN MUSEUM

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Abstract:
This research paper presents an applied study of reassembling inscribed stone pieces in the Grand Egyptian Museum. It covered one of the large archaeological limestone blocks divided into three parts. It was carried out in Saqqara excavations from the Kyiri Tomb, which dates back to the Eighteenth dynasty, numbered (1517GEM-CC) in the records of the Grand Egyptian Museum. The study was divided into two parts. First, inspection and analysis were carried out to identify the composition and components of blocks, damage, and previous restorations using ultraviolet microscopic imaging by a USB digital microscope, analysis by X-ray diffraction (XRD), and infrared spectroscopy (FTIR). Second, the engraved stone blocks were dismantled and reassembled using Araldite 1092 as an adhesive and Acryl 33 with stone powder as a binder after evaluating the use of Paraloid 72 immediately after revealing the defects of this previous assembly. The work stages included documentation using Auto CAD and the use of reflection transformation imaging (RTI).

1. Introduction

In the context of the Grand Egyptian Museum, a monumental endeavor aimed at housing and exhibiting Egypt's extensive collection of ancient artifacts. The evolution of reassembling techniques becomes paramount. This paper presented an evolution of the application of reassembling methodologies by Araldite 1092 on limestone in the Grand Egyptian Museum. For instance, it investigated different methods for identifying and classifying fragmentary pieces and proposing a comprehensive approach that incorporates materials analysis to aid in the accurate reassembly of stone objects [1]. The reassembly of broken archaeological stones is an open and complex problem, which remains the scientific process of extreme interest to the archaeological community. It depends on various aspects, such as the matching process of the broken surfaces, the outline of shreds or their inscriptions and geometric characteristics, and the corners of their contour beside the deterioration and physical-mechanical change of the forces of these stone carvings. Thus, the conservation and reassembly of such types of large objects are particularly challenging because of their uncontrollable size and heavy weight [2]. Additionally, some examples are worthy of mentioning related to the assembly of stone parts, mentioned using stainless-steel anchors of grade SS-304 to connect the two segments of the obelisk and the bottom part to the elevated steel frame for resisting the obelisk's weight and the seismic lateral loads. This Obelisk belonged to Ramses II and was found in San Elhagar [3]. A study explored the assessment of adhesive materials and techniques for physical reassembly, aiming to identify the most suitable adhesives that ensure structural stability while minimizing the visual impact [4]. Adhesives can cure in several ways, such as when they lose their solvent or carrier through evaporation (e.g., gums). Hot-melt adhesives (e.g., pine resin) are set when the material cools and solidifies. In situ, chemical processes like polymerization can also cause curing (e.g., linseed oil) or hydration and hydrolysis (e.g., cement). Finally, pressure-sensitive adhesives, such as on tape, never fully cure and remain tacky [5]. The application mechanics of adhesives depend on some surfaces, such as very polished and dense material, which may be harder to fasten with adhesives than rough or porous surfaces. Surface roughening may increase mechanical interlocking, and surface cleaning may do the same for chemical bonding [6]. The reassembling process is one of the important processes in the restoration in which the separated or partially broken parts are returned partially or completely to their original places. Additionally, it requires a trained, experienced, skilled restorer and uses adhesive materials like epoxy, polyester, araldite (such as 1092), polyvinyl acetate, and acril33 AC33. Stainless steel bars can also be used to assemble heavy and large separated parts besides using the adhesives. In another study [7,8], epoxy resin was chosen as a strong adhesive because of its strength suitable for the weight and magnitude of most substrates [8]. Mohamed (2022) mentioned that three types of binders were used in all mixtures (Araldite PY 1092, Araldite 106 IN, and white cement) and then examined in terms of compatibility [9]. They were used in the highest value of compressive strength related to a mix composed of Araldite 1092 (64.10 Mpa) as an indication of strength comparable to the original stone, which ranges from 102.96 to 133.17 Mpa. It is still in the safe range to use since it has less than the value of a stone artifact. The research mentioned that stainless steel bars were used to assemble the parts but presented the bond tests completed on commercially existing fiberglass-reinforced plastic (GFRP) bars that were used in the reassembly of this case study [10]. Mohammad et al. (2020) focused on developing new technologies to enhance the characteristics of conventional adhesive materials and methods used in the re-assembly of massive stones using epoxy resins due to their mechanical properties [11]. Epoxy-clay nanocomposites were chosen as the best re-assembly adhesive material reinforced with stainless steel to conduct the applied study project of three archaeological pharaonic massive limestones [12]. A comparison between epoxy resins and Paraloid ™ B-72 illustrated that different ceramic fabrics usually require different adhesive systems: for high-fired, non-porous ceramics or porcelain with high mechanical strength thermosetting epoxy resins are usually preferred, while for lower-fired, more porous earthenware, which is usually weaker thermoplastic adhesives are employed like Paraloid ™ B-72 which shows considerable plasticity [13]. Epoxy resins are durable, have outstanding mechanical strength and low shrinkage, and hold joints strongly together as they have good adhesion to many substrates. The effect of environmental constraints on long-term subcritical stresses on adhesive bonds (creep) should also be assessed [14]. Hefni (2022) used acril33 in mortars after making four types of mortars to select the best for filling the cracks in the studied archaeological basaltic stones in Abu Sir.: **1)** Paraloid B72 (CTS Company, Italy), **2)** Eucocolle (SwissChem Construction Materials, Egypt), **3)** Acril33AC 33 (CTS Company, Italy), and **4)** Acryclirsil (SwissChem Construction Materials, Egypt) [15]. This paper handled a block of limestone discovered separated in Saqqara (intaglio from the tomb) during the excavations and divided into three blocks with a registration number "1517 GEM" (Height: 55 cm, Width: 15 cm, Length: 107.5 cm, Weight: 229515 G). Mural's writings defined (Kyiry) as the army's treasury of weapons and equipment's military supervisor. They were divided into three registers: the upper part of the first one was missing. As for the rest of the part, the inscription illustrated some workers sitting on seats while they made arrows. At the end of the second register, a worker appeared seated in front of a potter's wheel preparing a pot. On the third register, four workers appeared carrying arrows to receive aquiver [16].

Two pieces were assembled in the previous restoration process. Later, it was found that it had a third part that had not been previously assembled, so it was re-assembled. It had some defects, such as the difference in the height level of the two pieces and the concealment of a small part of the engraving at the assembly area. Thus, this study aims to find the best method of assembling stone pieces to make them stable without affecting the inscriptions, condition, or composition of the object.

2. Materials and Methods

2.1. *Sampling*

Small samples of stone were taken from the edges of engraved limestone blocks, salts, old fillings mortars, and old adhesives to identify their chemical and mineral compositions. Furthermore, samples of the previous adhesive and ancient filling mortar were taken, fig. (1-a & b).

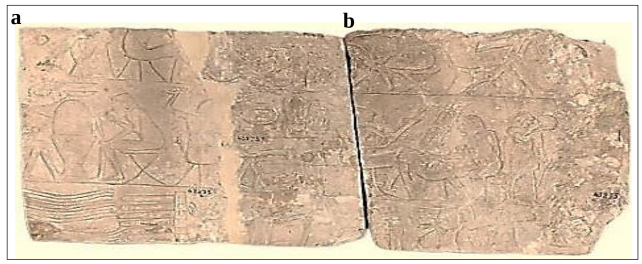

Figure (1) **a.** a block of two parts of limestone, **b.** the second block was discovered in Saqqara and preserved in the Egyptian Grand Museum.

2.2. *Investigation and analytical methods*

2.2.1. UV fluorescence imaging

UV imaging was used to find out what was blurred from the inscription. UV light is an instant tool that is easy to use at a low cost. All it needs are a dark room and goggles. UV fluorescence (Innovative Digital sensor 2.0 MP, variable magnification ranging from 20 to 1000-x, photo capture resolution 640×480,320×240, and LED illumination light resource adjustable by the control wheel) was utilized to show the wall inscriptions that were obliterated because of damage, blooming, crystallization of salt, and previous restorations. It is crucial to know the color changes in the samples that were given to every material due to different deterioration factors, as well as the previous conservation, as shown in UV light. The diffraction of light on the surface of the third piece was given a dark yellow color as the patina layer. [17,18]

2.2.2. XRD Analysis

Some deteriorated samples of the engraved limestone and salt samples were studied by XRD [19,20]. Three stone samples were taken from each piece of the mural separately for analyzing them by X-ray to ensure the type of stone. In addition to matching the shape of the inscriptions with each other, considering it had the same numbers in the database. The analysis was carried out using Analytical\X'Pert Quantify\hx\2046.xrdml C:\PANalytical\ X'Pert, XRD measurement of the raw data asset (XRDML Gonio scan axis.) to study the mineralogy and salts of the samples.

2.2.3. FT-IR analysis

A Shimatzu KBR-Pelletm infrared spectrophotometer was used to identify the types of previous adhesives that were used in the previous assembly.

3. Results

3.1. *UV fluorescence imaging*

Ultraviolet (50-x) images showed salt deterioration, making the surface of the inscriptions yellow under light, cracks in the previous filling, and the patina layer in the third piece, fig. (2-a, b & c).

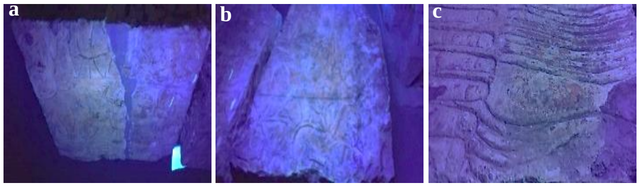

Figure (2) UV photos show **a** & **b.** salt deterioration that made the surface of the engravings yellowish under the light, **c.** a brown patina layer in the third piece.

3.2. *XRD mineralogical results*

The XRD analyses of studied samples, tab. (1) showed that the sample consisted essentially of calcite with a high percentage. The three samples of different stone blocks had calcite carbonate ($CaCO_3$), while salt sample no (4) essentially comprised halite (NaCl) in addition to quartz (SiO_3), fig. (3) [21]. The sample of old filling mortar was analyzed by the XRD method, showing that they contained quartz mineral (SiO_2), albite as stone powder by 7 %, quartz (72%) as a filler, and calcite as a binding material (21%), tab. (2) & fig. (4).

Table (1) XRD results of limestone samples

Ref. code	Mineral	Chemical formula	Percentage %
01-072-1937	Calcite	$CaCO_3$	95% samples (1,2,3)
01-070-2509	Halite	NaCl	90% sample (4)

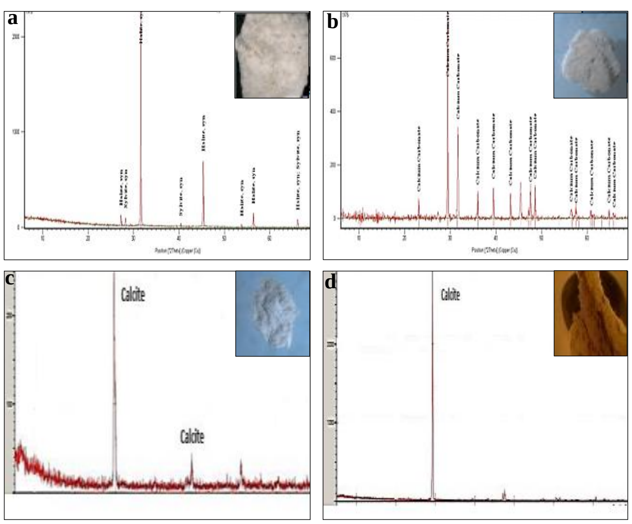

Figure (3) XRD patterns of studied samples; **a.** salt deposit covers mural sides, **b.** limestone on a surface, **c.** stone sample from the second part, **d.** stone sample from the third part.

Table (2) XRD results of mortar samples

Ref. code	Mineral name	Chemical formula	Semi Quant
01-089-1961	Quartz low.$_{Syn}$	SiO_2	72
01-072-1937	Calcite	$CaCO_3$	7
01-070-3752	Albite	$(Na_{0.98}CaO.O_2)(Al1.O_2Si_2)$	21

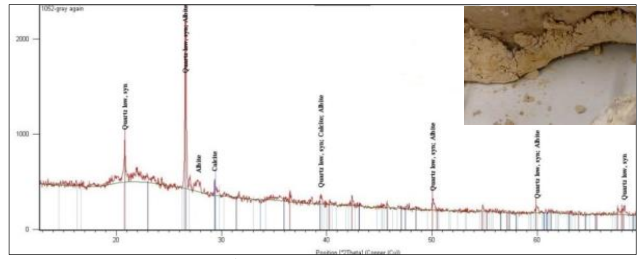

Figure (4) XRD pattern of the mortar sample

3.3. *FTIR analytical results*

The type of adhesive material between the tensor formations was identified by FT-IR, which showed Paraloid B-72 according to the resulting functional groups and compared with the reference sample, as shown in tab. (3) & fig. (5). Based upon relative stability and reversibility, Paraloid B-72 was found in a particularly wide range of uses as coating, consolidation, and adhesive. It was used in the mortars, the basic adhesive for fixing bars, and the assembly of the pieces, as mentioned by ICOMOS [22]. As a result, the functional groups showed the double carbonyl group C=O 1740: 1640 cm^{-1} in the standard sample, which was achieved by the analysis of the samples of previous mortar and adhesive material at 1743 cm^{-1}. This band specifically expressed the presence of Paraloid, as well as the C-H group, which ranged 1480:1300 cm^{-1} and achieved 1474:1485 cm^{-1}. Additionally, individual carbonyl band C-O ranged 1300:900 cm^{-1} and achieved in the sample at 875 cm^{-1}. These results confirmed the presence of Paraloid ™ B-72, which was identified as an adhesive [23].

Table (3) the wavelength of the sample compared to the wavelength of the standard sample no (1 & 2)

Samples	Wavelength of *Mortar (a)*	Wavelength of *Adhesive (b)*	Wavelength of *(B-72) Standard Sample*	Functional Group
a	2982 cm^{-1}	2981-2873 cm^{-1}	(1) 3100-2800 cm^{-1}	C-H stretching bands
b	1734 cm^{-1}	1734 cm^{-1}	(2) 1740-1640 cm^{-1}	C=O stretching band
c	1474:1485 cm^{-1}	1485 cm^{-1}	(3) 1480-1300 cm^{-1}	C- H bending band
d	859:1233 cm^{-1}	875 cm^{-1}	(4)1300-900 cm^{-1}	C-O bending band

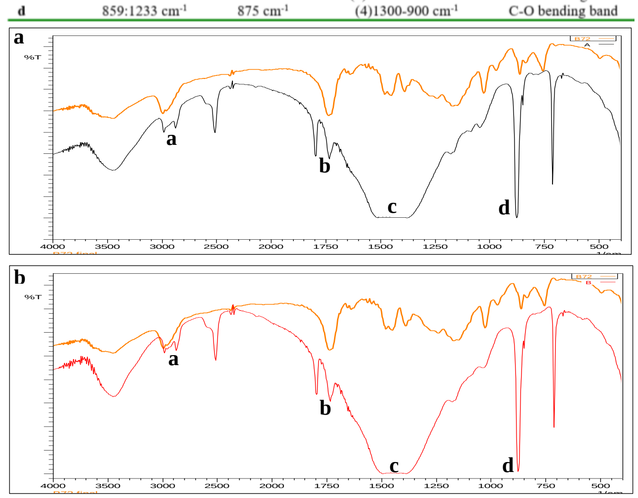

Figure (5) **a.** FTIR patterns of the sample from the old mortar, **b.** bars of the adhesive mortar

4. Reassembling Project

4.1. *Documentation process*

All manifestations of damage, previous conservation, engraving, the dimensions, and sizes of the three stone pieces, as well as missing parts, were documented and drawn using the auto drawing program AutoCAD, fig. (6-a). The reassembly progress and places of fiberglass bars were also documented using AutoCAD, fig. (6-b).

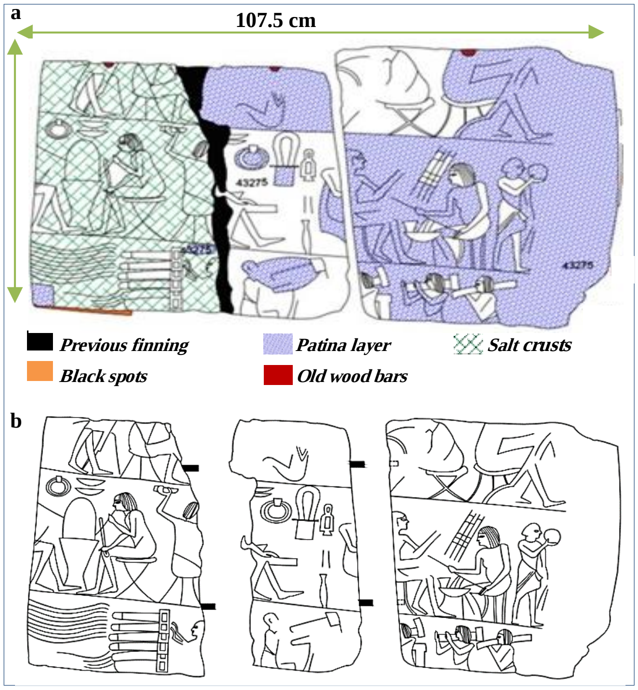

Figure (6) documentation steps by **a.** AutoCAD and Adobe Illustrator, **b.** after inserting re-assemble fiberglass bars inside the object

4.2. *Observation of the fracture separator and matching the edges of the blocks together using RTI (Reflectance Transformation Imaging)*

As previously discussed, the main objective of the research was to use the available technological means to find out the best way to display the mural and assemble its three parts to provide a clear view of the wall inscription and the stability of the three parts when displayed to reach a better final fragment of the piece. Photography features with RTI, as a computational photograph technique that calculates light positions and allows interactive relighting for vision, were utilized. Virtual light enhances surface details for examining morphological differences. By applying the Dome RTI method, stages of conservation treatment were recorded to enhance the overall characteristic features of the relief upon the object's surface and then detect and identify weathered characters. Patina removal and consolidation were documented along with the original state; a significant difference in the stone's surface was observed using different filters of the RTI viewer, an advanced technique using raking light, whereby multiple light sources were distributed over a hemispherical dome and processed using hemispherical harmonics, as a computational photographic method that records surface shape, color, recognized as a practical tool for documenting and evaluating conservation treatments by visualizing the change in surface [24]. At the same time, RTI representation enables mathematical enhancement of the captured object's surface shape and color attributes, as well as interactive change of lighting. It uses many images of the same artifact taken from the same location, each with light from a known direction, to create a composite image [25]. The computing is based on Polynomial Texture Mapping (PTM). The application of RTI has proved highly successful for gravestone recording and graffiti. Varying the light angle in the RTI Viewer can allow the reading of text that is not intelligible in the field. It can also be particularly effective in identifying very fine lines, such as lightly scratched graffiti, and setting outlines on inscriptions [26]. In our case, RTI was useful for recording the whole inscription on the surface to make a clear version and make sure the three pieces belong to each other, considering the missing parts, especially at the edges of each block. This method showed the difference between the two pieces in the level of surfaces and length that were re-assembled before and small and accurate cracks in the previous filling process, fig. (7).

Figure (7) RTI specular enhancement shows the difference between the two pieces in the level of surfaces and length that were re-assembled before, as well as small and accurate cracks in the previous filling process.

4.3. *Structural adhesive methodology*

Previous studies approved and confirmed that (Araldite PY 1092) was the best re-assembly adhesive material that could be used in the re-assembly of massive stone objects. The properties of all used chemical materials (Araldite PY 1092-1 and its hardener HY 1092, mixed with stone powder) and its hardener from (BODO Moller Chemie Egypt, Engineer chemistry made in Egypt), commercially as smooth fiberglass bars were used to reinforce materials with the adhesive material in the re-assembly processes to strengthen and tighten the reassembly process of stone blocks. The fiberglass bars have high mechanical resistances (tensile, flexural, etc.) and corrosion resistance. *The technical properties of the adhesive were* specific gravity: 1.9 g/cm^{2}., tensile elastic modulus: 35000 Mpa, tensile strength: 900 Mpa, flexural elastic modulus: 32000 Mpa, and flexural strength: 900 Mpa. The diameter of the bars was 10 mm, the length was 2 m, the solid was round, and the depth of the hole inside the stone to insert the bars depended mainly on the weight and thickness of the stone piece to be assembled. The fiber bars were cut in the process of collecting the stone blocks; a preliminary experiment was conducted on inserting them into the holes in the stone. (fiberglass bars supplied by JICA). ACRIL33 was chosen as mortar resin,100% pure acrylic resin in aqueous dispersion characterized by excellent resistance to atmosphere agents and chemical stability. Acrill 33 was used in our case as an additive for injection and filling mortar, consisting of (stone powder with limestone crushing mixed with Acril33).

Physical and chemical properties of Acrill33: White, milky liquid, solid content 46$\pm$1%, viscosity 3750 20°, pH 9.5, high resistance to yellowing, and excellent freeze stability (STC Company, Italy).

4.4. Re-assembly process of the objects

To find the optimum approach for the proper assembly of the engraving, the components were assembled based on the inspections and documentation processes. Because of the difference in level between the two edges of the previously formed components, the two pieces were first separated. This separation was carried out using the proper instruments, including a metal chisel and organic solvents to break the assembly material, tying the two pieces together, as in fig. (8). In preparation for their re-assembly, the two edges were extensively cleaned after being separated, the old bars were removed, and the previous adhesive was cleaned in preparation for reassembly fig. (8-e). It was discovered that the previous assembly had covered the original stone and part of the engraving, fig. (8-f). After mechanical and chemical cleaning of the pieces, a new concept was developed for the connection of the three parts. As a result, we reached the assembly of the third part with one of the two parts that were previously separated to balance the level of engraving well. Then, the last piece was added as a position, as shown in fig. (8), until the parts were assembled by using fiber bars with a diameter of 10 mm ϕ also the tensile strength and making holes for those bars' diameter of 15 mm ϕ as standard according to size of object. Special drills were made to the required size to fill it with (Araldite1092) mixed with stone powder). Using two bars to reassemble, the mixed material was put on the sides, and the same holes were made on the same level in the other piece to adhere, after making sure that the two pieces were on the same level using the water balance.

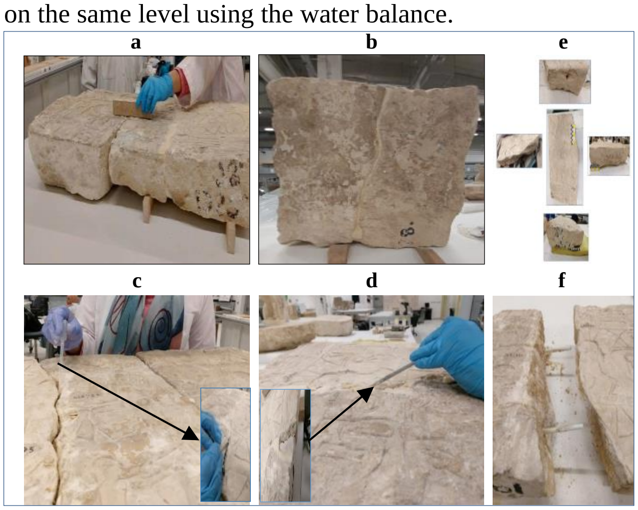

Figure (8) the object; **a.** & **b.** before separating and reassembling, **c.** & **d.** removing the old mortar to show the covered part of the inscriptions, **e.** the three pieces, **f.** two separated pieces after removing the old bars, and cleaning of the previous adhesive.

The two pieces were adhered to and left for 3 days to completely fill in the cracks and holes with suitable mortar (stone powder with limestone crushing mixed with primal), fig. (9-a, b & c). After the filling was completed, they were moved on a special hydraulic winch for the third piece's assembly fig.(9-d), and the holes for the bars were made in an uneven place so as not to weaken the piece's structure. Offset in the third piece, the same bars and adhesive (Araldite PY1092 hardener 1092 HY) were used, transferred using a winch, and settled on the two pieces that had previously been put together to ensure the level of the presumption fig. (9-d, e). A new conception was developed for the three connected parts. As a result, we assembled the third part with one of the two parts that were previously separated to equalize the level of engraving well. Then, the last piece was added as a position, fig.(9-f), until the parts were assembled using fiber bars and special drills of the required size. Two rods were made to reassemble, placing the Araldite (1092) adhesive, and mixing the Araldite with stone powder in a ratio of (2:1) to place it in the hole for fixing the bars at the same level in the other piece to be adhered after making sure that the two pieces were on the same level using a water balance ruler. The three pieces were left for 3 days to complete the filling of the cracks and holes with the appropriate completion mortar, fig.(9-f), which consisted of (stone powder and limestone crushing mixed with Acril33) to fill the big holes then filling the spaces with filler in a ratio of (2 stone powder: 1 water: 1 Acril33), tab. (4).

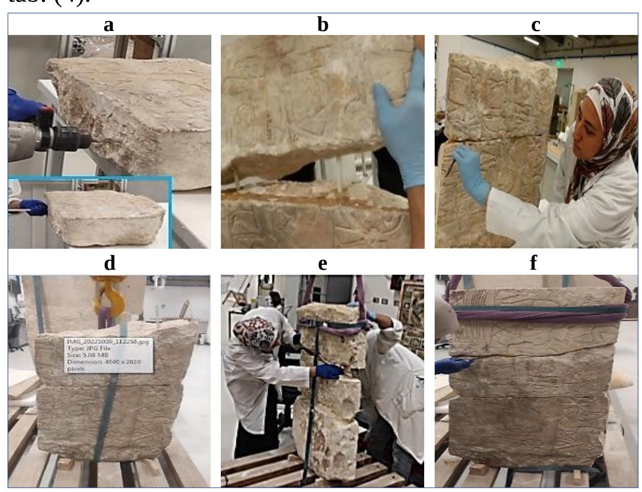

Figure (9) **a.** the drilling process for the new assembly places, **b.** the assembly process of two pieces using fiber bars with adhesive matching each other, **c.** filling with the appropriate mortar and sealing voids after assembly, **d.**, **e.** & **f.** assembling the three pieces with the adhesive and experiment with the third block using the dedicated winch to make sure the pieces match.

4.5. Conservation process after re-assembly

The conservation process started after finishing the reassembly process of the three stone blocks, considering the stone objects in good condition. The conservation process included filling stone separators between the assembly places and finishing them with the mortar that distilled water and stone powder with Acrill33 (1:2:2: 3 g yellow oxide as a pigment), tab. (4) & fig. (10-a & b), then mechanical cleaning using a soft brush and scalpels to remove dust, stains, and any impurities on the stone surfaces fig.(10-c). This was followed by chemical cleaning using some organic solvents, such as demonized water and ethyl alcohol fig.(10-d), to remove the remaining difficult stains and dust.

Table (4) Mixtures proposed as patching materials

Mix	Binder	Filler type
1	Araldite PY 1092(2:1 hardener)100 ml	1 part of stone powder
2	Araldite PY 1092(2:1 hardener)100ml	2 parts of coarse limestone grains + 1-part stone powder
3	Acrill33 (2:1 water)	3-part stone powder
4	Acrill33(2:1 water)	2-part stone powder + 3 g yellow oxide pigment

Figure (10) **a.** a part of the filling process of the stone objects, **b.** after filling the zones between the assembled places three blocks, **c.** cleaning the objects, **d.** the three stone objects after re-assembly and conservation process.

5. Discussion

The limestone block in the current investigation suffered from several deteriorating issues. Calcite made up a significant portion of the mineralogical composition, according to petrography investigations and X-ray analysis. Salts (NaCl) could penetrate deeply into the rock texture because of the rock's porosity. As a result, the stone became less cohesive and more porous, and the grains were loose. UV illustrated a clear color disparity on the surface of the two pieces collected in the past. One of the two pieces had salt deterioration that made the surface of the engravings yellowish under the light of the rays. Also, there were cracks in the previous filling mortar. the composition and properties of old mortars, lime-based adhesive, FTIR, and XRD analyses were used so that we could know the previous filling mortar and the adhesive that was used to stabilize the bars, i.e., Paraloid ™ B-72, well known in conservation practice. Araldite (1092) was chosen as an adhesive for re-assembling the mural because of its high adhesion strength, which was suitable for the size and weight of the pieces and strength and stability [27]. Ara ldite (*Epoxy EP 2101*) was used as a mixed limestone powder to reinforce, fix, and collect the disintegrated parts of six Egyptian archaeological stone sarcophagi in Tel El–Deir. The experimental study [28] used the uniaxial compressive tests for epoxy resins carried out by the MTS 815 rock and concrete test system. The density, porosity, and uniaxial compressive strength were determined for the epoxy-repaired rocks that were used to repair the shear zone at the Jinping Hydropower Station. Experimental tests and polarizing microscopy (PM) test results showed that the visible cracks and pores were filled and connected by epoxy resin from the rock core sample, and the epoxy resin could fill most of the cracks and pores because of the good flow properties and long operation time. The mechanical properties of epoxy-repaired rock were improved by the polymer grouting, and the permeability coefficient was decreased [29]. The manufacturing of an artificial stone made of granite residue agglutinated in epoxy resin and its physical and mechanical properties. The microscopic images obtained through SEM helped see the good adherence between the particles and the epoxy matrix, pointing to a low void incidence, which explained the good physical and mechanical properties of the material. Acril33 was also used with mortar resin for filling. Fiberglass bars for fixing the pieces and reassembling them were suitable for their sizes and masses, which were considered neither too large nor too small. It is worth noting that the experimental studies conducted on the use of epoxy in the field of assembling stone artifacts proved its stability and suitability for assembling stone blocks in a way that ensures their stability and resistance to mechanical factors and pressure. Therefore, it was recommended to use it to reassemble the blocks understudy in preparation for its museum display. According to the deterioration of the limestone block, the restoration processes were carried out. In addition, we chose two techniques for documentation and recording the overall characteristic features of the relief upon the object surface using a handheld USB digital microscope: UV and RTI to connect the three pieces together in clear vision and the extent of the surface level to their length before reassembling. Restoration and conservation processes included mechanical and chemical cleaning, extraction of salts of the disintegrated parts, and filling the missing parts.

6. Conclusion

Stone pieces transferred from archaeological sites or an archaeological excavation process to a museum to be displayed separately from their original location and environment are subject to separation or loss of parts during excavations or when removed from the wall due to the lack of safety of the site, damage to the bearing wall, or even transfer. In this case, preliminary studies before the re-assembly process confirmed that these pieces of stone in the original were one piece, and there was the possibility of regrouping to become one block complementary to each other. Epoxy resin (Araldite 1092) and fiber bars were used in the re-assembly process, which was performed with high technology and expertise in accordance with standards for this purpose. The role of the restorer was to develop an assembly plan to connect the separate pieces in a way that contributed to displaying them in the museum while not forgetting to support the piece and make sure that its parts were fixed. This highlighted the inscriptions on the most significant pieces of the cemetery's owner's work, along with previous restorations, assembly, and the potential for reassembling them once more in a way that would reveal a portion of the inscription that had been concealed by filling materials and allow for its best possible exhibition so that it could be in the Grand Egyptian Museum.

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