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MULTISCIENTIFIC APPROACH FOR THE CHARACTERIZATION AND ASSESSMENT OF THE DEGRADATION STATE OF THE HISTORICAL AL-SHAFI'I MOSQUE WALLS (JEDDAH, KINGDOM OF SAUDI ARABIA)

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ABSTRACT

Al-Shafi'i mosque, one of the most important heritage buildings at historic Jeddah, is located in the center of the historic district in Mahallat al- Mazlum. The aim of this study is to investigate the characteristics and quality of the construction materials of the multiple-leaf stone masonry walls at Al-Shafi'i mosque, and to diagnose and evaluate their current preservation/degradation state. For the study purpose, standard laboratory physical and mechanical testing including apparent porosity, bulk density, water absorption, uniaxial compressive strength and flexural strength were conducted for the collected samples. On the other hand, mineralogical, chemical, petrographical, and morphological characterization methodology applied comprises a large range of investigation and analysis techniques that complement each other, and namely include visual inspection, optical microscopy (OM), polarizing microscopy (PM), scanning electron microscopy (SEM) attached with EDX unit and X-Ray Diffraction (XRD) technique. The followed integrated diagnostic methodology based upon on-site direct observation data allowed the identification of the mineral-chemical composition, mineralogical characteristics, morphology features, physical–mechanical properties and the actual state of inorganic construction materials of the inner and external leaves of the multiple-leaf masonry walls, which were found to be fossiliferous limestone, coral stone and mud-lime mortar. These results provide very useful information to plan the necessary conservation measures.

KEYWORDS: Al-Shafi'i mosque, Multiple-leaf Stonemasonry walls, Fossiliferous limestone, Coral stone, mud-lime mortar, Material characterization, degradation state, Investigation

1. INTRODUCTION

Hijazi City Jeddah, the port of the two holy cities, the gateway to the city of Makkah and main seaport of contemporary Saudi Arabia (Bagader, 2014), is located at 21°29' north and 39°12' east on the Tihama coastal plain of the Red Sea in the western region of Saudi Arabia (Fig. 1a), (Al-lyaly, 1990). Historic or old Jeddah City, which is now a neighbourhood within the City Jeddah, is a square kilometer area with properties built during different time periods. The Historic Jeddah is the forefront of the Saudi Arabia heritage sites that UNESCO recently registered in the World Heritage List in 2014. It was established in 646 AD, the old Jeddah sites have long history that extends from the pre-Islamic eras and through all the following Centuries until the present. The main old district of Jeddah that named as "Al-Balad district" possesses hundreds (over 500) of unreinforced stonemasonry (URM) buildings that are recognized as historic (Bagader, 2014). The walls of these buildings are generally built of multiple-leaf (three layers) URM load-bearing system. These multiple-leaf unreinforced masonry walls are constructed using marine-origin limestone that is vernacularly named as "Mangabi".

Al- Shafi'i Mosque also known as Al-Jami' al-'Atiq literally means the old mosque and is considered by many historians to be the oldest and most famous mosque in Jeddah, it is called al-Shafi'i because it was dedicated to the Shafi'i rite teachings, and it is located in the center of the historical district in Mahallat al-Mazlum (Fig.1B). Many historians mentioned that it was built by the second Righteous Caliph 'Omer Ibn Al Khattab. However, the mosque was rebuilt in the reign of the Rasulid Dynasty by the second Rasulid ruler Al-Malik Al-Muzaffar Yusuf Ibn Umar in 1251. Then, this mosque was restored by al-Khawaja Muhammad 'Ali, an Indian merchant who visited Jeddah in 1533. He brought its wooden columns from India via Yemen and rebuilt the entire mosque except for the minaret. It is believed that the current minaret is the work of the Rasulid ruler (King, 1980; King, 1986; Taqi al-Din Muhammad et al, 1987; Abbas, 2014).

Al-Shafi'i mosque building covers an area of about 1500 m^2 with an open court in the middle having an area of 450 m^2. The mosque is a single story building with a timber roof and has a minaret located at its south-western corner. The timber roof is supported on the mosque exterior walls and a series of various interior columns (Fig. 1C and Fig. 2A), (Osman, 2012). The mosque exterior walls are multiple-leaf stone masonry walls with about 0.65m thick and about 7.05m in height from the ground level and are based on a shallow foundation with a depth of about 2m. These walls were built of ashlar facing stone wall with rubble infill in 3 sections, interior, exterior made of coursed ashlar stone masonry (outer leaves consisting of successive horizontal layers made of marine-origin limestone blocks with equal height stuck with each other by marine mud or mud-lime mortar), and filling in between with rubble stone fragments in abundance of mud-lime mortar (inner core leaf). To distributed the load on the light marine-origin limestone, to tie the interior and exterior sections together and also to prevent cracking that result from differential settlement, timber tie-beams were laid horizontally and transversally, every 5 or 6 stone courses (Fig. 2c, d).

Marine-origin Limestone and marine mud were widely used in construction of the traditional buildings at the old city of Jeddah, where those buildings in general and Al-Shafi'i mosque in particular have traditional low-quality construction materials, that have been subjected for centuries to the harsh marine environment conditions, such as marine aerosol or sea spray, salty fog, daily dry/wet cycles, strong thermal variations, direct sun, wind, friction of sand resulted from sand storms, rain, biological influence and other deterioration factors. Generally, the building materials used in the heritage buildings in coastal areas are widely affected by the surrounding marine climatic conditions including wind erosion, salt weathering, variation of air temperature and humidity (Moussa, 2019). As for the action of marine aerosol on construction materials of the coastal heritage buildings, in coastal areas, the atmosphere is enriched with particles that are naturally generated by the action of wind on the water surface (Santos et al., 2012; Hossain, 2009), where sea salt particles in the atmosphere mainly originate from breaking gas bubbles in waves. These particles compose the sea spray, which introduces ionic species into the atmosphere, principally chlorides and sulfates. These ions are able to penetrate into the interior of the lime stone and lime-based mortars through ionic diffusion (Borges et al., 2014), where the aerosol particles are removed from the air to those materials by dry deposition (impaction, gravitational setting) or wet deposition (wash-out and rain-out). This kind of environment has proved to be very severe for these construction materials (Torfs and Van, 1997).

Because the degradation of heritage buildings in historic Jeddah is mainly in deterioration of their masonry materials, this paper focuses on walling materials of Al-Shafi'i mosque (Marine-origin limestones and marine mud mortar).

Since the basic esthetical, mineralogical, chemical, physical and mechanical compatibilities between the original construction material and the new ones must be investigated to judge their overall performance and the overall behavior of the heritage building materials after the intended intervention process (Ulukaya et al., 2017). The investigation of the masonry materials characteristics (composition, microstructure, mineralogical characteristics, mechanical and physical properties, etc.) is essential and very useful for the evaluation of their structural behavior, strength, quality, durability and the current state, and also for providing the optimal conservation plan. As it is essential to replace the heavily deteriorated stone blocks and compensate the lost ones with new blocks of the same type of original stones or similar type in the properties of these stones, and also the new mortar for repointing should match the historic mortar in strength, physical properties and chemical composition. Based on these facts, the main characteristics and properties of the construction materials used in the Al-Shafi'i mosque walls, the object of this study, were investigated as guide towards restoration of the mosque building (Schueremans et al., 2011; Lucian, 2015).

To assess the quality and actual structural state of the masonry stone in the multi-leaf stone masonry walls at Al-Shafi'i mosque, their resistance to various deterioration forces and factors, and their bearing capacity and efficiency as bearer elements, it is essential to study the most important physical and mechanical properties that significantly affect their resistance and efficiency (Lucian, 2014; Yagiz, 2010).

This paper presents an integrated scientific methodology based on an interdisciplinary approach for the assessment and material diagnostic procedures which combines field and laboratory studies, since the combination of results obtained from different approaches produces more precise information and allows the identification of construction materials and masonry typology in the studied building. And it aimed at having a detailed and accurate characterization of the mineral/chemical composition, mineralogical characteristics, microstructural, textural characteristics, and physical-mechanical properties for the inorganic walling materials (masonry stone units and structural masonry mortar) used in the construction of the inner and external leaves of the multiple-leaf stone masonry walls of Al-Shafi'i mosque, and the extent and rates of their deterioration under their current states, against either overloading or the harsh weather conditions of the surrounding marine environment. As well as assessing the quality, durability and the current state of these materials for providing recommendations regarding the most appropriate intervention techniques and conservation materials. Moreover, the interpretation of the results obtained from the detailed diagnostic process, in combination with the direct observation, visual inspection and the architectural survey, were very useful for the knowledge of the overall behavior, strength and investigate the safety margins of the structure, for identifying the masonry stone and mortar types and properties, and also for providing very useful information for mosque restoration with effective and optimal scientific methods and materials.

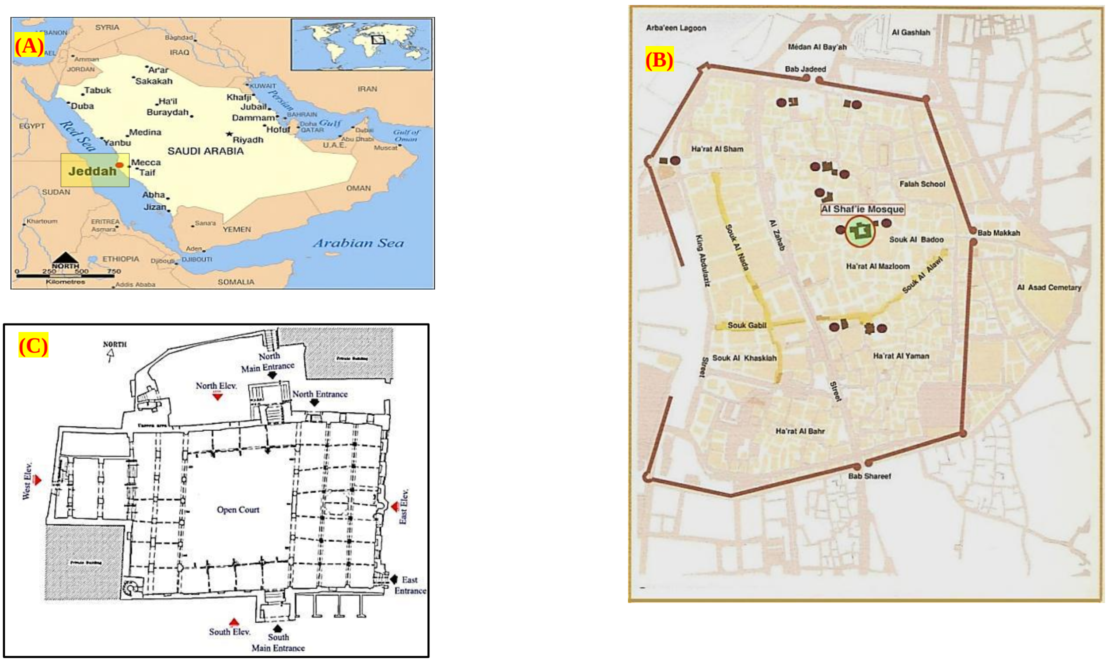

Figure 1. Map of Saudi Arabia showing the location of Jeddah city (A), with map of the old district of Jeddah "Al-Balad" showing the Al- Shafi'i mosque location (B), and a general plan to the Al- Shafi'i mosque (C).

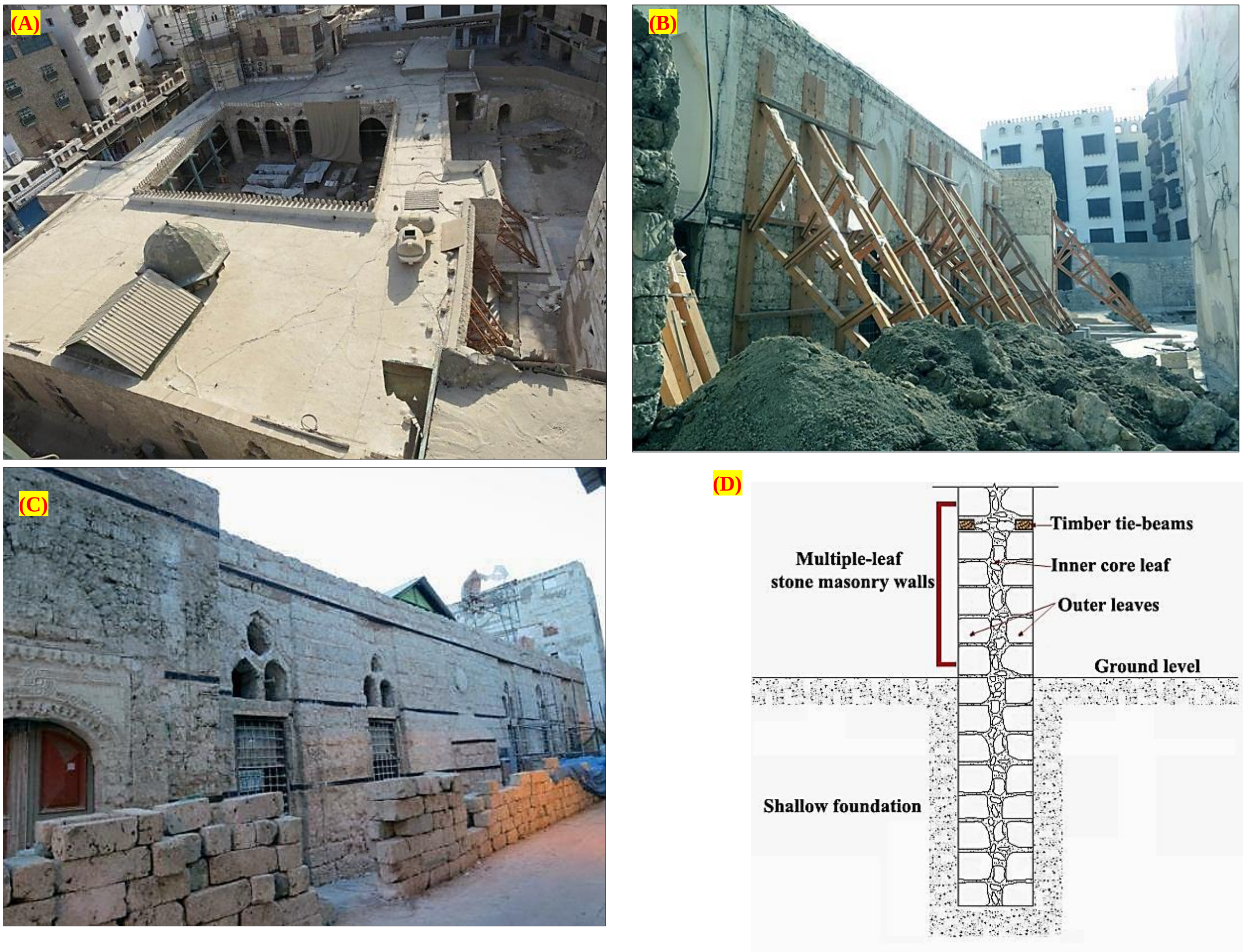

Figure 2. Photos of the Al-Shafi'i Mosque and the details of its external walls, (A) birdseye view of Al-Shafi'i mosque, (B) northern façade, (C) eastern façade, and (D) Sketch drawing of the external walls cross-sectional view.

2. MATERIALS AND METHODS

2.1. Characterization methodology

The walling materials characterization methodology of this study is based on an interdisciplinary procedure that essentially includes four principal steps:

i) Direct observation of the Al-Shafi'i mosque walls was carried out through the close up visual inspection, photographic recording and intensive complimentary survey of the mosque walls to identify, describe and document the current state of their constituent materials. This process is a preliminary and essential phase of the mosque wall building materials assessment processes, it is a simple method usually carried out by highly skilled and experienced conservators to provide an initial understanding of the walls structure and to give an appropriate direction to the subsequent investigations and analysis. The main objectives of direct observation include identifying decay, damage, deterioration patterns of wall building materials and their causes, and any ongoing environmental effects on the mosque building [ICOMOS, 2003; Abdelmegeed and Hassan, 2019].

ii) Mineral and elemental analyses were carried out through qualitative and quantitative analysis using XRD and SEM-EDX, respectively. These analyses were performed on the collected samples from walling materials (stones and mortar) in order to determine their constituent compounds and minerals (mineralogical composition), and their constituting elements (elemental chemical composition).

iii) Petrographic, microstructure and morphological investigations using polarizing microscope, scanning electron microscope and optical microscope in order to investigate the mineralogical and textural characteristics, mineral components, microstructure, morphological features, and the deterioration aspects of walling materials samples.

iv) Physical and mechanical properties determination for the main building stones through standard laboratory tests conducted on extracted samples from stone masonry units used in the outer layers.

2.2. Sampling

To achieve the purposes of the study methodology, standard laboratory examinations, analyses, and tests were carried out on representative samples of the main inorganic building materials of Al- Shafi'i mosque masonry walls, which were taken from various locations of the mosque building. Where a set of six small surface samples were taken from the investigated multiple-leaf stone masonry walls (that is, limestone units, joints mortar at outer leaves, and limestone fragments and binding mortar at inner filling leaf) using a chisel, were collected for mineralogical and chemical analyses, petrographic and morphological investigation. Moreover, large size specimens were extracted from stones units only by using a cutting machine for identifying the physical and mechanical properties of the marine origin limestone used in the outer leaves of the multiple-leaf stone masonry walls.

2.3. Characterization methods

For the complete characterization and determination of characteristics and the current actual degradation state of the collected samples taken from the investigated multiple-leaf stone masonry walls of Al-Shafi'i mosque, we used the following devices, equipment and methods:

2.3.1. X-Ray Diffraction (XRD) analysis

XRD analysis was performed using a PAN-Analytical X-Ray Diffraction equipment model X'Pert-PRO. The operating conditions were: Secondary Monochromator, Cu-radiation (λ=1.542Å) at 45 K.V., 35 M.A., with applied scanning speed of 0.04 / second. The recoded diffraction peaks for 2θ were between 2° and 60°, where the corresponding spacing (d, Å) and relative intensities (I/Io) were obtained. The diffraction charts and relative intensities are obtained and compared with 'ICDD' files for identification work. This analysis was performed at the central laboratories sector, Egyptian mineral resources authority. This method allows the detection of crystalline phases present in stones and mortars when their concentration is not very low usually less than 3-5% (Coroado et al., 2010), and thus the mineralogical composition (compounds or minerals) of these materials is determined.

2.3.2. Scanning electron microscopy (SEM-EDX) investigation and analysis

SEM investigations and EDX analysis of the collected samples were carried out using SEM Model Quanta 250 FEG (Field Emission Gun) attached with EDX Unit (Energy Dispersive X-ray Analyses), with accelerating voltage 30 K.V., magnification14x up to 1000000x and resolution for Gun.1n. This analysis was performed at the central laboratories sector, Egyptian mineral resources authority.

It was used **SEM** to investigate the morphology of the deteriorated surface and observe the weathering state of the collected samples, and **EDX** to determine the elemental composition of the collected samples (type and ratios of the constituent chemical elements of these samples). This analysis was necessary, where it proved complementary information to support the XRD technique (Ferretti, 1993). The chemical analysis of the building materials used in the heritage buildings helps to gain Information on the extent of the repairs historical (Elyamani and Pere Roca, 2018).

2.3.3. Polarized microscopy (PM) investigation

Thin sections from the collected samples were prepared and optically analyzed using optical polarizing microscope of model 'Olympus BX51 TF' (made in Japan), attached with digital camera under magnification 20X up to 40X in the laboratory of Micro analytical center, Science faculty, Cairo University. This method was used to determine the mineralogical composition, texture, microstructure, grain features, micro fracturing and percentage of pores and voids in the collected samples (Saleh, 2013a).

2.3.4. Optical microscopy (OM) investigation

OM investigation, by using a Smart-Eye USB digital microscope at various magnifications, up to a maximum of 200x fixed magnification, in order to characterize the morphological and optical features, superficial shape, the grain size and the deterioration aspects of the collected samples (Marey, 2011).

2.3.5. Mechanical properties testing

The mechanical tests were performed on the extracted samples aiming to provide reliable data for the mechanical behavior and strength of the masonry stones used in the multiple-leaf stone masonry walls. Uniaxial compressive test and flexural tensile strength test were carried out by using GALDABINI-QUASAR 600 testing machine at materials test lab, centeral unit for analysis and scientifical services (CUASS), national research center, Cairo, Egypt. **The uniaxial compressive strength test** is used to determine the maximum value of stress obtained before failure, and thus determine the ability of a material to resist deformation under load (Anania et al., 2012). The determination of this parameter was carried out on six oven dried stone specimens with dimensions 70X70X70mm, smoothly sawed using diamond saws from large size stone samples in accordance with ASTM C170 specifications (ASTM C170, 1990). **The flexural strength test** was performed on six oven dried stone specimens having dimension of 40x40x160mm, smoothly sawed using diamond saws from large size stone samples in accordance with ASTM C880 specifications (ASTM C880-98, 1991).

2.3.6. Physical properties testing

The main physical properties of the collected stone specimens including bulk density, apparent porosity and water absorption were measured at materials test lab (CUASS), by using the ISRM standard testing methods (ISRM, 1981). In order to perform these tests, eighteen stone specimens with dimension 70x70x70mm were prepared. Oven dried specimens were dipped in distilled water and weighed constantly at prefixed intervals of time until a constant weight was attained, and its saturated-surface-dry mass was also determined.

Density and porosity are the most important factors in assessing the mechanical properties of stone units. The density of samples may inform about the tightness of the rock components which will affect the overall properties of the rock (Zhao and Broms, 1993). Density and porosity are often related to the strength of rock materials. A low-density and high-porosity rock usually has low strength. The porosity of rocks is one of the prime determining factors with respect to rock durability as construction materials (Brown, 1981; Guruprasadi et al., 2012). Water absorption is an important rock index depending on mineralogy and porosity of rock. Porosity is one of the governing factors for the permeability and it provides the void for water to flow through a rock material. High porosity therefore naturally leads to high permeability [Al-Qahtani and Abo-Seif, 2013].

3. RESULTS AND DISCUSSION

Field inspection at the mosque site and laboratory examinations, analyses and tests on all the collected samples according to the study methodology were carried out, and then the attained results were discussed herein.

3.1. Direct observation

The close visual inspection to the building materials of the Al- Shafi'i mosque external façades at their exact location revealed that:

- There are two different types of the building stones (fossiliferous limestone and coral stone) were used. But, it was noted that the coral stone was used in a very small proportion in walls structure along with fossiliferous limestone (Fig. 3a). The fossiliferous Limestone used in the multiple-leaf stone masonry walls of the Al-Shafi'i mosque whether used as masonry unit in the external layers or as stone fragments in the inner filling layer was found in very poor state, severely deteriorated, is mostly friable and suffers from many forms of deterioration and degradation such as granular disintegration, powdering, pitting, sanding, alveolization, fissuring, flaking or exfoliations, spalling, crushing and salts crystallization. Also, the coral stone was found in poor state and there are fracturing and breakage in its skeletal (Fig. 3a, b, d). Close examination also revealed that the cause of the disintegration and dismantling in the masonry stone units is rooted in the decaying and deteriorated mortar leaving the stone units firmly intact (as shown in Figure 3A). In addition, partial failures to stones at certain locations were noted and the use of black cement as plaster at many locations was evident (Fig. 3c), and also the timber tie-beams utilized within the walls were severely decayed and damaged (Fig. 3d).

- The original structural mortars whether used in the external layers for jointing the limestone blocks or in the inner filling layer for binding the rubble limestone fragments are marine mud mortar with a pale grey colour, this mortar was found friable, badly deteriorated, crumble easily, and exhibits very low bonding characteristics. In addition to, this soft and friable mortar has completely disintegrated into dust, and is lost at many locations leaving the stones units completely exposed (as shown in Fig. 3a, d).

- The continued deterioration of the materials used in the mosque external walls due to lack or dearth of serious conservation, the fragility and weakness of these materials, aging process (natural wear), hard attack of the harsh marine environment agents (marine aerosol or sea spray, salty fog, daily dry/wet cycles, strong thermal variations, direct sun, wind, friction of sand resulted from sand storms, heavy seasonal rain… etc.), use of incompatible materials in previous improper restoration attempts such black cement mortar, and the defects of original construction techniques.

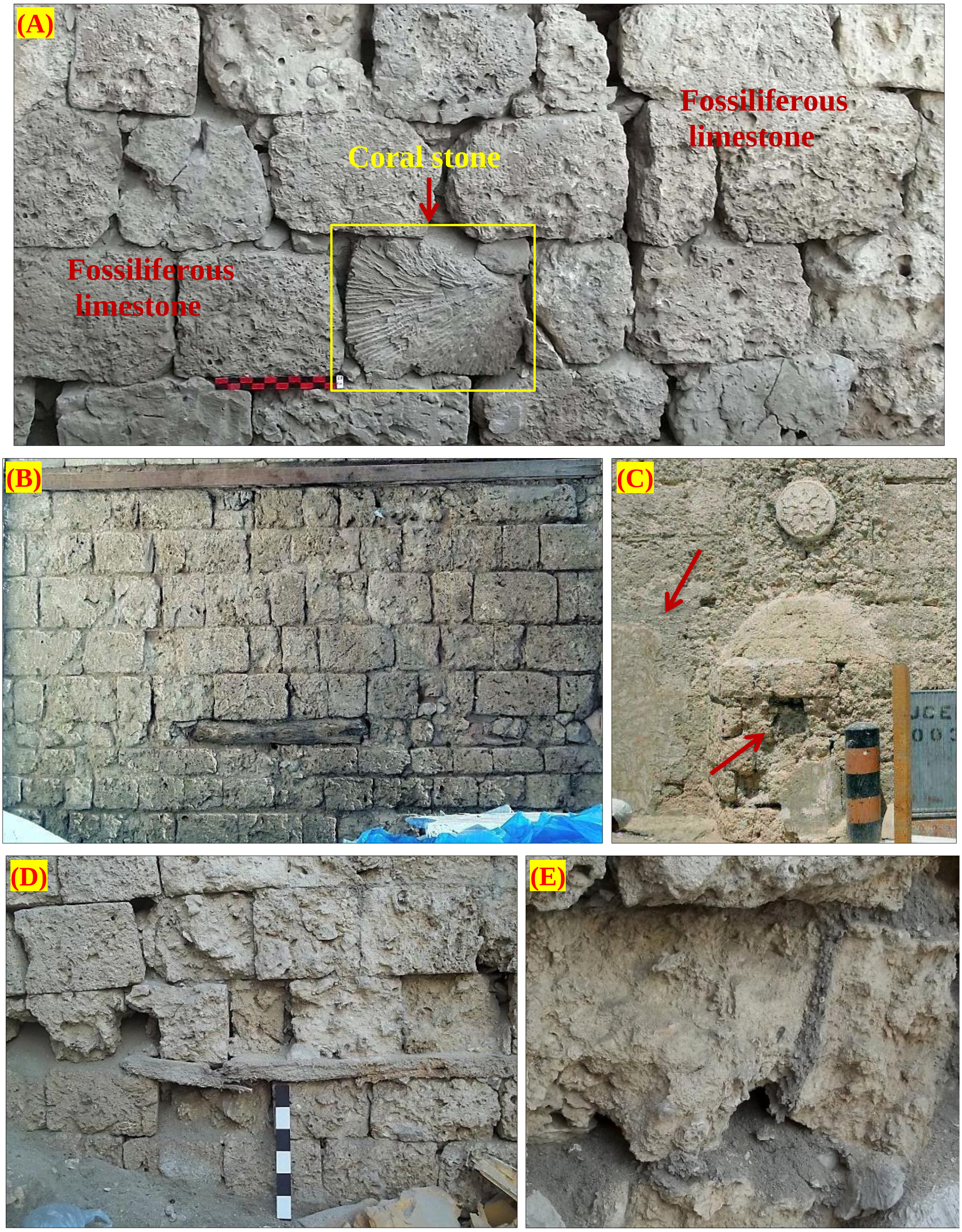

Figure 3. Photos close out to the masonry materials used in the investigated multiple-leaf stone-masonry walls at Al-Shafi'i mosque, show; (A) the deterioration patterns of the two different type of limestone blocks used in these walls (fossiliferous and coral limestone) and loss of joints mortar between these blocks, (B) pitting, sanding, alveolarization, fissuring, and salts crystallization in limestone blocks, (C) the use of black cement as external plaster in previous improper repair attempts and partial failures to stones at Mehrab. (D and E) sever decaying and erosion of limestone blocks (disintegration, powdering, fissuring, flaking, spalling and crushing), as can be noted the joints mortar was disintegrated severely, and also the timber tie-beams were severely decayed and damaged.

3.2. Mineralogical and elemental analyses

3.2.1. Mineralogical analysis XRD (Qualitative analysis)

Stone samples: The obtained results from XRD analysis of the stone samples taken from the outer layers and the inner filling layer of the investigated multiple-leaf masonry walls (Table 1 and Fig. 4) confirmed the following:

- Fossiliferous Limestone consisted essentially of calcite $CaCO_3$ of about 92%, and a small quantity of quartz SiO_2, halite NaCl, albite $NaAlSi_3O_8$ and traces of hematite Fe_2O_3. The presence of a low percentage of quartz and albite minerals as impurities, and sometimes a very low percentage of hematite as a trace mineral, which is due to the migration of iron oxides of geological origin, and the presence of mineral halite as a product of damage which indicates salt weathering of stone by sodium chloride salt, this salt arises from the marine environment rich in chloride ions.
- Coral stone consisted essentially of aragonite $CaCO_3$ of about 88%, and a small quantity of calcite $CaCO_3$. Aragonite forms naturally in almost all mollusk shells and as the calcareous endoskeleton of warm- and cold-water corals (Scleractinia), and it is one of the two common, naturally occurring, crystal forms of calcium carbonate, $CaCO_3$, the other form being mineral calcite. Aragonite is thermodynamically unstable at standard temperature and pressure and it tends to alter to calcite [Abdelwahab, 2003; Saleh, 2013b).

Mortar samples: The obtained results from XRD analysis of the mortar samples taken from the investigated multiple-leaf masonry walls of the Al-Shafei mosque whether from the outer layers or from the inner filling layer (Table 1 and Fig. 4) confirmed that, it is mud-lime mortar "marine mud"; as it is composed by calcitic lime binder and siliceous aggregates (quartz, feldspar), with a dominance of aggregates and very low amounts of binder, also with abundance of seashells and coral fragments. According to XRD results, mud-lime mortar is mainly composed of quartz SiO_2, calcite $CaCo_3$, aragonite $CaCO_3$, Na-feldspar (albite $NaAlSi_3O_8$) and traces of K-feldspar (microcline K Al Si_3 O_8), hematite Fe_2 O_3, halite NaCl and gypsum $CaSO_4$ $2H_2O$. The aggregate fraction is constituted by quartz and feldspar, components originating from very mature sediments nearby. The calcite phase is the binder component formed after the carbonation process of slaked lime. Aragonite phase originating from seashells and coral fragments found in mortar structure. The presence of vestigial amounts of halite and gypsum was considered to relate to the marine environment, because such compounds arising from the marine environment rich in chloride and sulfate ions. It is worth noting that the presence of gypsum in mortar samples may indicates a salt weathering, or it may originating as sediment in marine mud, or it could be added to the mortar mixture with a very small proportion to improve its strength.

Table I. Results of X-ray diffraction analysis of the collected walling materials samples

Material	Samples	Composition
Fossiliferous Limestone from external layers	F1	Calcite($CaCO_3$), Quartz(SiO_2), Halite (NaCl).
	F2	Calcite($CaCO_3$), Albite($NaAlSi_3O_8$), Halite (NaCl).
Fossiliferous Limestone from inner filling layer	F3	Calcite($CaCO_3$), Quartz(SiO_2), Hematite (Fe_2 O_3), Halite (NaCl).
Coral stone from external layers	C1	Aragonite ($CaCO_3$), Calcite($CaCO_3$)
Mortar from external layer	M1	Calcite($CaCO_3$), Quartz(SiO_2), Aragonite ($CaCO_3$), Albite($NaAlSi_3O_8$), Hematite (Fe_2 O_3), Gypsum ($CaSO_4$. $2H_2O$).
Mortar from inner filling layer	M2	Calcite($CaCO_3$), Quartz(SiO_2), Aragonite ($CaCO_3$), Albite($NaAlSi_3O_8$), Microcline (K Al Si_3 O_8), Hematite (Fe_2 O_3), Gypsum ($CaSO_4$. 2 H_2O), Halite (NaCl).

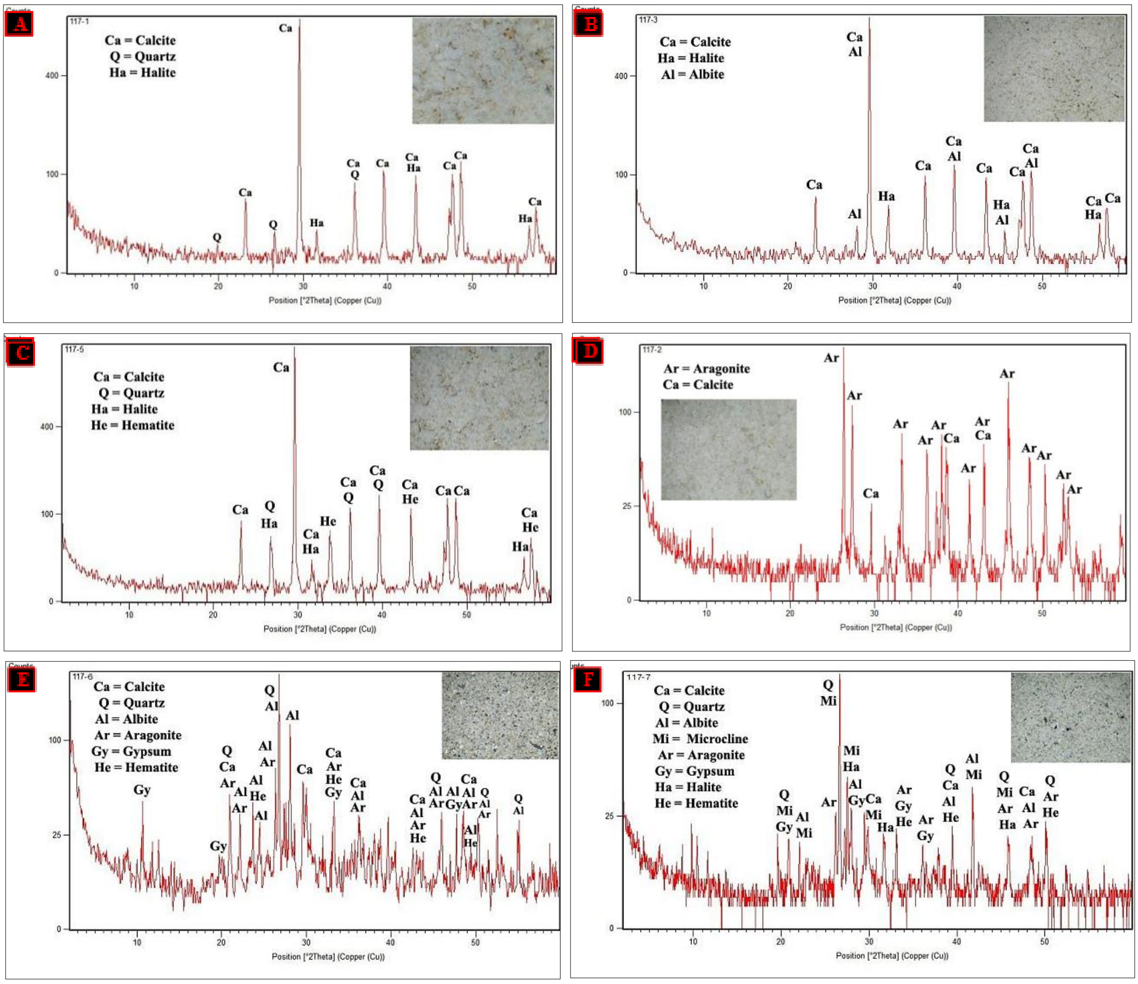

Figure 4. X-ray diffraction pattern of the collected samples from the investigated multiple-leaf masonry walls of the mosque: (A and B): Fossiliferous limestone samples taken from the outer layer, F1 and F2; (C): Fossiliferous limestone sample taken from the inner filling layer, F3; (D): Coral stone sample taken from the outer layers, C1; (E): the mortar sample taken from the outer layer, M1; and (F): the mortar sample taken from the inner filling layer, M2.

3.2.2. Elemental analysis EDX (quantitative analysis)

Stone samples: Elemental analysis by EDX (Energy Dispersive X-ray Analyses) compliments the mineralogical study made by XRD. The chemical data acquired by EDX Unit (Table 2 and Fig. 5) shows that the main elements of Fossiliferous Limestone are Ca, O, C and Si, related with calcite and quartz, as detected by XRD. Na and Cl are related with the presence of halite salt. The minor amount of Fe is related with the hematite and Al as well Na and Si are related with the albite in the samples, as seen in XRD. The other elements do not have significant amounts that point to other minor mineral phases not detectable by XRD. The main elements of coral stone are Ca, O, C, related with aragonite and calcite, as seen in XRD.

Mortar samples: The results of EDX show that the main elements of the original mud-lime mortar are Ca, O, C and Si, related with quartz, calcite and aragonite, as detected by XRD. Al, K, and Mg is related with the presence of feldspars, as seen in XRD. The small amount of Fe is related with the presence of hematite. The minor amount of Cl and Na is related with the presence of halite salt. The traces of S is related with the context of the samples and appeared as a gypsum salt. EDX results confirm that quartz and feldspar are related with the siliceous aggregate component and calcite with the binder component. Gypsum occurs either as efflorescence (or neo-formed gypsum), as it results from the availability of calcium ions (from the dissolution of the binder mortar) and sulfate ions (from sea spray and salty fog), or originating as sediment in marine mud.

Table 2. Quantitive EDX microanalysis (wt %) of the collected walling materials samples

Sample	C	O	Na	Mg	Al	Si	S	Cl	K	Ca	Fe
F1	7.02	41.48	2.86	1.76	2.73	5.74	0.26	1.85	0.63	33.73	1.95
F2	10.60	25.25	13.82	0.79	0.75	1.65	0.29	16.08	0.41	30.34	
F3	7.11	37.55	1.21	1.13	1.14	2.30	0.26	1.13		46.83	1.61
C1	6.94	53.50								39.56	
M1	5.72	41.06	1.52	3.61	5.68	17.29	0.38	1.08		17.35	4.82
M2	6.68	40.99	1.34	3.67	5.09	13.78	0.50	0.65	1.18	22.63	3.48

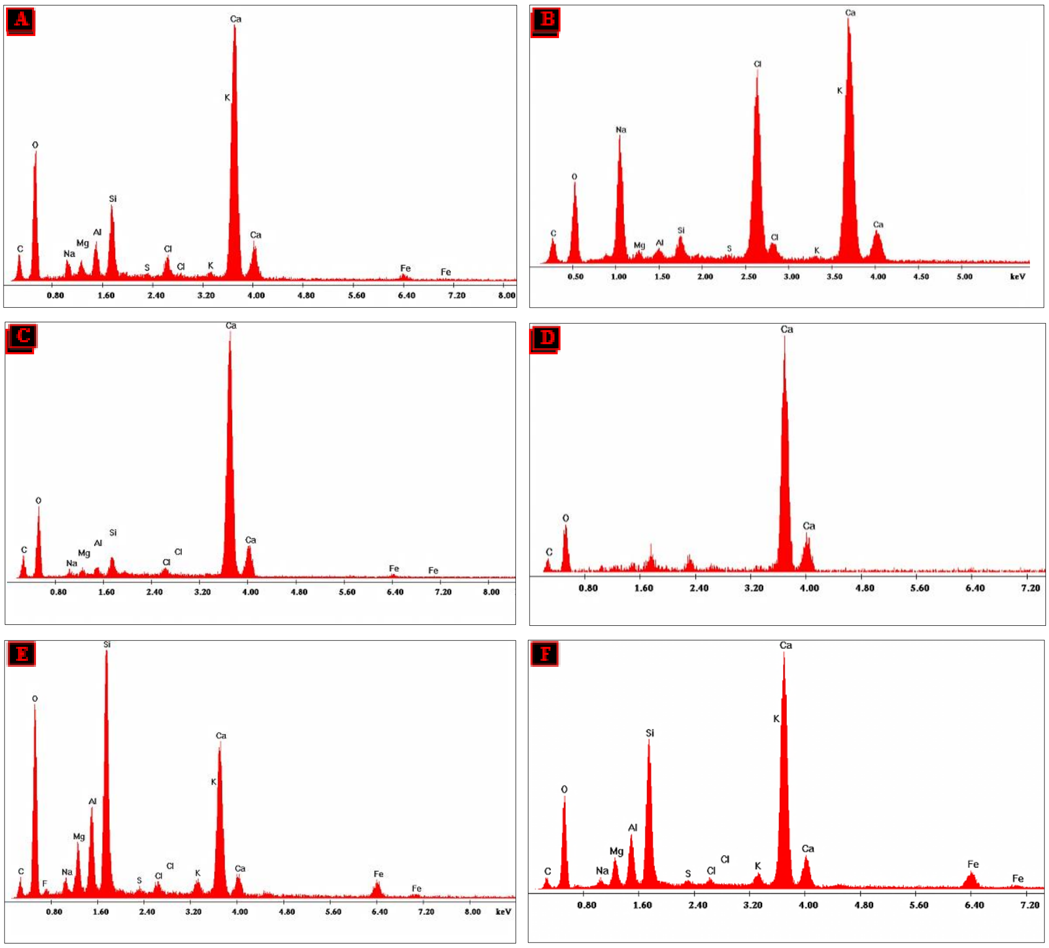

Figure 5. SEM-EDX spectrum of the collected samples from the investigated multiple-leaf masonry walls of the mosque, (A and B): Fossiliferous limestone samples taken from the outer layers, , F1 and F2; (C): Fossiliferous limestone sample taken from the inner filling layer, F3; (D): Coral stone sample taken from the outer layer, C1; (E): the mortar sample taken from the outer layer, M1; and (F): the mortar sample taken from the inner filling layer, M2.

3.3. Petrographic and morphological investigations

3.3.1. Optical microscopy (OM) investigations

Stone samples: The microscopic observations of the collected samples (F1, F2 and F3) from of the mosque walling stones by using USB digital microscope clearly revealed that the fossiliferous Limestone used in the multiple-leaf stone masonry walls of the Al-Shafi'i mosque whether used as masonry unit or as stone fragments is mostly friable, and has a coarse and heterogeneous texture of the pale beige colour with some dark red spots, and in addition to many marine fossils which differ in shape, volume and number from sample to sample. Moreover, this stone has suffered from many forms of degradation such as granular disintegration, powdering, pitting, sanding, alveolar, fissuring, spalling, flaking, and salts crystallization (as shown in Fig. 6). As for the coral stone sample (C1), the microscopic observations revealed that this stone is coral skeletals with interskeletal pores and cavities, and showed the weakness, fracturing and breakage in these skeletals (as shown in Fig. 7).

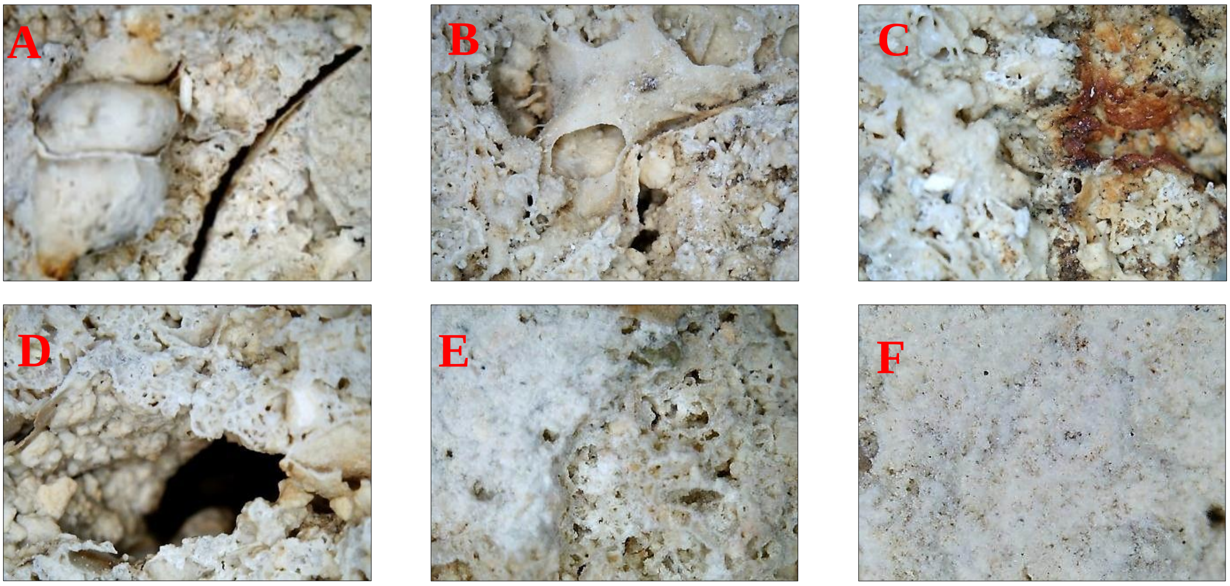

Figure 6. OM observation of the fossiliferous limestone samples, (F1, F2 and F3); (A and B) a coarse and heterogeneous texture of fossiliferous limestone contains shells fragments, (C) dark red spots, (D) holes and cavities, (E and F) crystallization of salt (OM images, magnification 100 X).

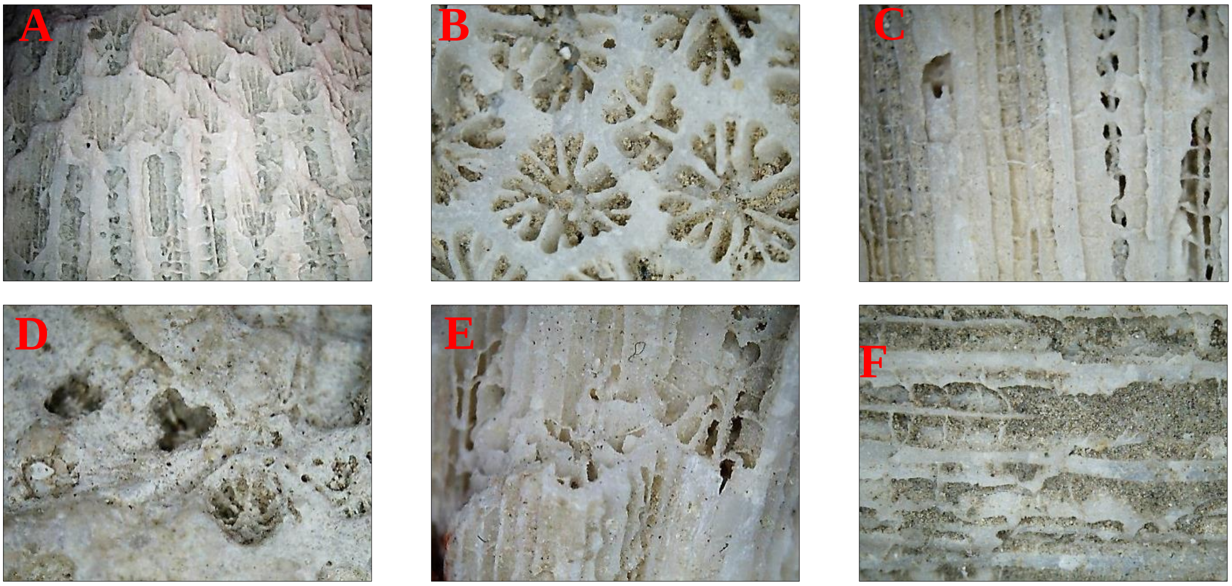

Figure 7. OM observation of coral stone sample, C1; (A) texture of coral stone shows a cut face of stone exposed on a step, (B) the coral's branches look circular on top of the step (where they are in cross section), (C) but these branches look like long pencils on the side of the step (where they are in long section), (D, E, F) show weakness, breakage and erosion in the coral skeletal (OM images, magnification 100 X).

Mortar samples: The microscopic observations of the collected samples (M1 and M2) from of the walling mortar (original structural mortar whether used in the external layers for jointing the limestone blocks or in the inner filling layer for binding the rubble limestone fragments) by using USB digital microscope clearly revealed that this mortar is marine mud or mud-lime mortar, its texture is heterogeneous, coarse, incoherent, light grey-colored. This mortar is friable, crumble easily, exhibits very low bonding characteristics and mechanical strength, and it contains high contents of shell fragments with elongated morphology or spherical, some organic fibers and inclusions of stone fragments, also it has cracked structure (as shown in Figure 8).

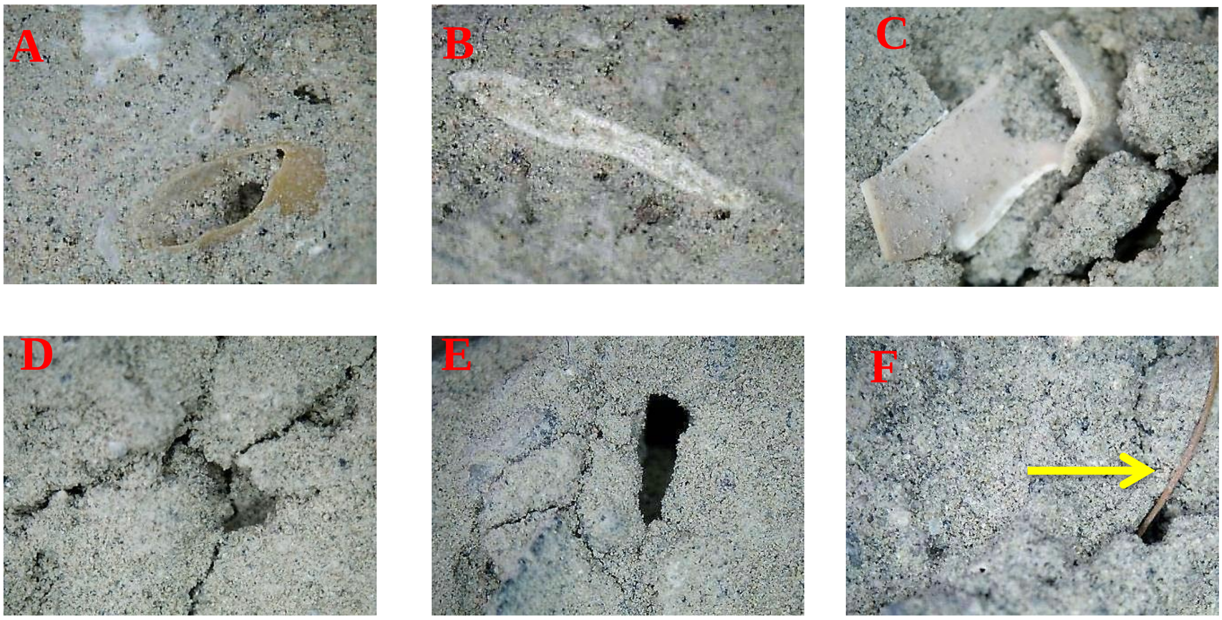

Figure 8. OM observation of the original structural mortar samples, M1 and M2; (A, B) texture and internal microstructure of mortar characterized by shell-formation inside, (C, D, E) cracks, micro fracturing and cavities in mortar structure, (F) organic fiber in mortar structure (OM images, magnification 100 X).

3.3. 2. Petrographic investigation (PM)

Stone samples: The obtained results from Polarized microscopy examination of limestone samples (F1, F2, and C1) were taken from the external layers and (F3) from the inner filling layer of the investigated multiple-leaf stone masonry walls revealed that: two types of limestone (fossiliferous limestone and coral stone) were used in these walls.

Fossiliferous limestone "Shelly limestone" is cut from a fine sandy to silty fossiliferous carbonate rock consisting of skeletal allochems and quartz grains embedded mainly in silty lime-mudstone (micrite). Petrographically, the rock is highly fossiliferous composed of molluscan shells, echinoid spines, benthonic foraminiferal and algal skeletals fragments. The shell fragments show the original internal microstructure, fine fibours wall, vesicular tissue and fine cellular structure (Fig.9a, b). Some allochems (e.g echinoid spines) are composed of fine elongated empty cavities surrounded by dark micritic envelope (Fig. 9c). The main cavities of the molluscan shells (e.g gastropoda) are partially filled by silty micrite (Fig. 9d). The original internal structure of aragonite fibrous wall may be maintained or preserved through replacement by calcite (Fig. 9a, b, d). Some bivalves chambers are filled with quartz silty grains that amalgamated by iron oxide stained micrite paste (Fig. 9a, b).

Coral stone essentially composed of coral skeletals associated with thin coralline algal rims that show interskeletal pores and cavities (about 40%). These pores and cavities are almost empty, or partially filed with micritc materials. The cavities walls are mainly fringed by columnar fibrous or acicular aragonite crystals that perpendicular to the cavities walls and then by micrite envelope around them which is composed of calcitic materials. The distribution of these cavities indicates longitudinal thin section. But the cross-section that perpendicular to the thin section compositionally is the same but showing such internal features as septa internal and plate voids tabular cross section. The irregular cavities are merged by fibrous or acicular aragonite crystals that perpendicular to these walls (as shown in Fig. 10).

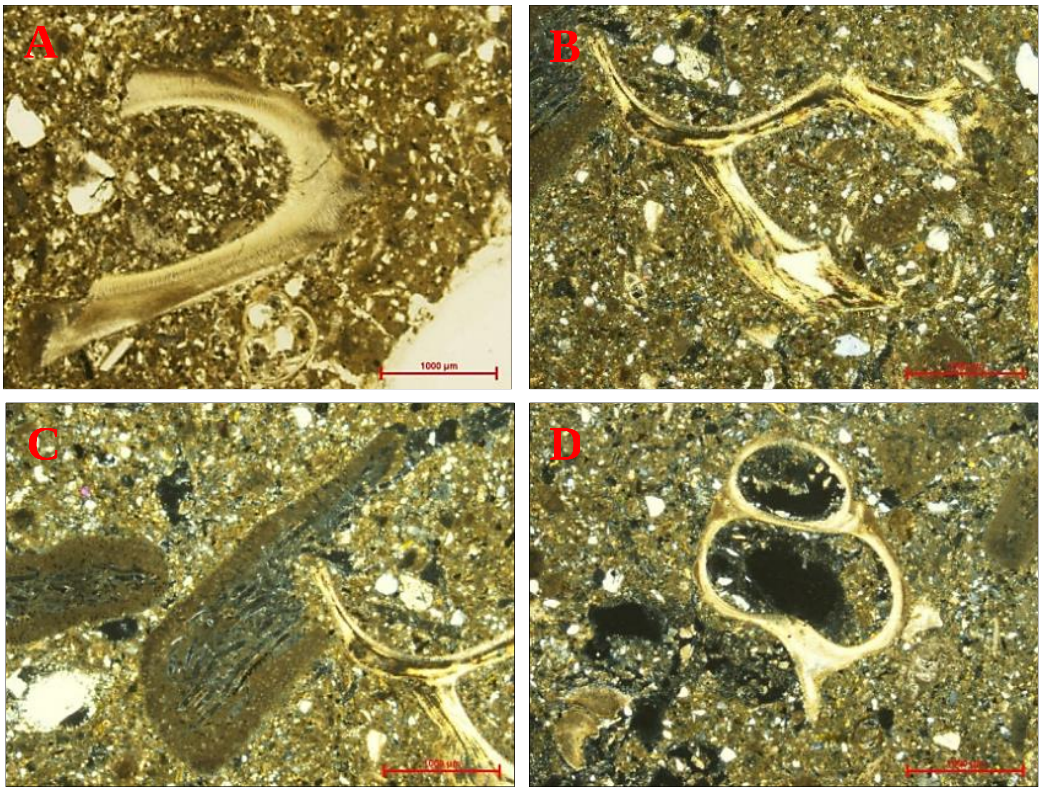

Figure 9. (A, B, C and D) Polarizing (PM) micrographs of Shelly limestone samples (F1, F2, F3) taken from the investigated multiple-leaf masonry walls of the mosque, showing the shelly micro-structure of the Shelly limestone.

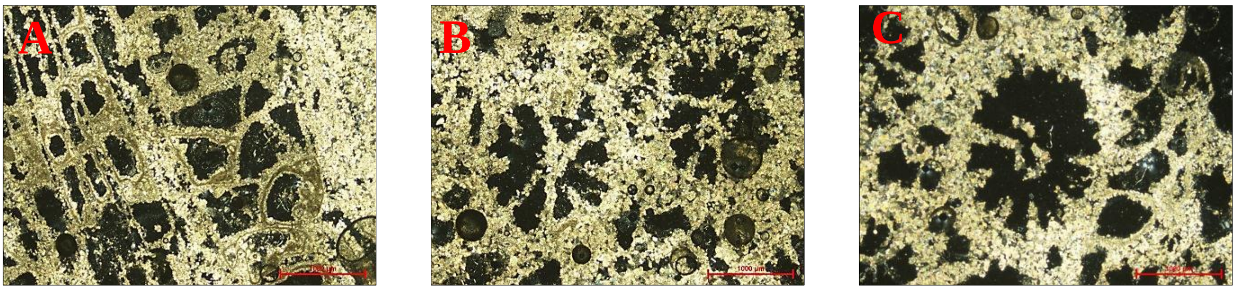

Figure 10. Examples of thin section photomicrograph of coral stone sample taken from the external layer of the investigated multiple-leaf masonry walls, (A) longitudinal thin section, showing the cavities walls, (B and C) cross-section, showing internal features as septa internal and plate voids tabular.

The texture classification of the Dunham (1962) and its modification by Embry and Klovan (1971) and James (1984) are followed during the description of the carbonate rocks. The composition of the carbonate rocks is described using the classification of Folk (1952). Accordingly, the skeletal and non-skeletal of the carbonate components are mainly represented by corals, algae, benthonic foraminifera tests and molluscans shells (fragments) as well as peloids and ooides. These allochems are associated with rock fragments and quartz grains or even with intraclast carbonate fragments, are embedded in lime-carbonate matrix (Dunham, 1962; Embry and Ashton, 1971; Allaby, 1999).

Fossiliferous limestone is termed biosparite limestone under the Folk classification of sedimentary rocks. It is an organic limestone, made mostly of calcium carbonate $CaCO_3$ in the form of the minerals calcite or aragonite (polymorphs of $CaCO_3$) form shells, corals, etc, the latter is metastable and reverts to the calcite structure. It contains an abundance of shells or shell fragments [Marshak, 2001]. The fossils in these carbonate rocks may be of macroscopic or microscopic size. These carbonate rocks usually found associated with coral reefs (Crespin, 1955), and are effectively sediment made up primarily of calcium rich skeletons and shells of sea creatures. These sediments were laid down millennia ago in layers of what eventually, through various geological processes became calcium rich stone. Limestone will often show some of the fossilised shells of these ancient sea creatures in its make up (Holmes and Rowan, 2015).

Mortar samples: The mortar samples (M1, M2) taken from the outer layers and from the inner filling layer of multiple-leaf masonry walls of the Al-Shafei mosque is mud-lime mortar. Petrographically, it consists of molluscan shell fragments, algal fragments and coral skeletals that associated with few coarse quartz grains embedded in silty lime matrix. Few fractures and voids are scattered within the mud matrix. The majority of the quartz grains are angular grains in the silt size, however some of them are in the sand size showing, rounded to sub rounded shape (as shown in Fig. 11a, b, c).

Figure 11. Examples of thin section photomicrograph of the structural mud-lime mortar samples taken from the outer layers and the inner filling layer of multiple-leaf masonry walls of the Al-Shafei mosque, (A and B) showing molluscan shell fragments with coarse quartz grains embedded in silty lime matrix, along with few fractures and voids, (C) showing coral skeletals, algal fragments and shell fragments and with few coarse quartz grains embedded in silty lime matrix.

3.3. 3. SEM investigation

Stone samples: SEM photomicrographs of the collected fossiliferous limestone samples (F1, F2, F3) show that there are weakness and disintegration in the microstructure of stone. Many pores, voids and large cavities (fossils trace) are scattered within the internal microstructure of stone. There are few fractures, poor adhesion between mineral grains and some of them are loose and disintegrated, as well as crystallization of halite salt (as shown in Fig. 12).

As for coral stone, SEM photomicrographs of the collected coral stone sample (C1) show that there are weakness and fracturing in the coral skeletal, particularly, the cavities walls and the columnar fibrous aragonite crystals that perpendicular to these walls (as shown in Fig. 13).

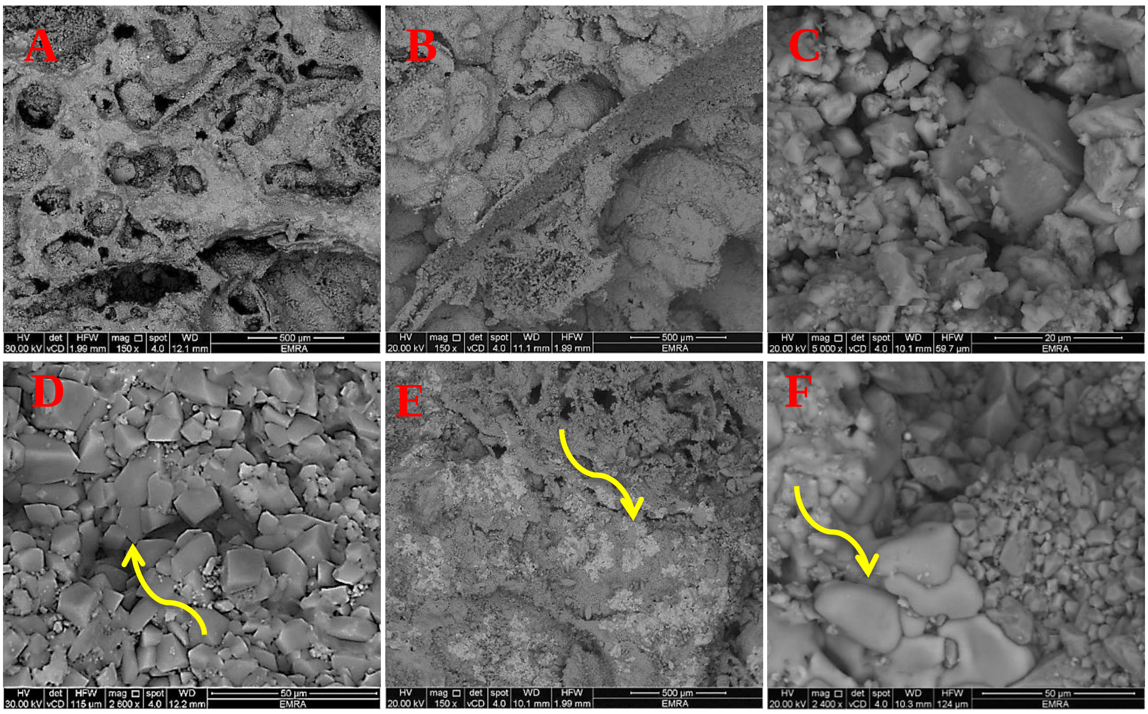

Figure 12. SEM micrographs of the deteriorated fossiliferous limestone of Al- Shafi'i mosque walls show, (A and B) showing the coarse texture of this stone with the presence of voids and cavities, (C and D) showing granular disintegration and the loss of cohesion between grains, (E and F) showing the flat halite salt crystals.

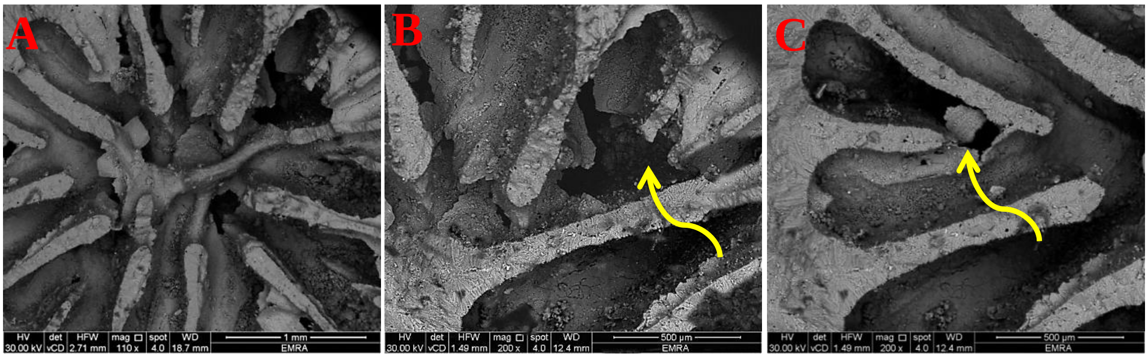

Figure 13. SEM micrographs of the deteriorated coral stone of Al- Shafi'i mosque walls, (A) showing the coral skeletal with cavities walls, (C and D) showing the weakness and breakage in the coral skeletal.

Mortar samples: SEM photomicrographs of the collected mortar samples (M1, M2) show that the original structural mortar of Al-Shafi'i mosque walls is friable and contains high contents of shell fragments, inclusions of stone fragments and some organic fibers. As well as, it has suffered from crystallization of halite and gypsum salts (as shown in Fig. 14)

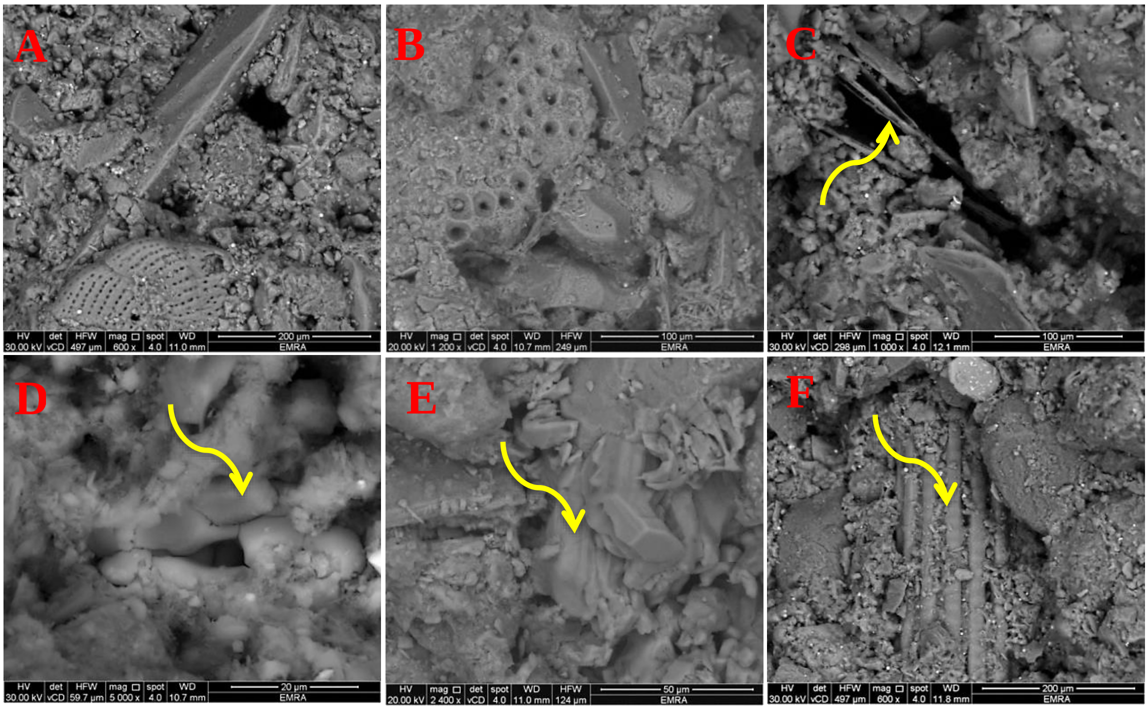

Figure 14. SEM micrographs of the deteriorated mortar of Al-Shafei mosque walls; (A and B) showing the mortar microstructure consists of shell and stone fragments with quartz grains in mud matrix, (C) showing the organic fibers, (D) showing the halite salt crystals; (E and F) showing the elongated gypsum salt crystals.

3.4. Physical and mechanical properties characterization

The physical and mechanical properties for the stone samples taken from the external layers of the investigated multiple-leaf masonry walls of the mosque were tested and determined (as shown in Fig. 15), and the average values of the tests results (as shown in Table. 3) revealed that:

- The fossiliferous limestone used mainly in the construction of the Al-Shafi'i mosque walls is characterized by very low density, highly porosity and high water absorption, where the average bulk density of this stone was found to be 1.48 G/cm^3, the average water absorption was found to be 19.7% and the average apparent porosity was found to be 29.4%, and it has also a very low resistance to vertical axial stresses, where the average compressive strength of this stone was found to be 7.3 N/mm^2, and a low resistance to bending stress, where the average bending strength this stone was found to be 3.3 N/mm^2.

- The coral stone used in a very small proportion in the construction of the Al-Shafi'i mosque walls is characterized by extremely high porosity, very low density, very high water absorption and weak mechanical strength, where the average bulk density of this stone was found to be 1.42 G/cm^3, the average water absorption was found to be 26% and the average apparent porosity was found to be 37.1%, and it has also a low resistance to vertical axial stresses, where the average compressive strength of this stone was found to be 12.4 N/mm^2, and a low resistance to bending stress, where the average bending strength of this stone was found to be 4.6 N/mm^2.

It is clear from the results of the previous tests that the fossiliferous limestone samples display lower values of strength, porosity and water absorption compared to the coral stone samples. But, the coral stone samples display values of density are lower than the fossiliferous stone samples. Finally, we concluded from these results that the main building stones of Al-Shafi'i mosque walls are of very low quality and in very deteriorating condition, which is the major problem causing defect and deterioration to the building structure along with the influence of the harsh marine climate conditions.

Table 3. Physical and mechanical properties of stones samples from the external layers of the investigated walls

Stone type	Average values of the tested physical properties			Average values of the tested mechanical properties	
	Density, g/cm3	Water absorption, %	apparent Porosity, %	Compressive strength N/mm2	Flexural tensile strength N/mm2
Fossiliferous limestone	1.48	19.7	29.4	7.3	3.3
Coral stone	1.42	26	37.1	12.4	4.6

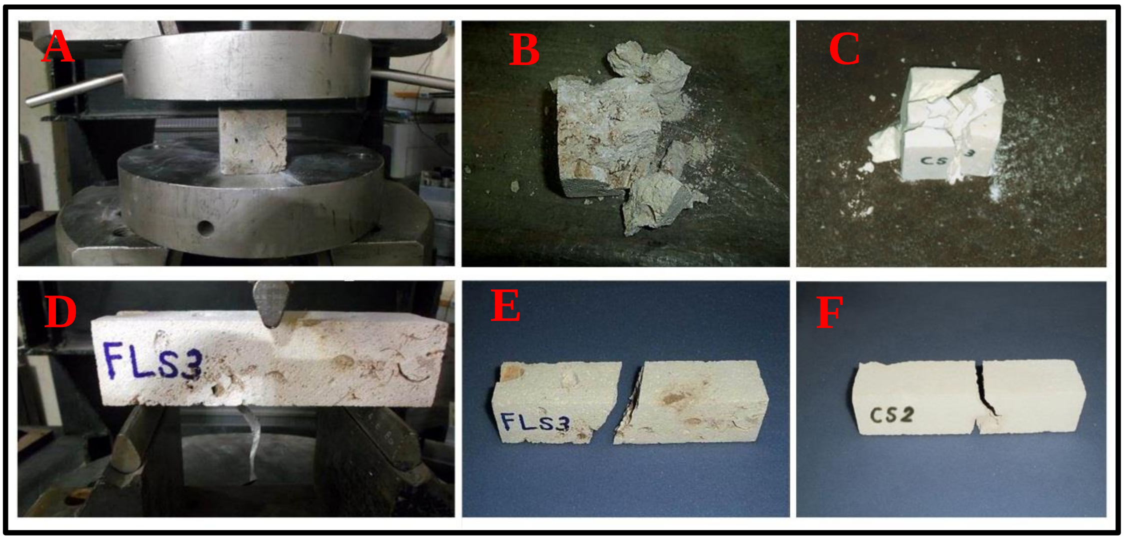

Figure 15. Standard mechanical tests conducted on the extracted stone samples, (a) compressive strength test on stone cubic specimen; (b) failure mode of Fossiliferous limestone and coral stone samples respectively; (D) flexural tensile strength test on stone prismatic specimen; (E, F) failure mode of Fossiliferous limestone and coral stone samples respectively.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the analyses, investigations and tests that we carried out according to the methodology adopted in this research, the following conclusions can be drawn:

- All the existing multiple- leaf stone masonry walls of Al-Shafi'i mosque are mainly built from fossiliferous limestone "Shelly limestone", where it used as unity in the external leaves masonry and as stone fragments in the inner core, this stone consists essentially of calcite and very small amounts of quartz and red iron oxide (hematite) as impurities, beside halite which was found as a product of damage indicates salt weathering of stone by sodium chloride salt, this salt arises from the marine environment rich in chloride ions. As well as coral stone used in a very small proportion in the construction of these walls along with fossiliferous limestone, which consists essentially of aragonite and a small amount of Calcite.

- There is one type of the original structural mortar, which jointing the stones blocks in the outer layers and binding the stone fragments in the inner core layer. This mortar was typically mud-lime mortar "marine mud", and it is composed by calcitic lime binder and siliceous aggregates (quartz, feldspar), with a dominance of aggregates and very low amounts of binder with abundance of seashells and coral fragments, In addition to the presence of some organic fibers. In this mortar chlorides and sulfates compounds were also present, namely halite and gypsum, which arising from the marine environment rich in chloride and sulfate ions. These salts are believed to have influenced the disintegration processes of soft and friable masonry mortar in Al-Shafi'i mosque walls.
- The current actual state of the walling materials of Al-Shafi'i mosque was found to be extremely poor; the main building stones are more friable, have a low strength and low-bearing capacity, and exhibit a high proportion of pores, holes and cavities, which led to reduce of their mechanical strength and degradation of their structural state. Beside, these walling materials exposure to various factors and forces of deterioration, where these materials have undergone various deterioration processes caused by external and internal stresses due to the mineral composition of these materials, to the extremely harsh marine climate factors, and also to the use of black cement mortar in the previous restoration attempts. Consequently, it is essential to consolidate the fragile stone blocks in Al-Shafi'i Mosque walls and enhance their properties with consolidant and injection grout compatible with their components and suitable for their state, and to isolate them from different sources of surrounding moisture. This would raise the overall mechanical strength of the stone masonry loadbearing walls and enhance the structural safety levels of this heritage building against various affecting loads.

The obtained results from this study provide very useful information for the selection of compatible materials and the most appropriate techniques when Implementation of the intended structural interventions for the Al-Shafi'i mosque. From the premise that we should use merely similar materials which were used originally or materials with comparable characteristics to the original materials so as to preserve the authenticity of the Al-Shafi'i mosque as a heritage resource. It is recommended that the new mortars for any future structural conservation works should be formulated based on the composition and texture of the original mortars with the addition of some compatible additives to improve their properties (the friable and badly deteriorated structural mortar should be removed and replaced with stabilizing mortar such a pozzolana-lime based mortar which is make from slaked lime "lime putty" combined with local sea sand and red brick dust, that will ensure long term performance of mortar). The stone to be used in possible replacements of severely damaged parts in the mosque walls will be selected based on criteria of suitability, compatibility, and durability, to enable successful repair works essentials for intervention in this very important heritage building.

Finally, the masonry materials (stone units and joints mortar) after being treated should be protected from the combined effects of humidity, heat, salts, heavy seasonal rains, sand storms by applying a thick coat of traditional lime plasters on them to cover and protect the Al-Shafi'i mosque walls.

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