# Deterioration Types of Stones Used in Suleymaniye Mosque (Istanbul, Turkey)

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**Abstract**. Suleymaniye Mosque located in the historic peninsula of Istanbul, is one of the most important monument of classical Ottoman Architecture. Different types of natural stones having varied lithological characteristics were used in the mosque. Chemical composition, mineralogical, petrographic characteristics and external conditions such as atmospheric effects, earthquake and human impacts have deteriorated these stones over time. The aim of this study is to investigate different natural stones and their deterioration types used in Suleymaniye Mosque. According to the results obtained, generally different types of granites, marbles, limestones, pudding stones, porphyry, serpentinite were used in Suleymaniye Mosque. Detachment, material loss, biological colonization, discoloration and deposits have been determined as a deterioration types on these stones.

## 1. Introduction

In the past, Istanbul was the capitol of Rome, Byzantine and Ottoman Empire so that it is a rich city in terms of historical monuments. Suleymaniye Mosque is one of the most important historical building of classic Ottoman architecture. Suleymaniye Mosque resides in Historic Peninsula of Istanbul province (Figure 1). This mosque was built on the time of Sultan Süleyman the Magnificent and constructed by the great Ottoman architect Sinan. Suleymaniye mosque and its complex is a group of buildings, which were built between the years 1550-1557. All rocks used in construction of mosque are exposed to an environmental deterioration as a result of physical, chemical, mechanical and biological processes. The factors considered to be among the leading causes of building stone deterioration include salt crystallization, aqueous dissolution, frost damage, pollution, microbiological growth, human contact, and original construction. There was not any restoration works on Suleymaniye mosque for conservation, while this study was proceeding. Therefore, only observational studies was conducted on natural stones used in the construction of the historical buildings. As a result of this observational study various natural stone used in Suleymaniye mosque and their deterioration types were identified as macroscopic (Table 1).

## 2. Deterioration types of natural stones used in Suleymaniye Mosque

The macroscopic observation of deterioration types in all rocks used in the construction of the mosque has been defined based on the deterioration classification of [1] (Table 2). As a result of observational

study different kinds of deterioration types were identified in natural stones used in Suleymaniye mosque (Table 3).

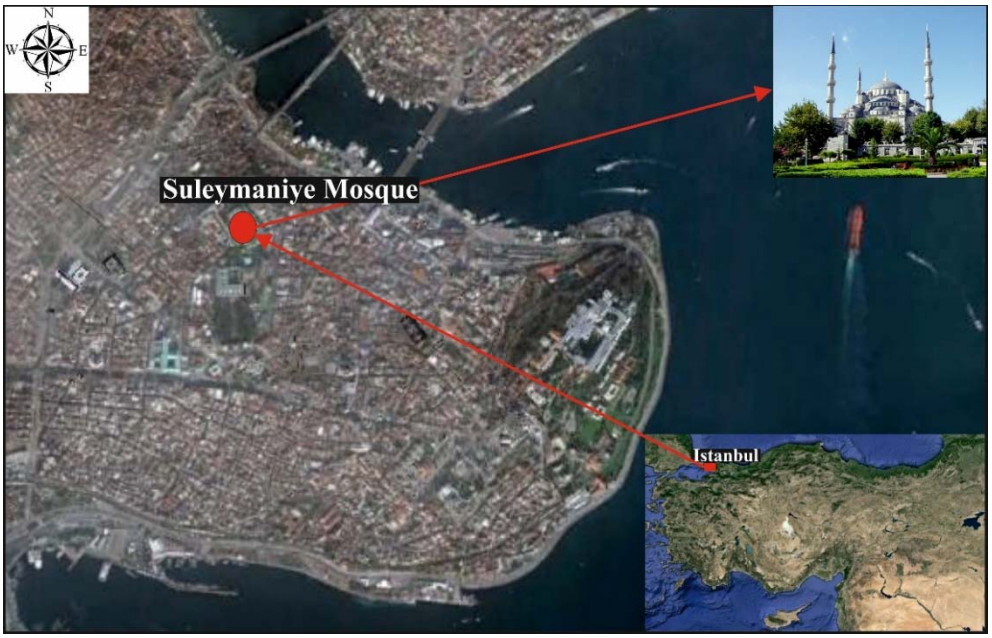
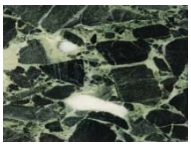



**Figure 1.** Location map of study area

**Table 1.** Properties and place used of natural stone in the Suleymaniye Mosque.

| Name of natural stone | Lithology | Place used in the Mosque | Texture and colour |
|---|---|---|---|
| **Marmara Marble** | Marble | Column, column base and head arch, masonry and floor, balustrade and foot step |  |
| **Bakırkoy Kufeki** | Limestone | Foundation, body and nonbearing masonry, masonry footing, buttress, arch, floor, capstone, jamb |  |
| **Kestanbol Granite** | Quartz Monzonite | In the courtyard and outdoor sofa upstairs columns |  |
| **Armutlu Granite** | Granite | Courtyard porches columns |  |
| **Iznik Marble** | Marble | Floors |  |
| **Gulumbe Limestone** | Oolitic limestone | Outside sofa upstairs columns and courtyard floor curbstone |  |

| | | | |
|---|---|---|---|
| **Bandırma Breccia** | Brecciated Marble | In the courtyard colonnade arch and floor curbstone |  |
| **Gebze Rudist Limestone** | Rudist Limestone | Interior sofa column and entrance in port covering |  |
| **Afyon Violet Marble** | Brecciated Marble | Sultan's loge column and in the courtyard floor curbstone |  |
| **Hereke Pudding** | Pudding (conglomerate) | In the courtyard arch, in-window jambs and floor curbstone of courtyard terrace set |  |
| **Egypt Aswan Granite** | Syenite | Courtyard porch, exterior sofa and column of inside the mosque |  |
| **Red Porphyry** | Andesite-dacite porphyry | At the main entrance courtyard porch column, sofa front small discs, rectangular and circular flooring curbs of courtyard |  |
| **Green Porphyry** | Dacite porphyry | Sofa front small discs |  |
| **Greece Serpantine Breccia** | Serpentine breccia | Courtyard porch columns and flooring curbs and discs, courtyard side entrance doors masonry covering and door arches, column of the Sultan's gathering-place and inside the Mosque |  |

*2.1. Crack and Deformation*

Cracking results from a variety of conditions, such as structural settlement of a building, plant root cause human-induced or natural disasters. Certain stones which are exposed to frost damage. The frost susceptibility of a stone is largely controlled by its porosity and pore size distribution. Generally, crack deformations are occured by frost damage and earthquake which were observed nearlly all of natural stones used in Suleymaniye Mosque (Figure 2).

*2.2. Detachment*

Detachment process affecting laminated stones (most of sedimentary rocks, some metamorphic rocks). It corresponds to a physical separation into one or several layers following the stone laminae. According to ICOMOS, detarioration type of Detachment is investigated into two parts as Peeling and Fragmentation.

*2.3. Material Loss*

Material loss was observed as Alveolization, Erosion, Karst, Missing part. Alveolization can occur from many processes: granular disintegration and flaking, salt mechanics, wetting and drying, frost

weathering, and solutional or chemical alteration. In nearly every case, alveolization begins with small indentations in the rock that collect water. The water evaporates leaving sediments that can be moved by wind and water, leaving a larger indentation. With this occurring over and over for long periods of time, the caverns enlarge. In general, alveolization was just sighted in Marmara Marble and Granite column (Figure 4).

**Table 2.** According to International Council on Monuments and Sites (ICOMOS) Type of Deterioration

| Type of Deterioration | | | Type of Deterioration | | |
|---|---|---|---|---|---|
| **Crack & Deformation** | Crack | + | **Discoloration & Deposit** | Crust | + |
| | Deformation | + | | Deposit | |
| **Detachment** | Blistering | | | Discoloration | + |
| | Bursting | | | Efflorescence | |
| | Delemination | | | Encrustation | |
| | Disintegration | | | Film | |
| | Fragmentation | + | | Glossy aspect | |
| | Peeling | + | | Graffiti | |
| | Scaling | | | Patina | |
| **Material Loss** | Alveolization | + | | Soiling | |
| | Erosion | + | | Subflorescence | |
| | Mechanical damage | | **Biological Colonization** | Alga | + |
| | Karst | + | | Lichen | + |
| | Missing part | + | | Moss | + |
| | Perforation | | | Mould | |
| | Pitting | | | Plant | + |

+ : Observated deterioration types of natural stone used in mosque

**Figure 2.** Crack deformations in different natural stones used in Suleymaniye Mosque

Peeling of stone caused by an inherent defect in the surface of the masonary and columns or the result of weathering [2]. This type of deterioration was occured depend on atmospheric effects in Marmara Marble column (Figure 3).

**Table 3.** Lithology and deterioration types of natural stones used in Suleymaniye Mosque.

| Types of Natural Stones | Deterioration Types |
|---|---|
| **Marble** | Discoloration, missing part, perforation, sugaring, alveolization, erosion, peeling, fragmentation, crack deformation, karst, biological colonization |
| **Limestone** | Discoloration, missing part, fragmentation, karst, crack deformation, erosion, biological colonization |
| **Granite** | Discoloration, missing part, perforation, sugaring, peeling, fragmentation, crack deformation |
| **Breccia** | Missing part, discoloration, crack deformation, erosion |
| **Pudding Stone** | Missing part, erosion, discoloration, crack deformation |
| **Porphyry** | Crack deformation, missing part, erosion, discoloration |

Fragmentation is related to water influence in microcrack and among foliation layers, at the end of this situation portion is seperated from natural stone, not break off. In general, Fragmentation was sighted almost all natural stones used in mosque (Figure 4).

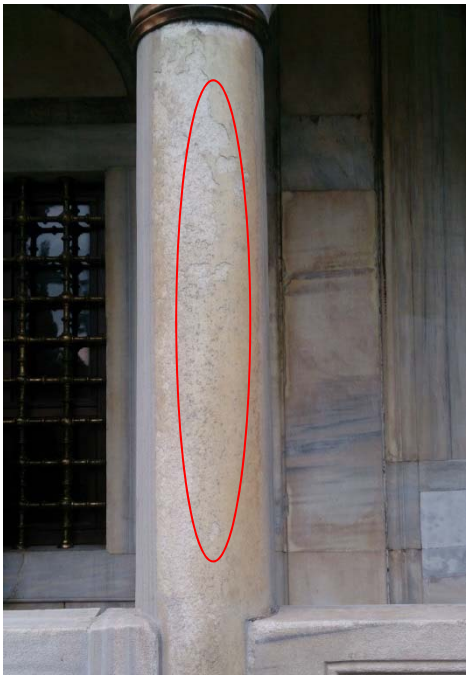


**Figure 3.** The view of peeling on the surface of Marmara Marble

Erosion is occured by weathering away of the surface edges, corners, fretwork, up to stairs or carved details of masonary slowly and usually by the natural action of wind or windblown particles and water [2]. Because of an increasing interest by the public in historic structures, the effects of human contact upon the condition of stone floors are gradually worn by foot traffic, stones are damaged by people [3]. Surface wear occurring on Hereke Pudding column (Figure 9) and Marmara Marble used as floor coverings (Figure 5).

**Figure 4.** Alveolization (ellipse) and fragmantation (square) the view of granite column located in mosque courtyard

**Figure 5.** The view of erosion (right up) and abrasion (right down) in Marmara Marble, Hereke Pudding and Küfeki Stone

Karst developed on the base of a chalk column particularly exposed to water. The chemical processes of deterioration the role of water is very important because of the phenomena of dissolution, hydrolysis and hydration. The other effect of water is moving from inside the core of the wall outward via the stones instead of through the joints. This situation has led to accelerated deterioration of the building stones. The carbonic acid that causes these features is formed as rain passes through the atmosphere picking up carbon dioxide ($CO_2$), which dissolves in the water. Once the rain reaches the ground, it may pass through soil that can provide much more $CO_2$ to form a weak carbonic acid solution, which dissolves calcium carbonate [4]. Bakırkoy limestone with plenty of fossil shelled, fractured and dissolution of voids cause to karst formation by accelerating the movement of the water. Especially this deterioration type was observed on wall (Figure 6).

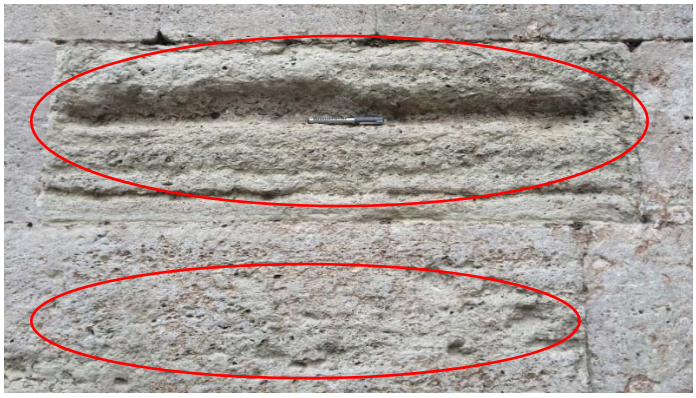


**Figure 6.** The view of karst in Kufeki Stone

Missing part is the result of a complete break (or failure of an original construction joint) in which the detached portion of outdoors survives intact. This situation is occured by atmospheric effects in weakness zone of stone. In general, missing part was observed almost all natural stones used in Suleymaniye Mosque (Figure 7).

**Figure 7.** Cracking and loss occur with freeze-thaw effect on the porphyry column and floor

*2.4. Discoloration and Deposit*

The pollution is effective on building stones used in either present day constructions or historical buildings and monuments. As many researchers have also observed, deterioration and pollution of the stones used in the building is originated from air pollution [5], [6], [7]. In particular, the rapid development of industrialization in Istanbul in recent years have affected the atmospheric conditions and considerably damaged to the natural stone used in buildings.

It has been shown recently that in polluted areas (exhaust gas, factory smoke) when sulphur dioxide, sulphuric acid and airborn particulates enter into contact with a calcite surface the sulphation takes place and some of the solid is dissolved. Water evaporates and crystals of the soluble salts (gypsums) are deposited on the stone surface. Repeated wet and dry cycles cause water absorbed into the stone grains [8]. Crystallization of salts within the pores of stones can generate stresses to cause the cracking of stone, often into powder fragments.

Crystallization damage caused by highly soluble salts, such as sodium chloride and sodium sulfate, is usually manifested by powdering and crumbling of the stone's surface. Especially black crust was observed in Marmara marble and Küfeki limestone (Figure 8).

**Figure 8.** The view of black crust on Marmara Marble

Some process of stone deterioration will be accelerated by atmospheric effects (ie. acid rain, sea spray (salt evaporation) and north wind).This situation cause to change colour of stone. Hereke Pudding and Serpantine Breccia which is located in the northeast of mosque is affected by wind comes from Haliç (Figure 9).

**Figure 9.** The lose colour of stone in Serpantine Breccia (left) and Hereke Pudding (right)

The colour changes occurred in stone surface based on reduction of iron and manganese which are present in mineralogical composition of stone (Figure 10). On the other hand, discolouration is occurred due to corrosion of the metal at the surface of stone (Figure 11).

**Figure 10.** The colour change due to composition of marble

**Figure 11.** Remaining trace of metal corrosion on granite and marble surfaces

*2.5. Biological Colonization*

The attack of stone by a variety of plants, animals and microorganisms appear to be the most destructive. The term biodeterioration refers to any undesired change in material properties due to the activity of microorganisms or organisms belonging to various systematic groups: microscopic algae, linchens, higher plants and animals (bird excrement) [9]. Some types of bacteria, algae, lichens produce acids and other chemicals which can attack carbonate and silicate minerals [10]. Local deterioration as a consequence of crust formations due to lichen and moss was most commonly observed [11]. Lichens cling tightly to rocks by secreting acids and cause to abrasion in time. Physical and mechanical effects of plant and tree roots leads to fragmentation of stones.It is seen on graveside and bottom of wall (Figure 12).

**Figure 12.** The view of plant effects in marble (left) and limestone (right)

## 3. Results and discussions

Some stone types (ie. limestone, marble, granite, pudding, breccia, phorphry) used in the mosque outdoors (arches, masonrys, columns, border); have been deteriorated and damaged as physical and chemical properties due to the external factors (climatic effects, rain, saturated water impact, wind, humidity, factory smoke, exhaust gas, all biological action and human impact etc.) and earthquakes until today. A lot of deterioration types were observed such as crack and deformation, detachment material loss, discoloration and deposit, biological colonization, and the most sighted of among these were crack, erosion, missing part and discoloration.

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