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Sustainable approach in the restoration of his approach in the restoration of historical monuments using geopolymer material

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Abstract. The restoration of historical monuments using eco-friendly materials such as geopolymer is a good aspect that is being developed for a more sustainable approach. It takes into account several factors such as cultural heritage preservation, durability, and environmental sustainability [1]. While providing excellent durability and strength properties when submerged in different environmental conditions, the use of geopolymer material in the restoration of old sandstone rocks can significantly reduce the carbon footprint associated with traditional construction materials. This approach can support the preservation of cultural heritage by maintaining the monument's original aesthetics and offering a long-term solution for its restoration [2]. Overall, a sustainable restoration approach that incorporates geopolymer material can be environmentally friendly while assisting in the long-term preservation of cultural assets.

1 Introduction

To preserve historical buildings and monuments, more attention should be paid to the preservation of architectural heritage. However, about half of construction and demolition products are generating waste during renovation. Environmentally friendly materials are therefore needed to replace cementitious materials and reduce the environmental impact of retrofitting. This study aims to prove that geopolymer paste can be a potential alternative in the renovation of architectural elements of the Al-Atar Mosque in Tripoli by assessing their durability. Various application samples were prepared and immersed in different aggressive media to test their compressive strength and properties when immersed in the different mediums.

1.1 Geopolymer

Geopolymer materials are inorganic materials that have attained a lot of attention in recent years due to their unique properties and potential applications. Unlike conventional materials such as cement, which rely on the hydration of calcium-based compounds, geopolymers are formed by the chemical reaction of silicon- and aluminum-rich starting materials with alkaline activator solutions. Geopolymers are produced from a variety of raw materials such as metakaolin. These materials are rich in amorphous and reactive aluminosilicate compounds that serve as the main precursors for the geopolymerization reaction. This reaction is the key point that occurs during the process where the metakaolin (aluminosilicate precursors) dissolves in an alkaline solution (sodium or potassium based) and subsequently forms the three-dimensional polymer network. This network consists of chains and rings of silicon and aluminum atoms connected by oxygen bridges. The resulting structure gives the geopolymer material strength and stability [3]. Geopolymer has several advantages, one of the most significant is the low carbon footprint compared to traditional Ordinary Portland Cement (OPC). Cement production is a major source of greenhouse gas emissions whereas geopolymers use industrial waste, reducing the need for new resources and minimizing environmental impact having the same time excellent mechanical properties [4].

Geopolymers also achieve high mechanical properties such as high compressive strength, and durability. They have shown promise in a variety of applications such as building materials, coatings, refractories, and even restoration applications. [5] Geopolymer composites can be tailored to specific properties, making them versatile for a variety of engineering and manufacturing applications. Although there is not much research and papers about using Geopolymer in cultural heritage, the material proved that it has good potential for use in restoring monuments due to its eco-friendly properties and the ability to be a product free of using water or using a small quantity of it [5]. Rescic et al (2011) are the explorers of the concept of using the Geopolymer as a product for restoration or using it as a mortar [6]. He modified the material mechanically by grinding different grains into different

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sizes and chemically by adding different alkaline solutions at different PH levels to ensure the best mechanical properties. S. Rescic. (2011) and Clausi et al. (2016) tested the interaction between geopolymer formulated with natural and artificial stones in historical Italian architecture and construction materials by SEM-EDS [6,2]. The result was an interest in replacing the traditional material with this new material due to its adhesion, eco-friendly properties, and mechanical properties.

1.2 Restoration of the old Al-Attar Mosque

Restoration of the ancient Al-Atar Mosque is a significant effort to preserve and revitalize the historical and cultural landmark. With its rich architectural heritage, the Al-Atar Mosque is of great importance to the local community and a testament to the region's history. The mosque is a historical building and is currently being restored. Concrete, cement gypsum, and carbon fiber panels have been used to renovate and reinforce the structure of the mosque. However, the use of these materials detracts from the natural appearance of the monument. The aim of the study is therefore to test whether geopolymers can be used as a replacement for concrete in the retrofitting of this old building. The mosque has a rectangular shape, oriented North-South, with a deviation of 12 degrees to the South-West direction. Where the main prayer hall consisting of barrel vaults, dome, and iwans, occupies an area of approximately 400 m2 (25 x 16m). Adding general facilities areas such as toilets located North of the mosque, an ablution room located East of the mosque and adjacent to the East entrance, as well as an open space area, resulting in a total area of the mosque of 600 m2 as observed in Figure 1.

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Fig 1. Ground floor map of Al Attar Mosque [12].

1.3 Durability

Durability is the main issue that concerns engineers. Arrifin et al. (2013) and Bhutta et al. (2014) did a study to measure the performance of Geopolymer concrete when it is cured in alkaline activators for 18 months [7,8]. They found that geopolymer experienced lower mass loss when compared to ordinary Portland concrete, 8% compared to 20% [9]. In addition, Geopolymer showed a lower loss in compressive strength compared to ordinary concrete, 35% to 68% [9] thereby hindering that geopolymeric materials are more sustainable and durable. As for the experimental setup done by Thokchom et al. (2010), it has shown that the durability of Geopolymer in nitric acid, inserted in a 10% by weight nitric acid solution for 24 weeks had very little weight loss, while the compressive strength showed high retention, thereby also proving that the specimens remained structurally well after the long period of soaking in nitric acid. This proves that geopolymer is resistant to acid attack [10]. In another recent study done in 2019, geopolymer showed mass loss after soaking in sulfate attack for a long period. It was concluded that the long attack of sulfate for the composites cause deterioration and damage due to the formation of a crystalline phase. Moreover, the same study stated that the influence of sulfate attack in the geopolymer deterioration is mainly on the pores and cracks. So increasing the concentration of sulfate leads to an increase in the porosity and pore size of the Geopolymer composite, which means higher porosity and a decrease in compressive strength [11]. As such, the geopolymer samples in all studies assessed showed excellent durability and were seen as promising alternatives to conventional building materials. Geopolymers exhibit outstanding resistance to a wide variety of chemicals, including acids, alkalis, and aggressive substances, making them suitable for environments vulnerable to corrosive and chemical attacks. In addition, its excellent fire resistance due to its inorganic nature and high-temperature stability allows it to withstand high temperatures without noticeable structural degradation or loss of strength. Additionally, geopolymer samples have been demonstrated to be durable under harsh conditions such as extreme temperatures, freeze-thaw cycles, and high humidity, showing minimal susceptibility to degradation. Overall, these properties make geopolymer materials suitable for a variety of applications requiring strong and durable building materials [5].

2 Methodology

The first step for the assessment of the geopolymer paste was the preparation of the old sandstone rocks as mentioned in the previous work done by *Adgham* S. et al (2022) [12]. The samples as observed in Figure 2 were tested for their respective mechanical properties and showcased as mentioned good results [12]. To persist and assess this work, durability tests were done as follows to assess the impact of the various harsh environments.

Fig 2. Geopolymer paste used on the sandstone rock.

The following tests were performed according to ASTM standards to compare the results and show how geopolymers act on different specimens and in different applications. First, the natural sandstone (4x4x16 cm) was immersed in various environments as is without geopolymer paste to assess the natural impact. Second 2 sandstone rocks (2x2x16 cm) were used and bound by the produced geopolymer paste to assess the environmental impact of the various environments on both the binder (GP) and the sandstone rocks. (Figure 3)

The admixture gel was inserted to achieve a porosity of 0%, 0.1%, and 0.2% in the samples according to a mass addition. The alkali solution was gradually added to the mix, after mixing the solid powders with the admixtures altogether, where a homogeneous-like state was observed. The following was mixed for an additional 5 minutes and was, later on, poured into molds and vibrated for 60 seconds with the use of a vibrating table to leaze the air bubbles escape and ensure good settlement. The samples were set aside to dry for 24 hours. The several steps involved in the sample preparation are shown in Figure 3 and summarized in Table 1To thoroughly evaluate the potential of geopolymer material for the restoration of historic monuments, a range of durability tests were carried out in the laboratory. In accordance with ASTM C1012/C1012M-13 standards, the Sulphuric Acid test entailed submerging samples in 1% and 3% acid solutions to evaluate the material's ability to survive corrosive environments. According to ASTM C1202-10 recommendations, the NaCl Immersion Test included immersed samples in a 20% NaCl solution to assess their resistance to chloride, a crucial consideration for prolonged exposure in coastal environments. The Water Immersion test allowed for the assessment of the geopolymer's resistance to moisture intrusion and probable deterioration due to prolonged water exposure while conforming to ASTM D570 requirements. Samples were submerged in water during the test. The Ambient Curing Test included a curing component. As for the Freez & Thaw test, it followed the ASTM C936/C936M standards. This durability test was vital in thoroughly evaluating the suitability of geopolymer material for historical monument repair to extreme climatic conditions geopolymer specimens can encounter, cycles of freezing and thawing were used in this test.

Table 1. Summary of tests applied in different environments.

Test	Description & Purpose
Sulphuric Acid	Samples immersed in 1% and 3% Acid
	ASTM C1012/C1012M–13
NaCl Immersion Test	Samples immersed in 20% NaCl solution
	ASTM C1202-10
Water Immersion	Samples immersed in H2O
	ASTM D570
Ambient Curing Test	Samples cured at ambient temperature
	ASTM C192/C192M-19
Freez & Thaw	ASTM -C936/C936M

Fig 3. Sample preparation [12].

Sulfuric acid is a main constituent of acidic rain, it is formed due to the atmospheric oxidation of sulfur dioxide in the presence of water. Also, sulfate exists in soil and groundwater and could affect the foundations of the building. For that, the test was done to assess the sulfate resistance of the geopolymer paste used over the sandstone compared to the sandstone.

The research relied on ASTM C1012/C1012M–13, the sulfuric acid with 1 % and 3% concentrations was used as the exposure solutions [13]. The specimens were immersed in a tank containing the sulfate acid after 28 days of its production to achieve good stability.

Fig 4. Samples in sulfuric acid.

The second most needed and reliable test to be done was the chloride test as it is found primarily in seawater, and may cause corrosion, especially for structures that are in the coastal region. Identical samples were prepared for the immersion and are seen in Figure 5.

Fig 5. Samples in 20% NaCl.

Sodium chloride (NaCl) with a 20% concentration was used as the exposure solution. The specimens were immersed in a tank containing NaCl. The chloride attack was evaluated based on its change in mass.

The third durability test done was water absorption as it is an important issue for sustainability. The test was done based on ASTM standards. According to ACI 201 [14], "Freshwater refers to aqueous solutions with nearly neutral pH, very low ionic strength, and low dissolved solids content. Freshwaters include rainwater; waters in most streams, rivers, and lakes; and domestic water that is chlorinated and fluorinated. Freshwaters can also occur in industrial, manufacturing, and other facilities where distilled water is produced or used in various processes. In nature, lightning produces weak nitrous, nitric, sulfurous, and sulfuric acids in natural waters that can cause some surface deterioration of concrete, especially in areas that experience frequent thunderstorms. Some freshwater may be somewhat acidic due to exposure to acid rain, or it may contain small concentrations of sulfates, nitrates, and other salts that, in higher concentrations, could attack concrete.

The significant chemical attack by freshwater, however, is virtually unreported. That concrete is not significantly deteriorated by freshwater is evidenced by highways, culverts, pipes, and buildings that are built with the full expectation that their function will not be significantly affected by such exposure during their expected service life" [15].

The fourth test done for durability purposes was the freeze and thaw. According to ACI 201, the deterioration of concrete exposed to freezing can occur when there is sufficient internal moisture that can freeze at the given exposure conditions. The source of moisture can be either internal or external. Internal is water that is already in the pores of concrete that are redistributed by thermodynamic conditions to provide a sufficient degree of saturation at the point of freezing to cause damage. External is when the water enters the concrete from an external source, such as rainfall). Dry concrete (generally below approximately 75 to 80 percent internal relative humidity) is normally immune to damage from freezing. Mature concrete may be able to withstand repeated cycles of freezing and thawing without damage. The severity of exposure should be quantified by a combination of freezing, which is the number of annual cycles of freezing plus average low temperature reached during each cycle, and moisture condition before each cycle of freezing" [15].

As such the tested specimens followed the ASTM code and were presented in Figure 6. A heating test is done to study the effect of temperature on the concrete properties. For that, we did the same test to study the effect of temperature on the Geopolymer properties, to observe any damages, changes in color, etc.

Fig 6. Freezing and thawing specimens.

3 Results & Discussion

The findings of the weight variations for the different samples submerged in different environments are assessed below Sandstone is a natural sedimentary stone that is known to be durable, but not the strongest available one. it was a popular building material since 1000 years ago, used to build castles, and temples, for its natural and attractive look, and its thermal and acoustic properties. Its composition mainly consists of sand-size grains rock fragments, minerals, and organic material, while it holds good properties that make it suitable for construction, as it is fine-grained, rough & tough, fireproof, and non-slippery, compact, and quite hard. Also, It has good compressive strength and low absorption properties [16].

When soaked in a different medium, compressive strength, and shear stress were tested after 90 days showing variation in the mechanical properties. It was seen that the more sulphuric acid exists in the solution, the less the compressive strength. As seen in Figure 7, the compressive strength of sandstone in 1 % sulphuric acid was more than 10 times the compressive strength in 3% sulphuric acid. This is explained by the fact that an acidic medium tends to fill the pores available in natural stones and weakens their properties.

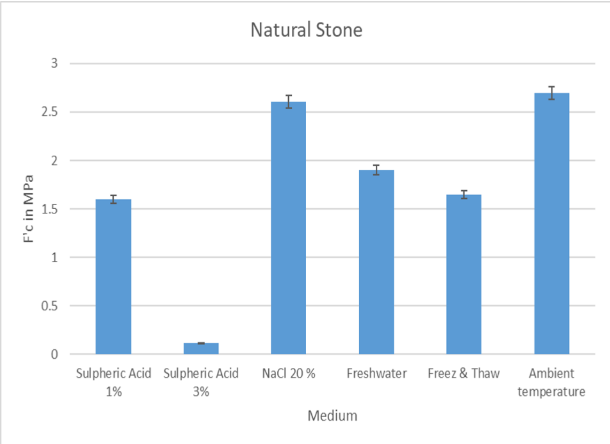

Fig 7. Compressive strength of Sandstone in different mediums.

When the natural stone that is preserved at ambient temperature, which is already 300 years old based on the available history of the mosque that related the construction of the mosque to the seventeenth century, is compared with the same specimen under 20 % NaCl which is equivalent to seawater, it is observed that compressive strength decreases when submerged in saline water. This can be explained by the high amount of salts that fills the pores of the sandstone and weakens its properties giving a compression strength= of 2.605 MPa.

When comparing the natural stone in its natural ambient environment with freshwater it has been observed that the compressive strength decreases when compared to saline water and specimens at ambient temperature. This is commonly explained by the high amount of cations and anions available in the freshwater (Mg+, Na+, Cl-, Fe +, K+, fluoride, sulfate) that will interact with the natural stone and weakens its properties.

Similar to the natural stone, the sandwich stone was observed to have less compressive strength in 3% sulphuric acid when compared to 1% sulphuric acid. it has been related to the effect of acid on filling the pores and weakening the stone. While preserving the sandwich stone at ambient temperature gave the strongest compressive strength when compared to the other mediums. This is because of the geopolymer paste that strengthens the stone. Also, it has been noticed that the sandwich stone that is soaked in freshwater gave higher compressive strength than that soaked in Saline water. This was explained by the impact of salts on the stone causing weakening it. Figure 8 can illustrate the results.

In all harsh environments (NaCl, 1%, and 3% sulfuric acid), sandwich bricks were observed to exhibit superior compressive strength. This can be logically explained by the fact that most samples collapse in the stone itself rather than in the geopolymer paste when testing compressive or shear stress. The use of geopolymer pastes as binders in construction, therefore, offers great potential for the treatment of all kinds of structures. As a second option, coated stones exhibit good properties in all media. This is because the entire cube is preserved with geopolymer paste from all sides. Good compressive strength was observed in sulfuric acid (1% and 3%) compared to natural stone. In NaCl media, the presence of a lot of geopolymer paste in the covered rock was observed to reduce the compressive strength of the samples compared to the sandwich bricks. This can be explained by the alkaline reaction between geopolymer paste and NaCl.

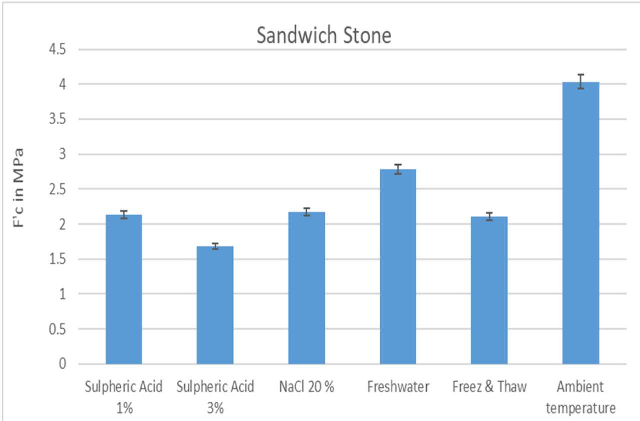

Fig 8. Compressive strength of Sandwich stone rock in different mediums.

As for the weight variations, the following has been done based on the identification of the samples as listed in the table below.

Table 2. ID for the weight assessment

1	Natural sandstone 4x4x16 cm
2	Sandwich stone 4x4.5x16 cm
3	Sandwich stone 4x4.5x16 cm

The weight variation assessed in the various medium represented in Figures 8, 9, and 10 showcased the following points. The analysis was done on the sandstone rocks immersed naturally or with GP paste and considered as sandwiches stone (ID 2 & 3) gave similar variations. The sample batches presented in Table 2 were accurately weighted. The monitoring of the samples over time showcased an increase in the weight no matter what was the sample type. This was related to the continuous swelling/ absorption of water due to the sandstone rock.

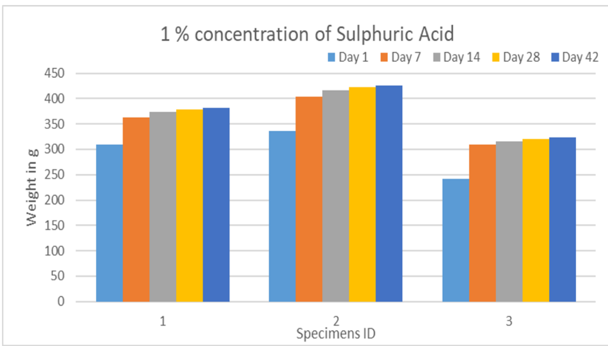

Fig 9. Weight variation in 1 % Sulfuric Acid.

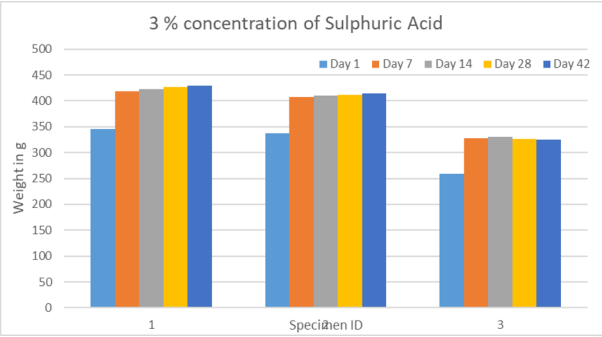

Fig 10. Weight variation in 3 % Sulfuric Acid.

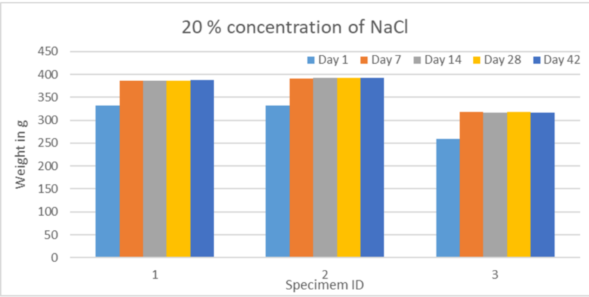

Fig 11. Weight variation in 20 % NaCl.

4 Conclusion

In this paper, the sustainable and durable approach to asses old monumental rocks was highlighted. This study is the first of its kind to evaluate the incorporation of geopolymer with aluminum powder in sandstone blocks, offering novel perspectives on the restoration of old monumental buildings and showcasing a special combination that improves durability and preserves authenticity. Geopolymer material can be integrated through a variety of approaches in the context of restoration. Geopolymer-based pastes can be used to restore surfaces and deteriorating facades, which are frequent problems in old buildings. These pastes, which incorporate recyclable materials like aluminum powder, provide a way to fix damaged areas while preserving the old monumental original architectural style. The durability of these repairs is increased by the geopolymer's resistance to several environmental and durability tests, which reduces the need for repeated interventions and therefore protects the monument's structural integrity. This assures long-term preservation for the restoration of historical monuments and the use of geopolymer as an innovative and green technique to achieve this goal. This study proves the potential of geopolymer to renovate an old structure such as the Al-Attar mosque located in Tripoli, Lebanon. Based on the experimental results, it can be concluded that the geopolymer paste put under different acidic conditions didn't get affected like the stone itself which indicates that it is good, sustainable, and durable with various features.

References

1. L. Ricciotti, A. J. Molino, V. Roviello, E. Chianese, P. Cennamo, and G. Roviello, Env. , **4**, 91 (2017).
2. M. Clausi, S. C. Tarantino, L. L. Magnani, M. P. Riccardi, C. Tedeschi, and M. Zema, Appl. Clay Sci., **132**, 589 (2016).
3. J. Davidovits, in (Geopolymer 2002 Conference), **28**, 29, (2002).
4. Y. S. Dai, L. C. Yang, Y. C. Ding, C. W. Jhong, T. W. Cheng, and K. L. Lin, **3** (2013).
5. S. Pagnotta, A. L. Tenorio, M. R. Tinè, and M. Lezzerini, in (IOP Publishing), **609**, 012057 (2020).
6. S. Rescic, P. Plescia, P. Cossari, E. Tempesta, D. Capitani, N. Proietti, F. Fratini, and A. M. Mecchi, Procedia Eng., **21**, 1061 (2011).
7. M. A. R. Bhutta, N. F. Ariffin, M. W. Hussin, and N. H. A. S. Lim, J. Teknol., **61**, (2013).
8. M. A. R. Bhutta, W. M. Hussin, M. Azreen, and M. M. Tahir, J.Mater.Civ.Eng., **26**, 04014080 (2014).
9. G. F. Huseien, J. Mirza, M. Ismail, S. K. Ghoshal, and A. A. Hussein, Ren. Sust. En. Rev., **80**, 54 (2017).
10. S. Thokchom, P. Ghosh, and S. Ghosh, J. Civ. Eng., **17,** 393 (2011).
11. L. Guo, Y. Wu, F. Xu, X. Song, J. Ye, P. Duan, and Z. Zhang, Compos. B. Eng., **183**, 107689 (2020).
12. S. Al Adgham, M. Saba, G. Sabalbal, W. Arairo, and J. Absi, in (IOP Publishing,), **1123**,012023 (2022).
13. A. Ananthi and J. Karthikeyan, (n.d.)
14. J. H. Ideker and S. H. Smith, (2020).
15. A. Committee, in (American Concrete Institute, 2001).
16. "Sandstone," GeologyScience, 2022.