*SQU Journal for Science*, 2017, 22(2), 81-88 DOI: http://dx.doi.org/10.24200/squjs.vol22iss2pp81-88
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# Engineering Properties of Volcanic Tuff from the Western Part of Yemen

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**ABSTRACT:** This paper deals with a study of the physical and mechanical characteristics of volcanic tuff and ignimbrite from six quarries located at different areas in the western part of Yemen (Manakha, Jahran, Bakhran, Dar Al-Hanash, Abaser and Soraifa). In the region, volcanic tuffs and ignimbrite are locally known by their location names and have been used as solid masonry and cladding stones. All the investigated pyroclastic rocks belong to the Tertiary volcanic. The standard physical and mechanical tests (void ratio, porosity, density, specific gravity, water absorption, uniaxial compressive strength and tensile strength) were carried out on the tuff and ignimbrite samples collected from different parts of the region.

Laboratory tests revealed that the void ratio average values range between 0.12 and 0.37, the porosity ranges between 10.57 and 27.12%, the dry density ranges between 1.66 and 2.25 gm/cm$^3$, specific gravity ranges from 1.45 to 1.94, and water absorption ranges from 4.69 to 16.39%. The measured uniaxial compressive strength values range from 24 to 68 MPa, and the tensile strength values range between 4 and 10 MPa. These tuffs and ignimbrites generally are light green, gray, beige, or yellowish in color. With these colors they are favoured for building, coating and decorative stone. This paper concludes that the studied stones have acceptable to good properties as dimension stone. Jahrani and Manakhi tuffs are the best quality, whereas Hanashi ignimbrite is of poorer quality.

**Keywords:** Yemen; Volcanic tuff; Physical and mechanical tests; Dimension stone; Uniaxial compressive strength.

**الخواص الهندسية للتف البركاني في الجزء الغربي من اليمن**

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**الملخص:** هذه البحث يهتم بدراسة الخصائص الطبيعية والميكانيكية لعدد ستة مقالع من صخور التف البركاني و الاجنبرايت، التي تقع في مديريات مختلفة غربي اليمن (مناخة، جهران، بخران، دار الحنش، عباصر وصريفة)، وتسمى هذه الصخور بأسماء محلية نسبةً لأماكن تواجدها واستخراجها، حيث تستخدم كأحجار بناء وواجهات. الرواسب الفتاتية البركانية قيد الدراسة تنتمي الى بركانيات اليمن والتي يعود عمرها للعصر الثلاثي.
تم اجراء الفحوصات المعيارية الطبيعية و الميكانيكية (نسبة الفراغات، المسامية، الكثافة، الوزن النوعي، امتصاص الماء، قوة تحمل الضغط أُحادي المحور ومقاومة الشد) لعينات من التف البركاني و الاجنمبرايت جمعت من مواقع مختلفة.

أظهرت الفحوصات المختبرية ان متوسط قيم نسبة الفراغات بين 0.12 و 0.37، المسامية في المدى بين10.57 و 27.12%، الكثافة الجافة من 1.66 الى 2.25 جرام/سم3 ،الوزن النوعي من 1.45 الى 1.94، امتصاص الماء من 4.69 الى 16.39%، مقاومة الضغط أحادي المحور من 24 الى 68 ميجاباسكال ومقاومة الشد من 4 الى 10 ميجاباسكال. هذه الصخور بشكل عام ذات الوان أخضر، رمادي، بيج و اصفر، هذه الالوان الطبيعية الجميلة والجذابة جعلتها مفضلة كأحجار بناء, واجهات و زينة. و خلص البحث الى ان الصخور موضوع الدراسة تمتلك صفات مقبولة إلى جيدة كأحجار بناء، واجهات، زينة و ديكور. و من حيث الجودة كان التف الجهراني الافضل ثم المناخي ، بينما التف الحنشي هو الأسوأ.

**الكلمات المفتاحية:** اليمن، التف البركاني، الفحوصات الميكانيكية و الطبيعية، احجار الواجهات، المقاومة الانضغاطية احادية المحور.

## 1. Introduction

Dimension stone refers to rock that has been cut and worked to a specific size or shape for use in building [1]. It is an important construction material, and can essentially be subdivided into structural stone and facing stone. Dimension stone is used extensively for paving and tiling, interior finishes, landscaping, monuments and statuary and building restoration [2]. Volcanic tuffs have been used as dimension stones in many countries since ancient times, including Italy [3] and The Netherlands [4]. Up until the early part of the twentieth century structural stonework dominated, but with the development of steel-framed buildings, facing stone became more important [2].

Generally, knowledge of the engineering properties of rock material has a significant role in the construction industry. No safe design of a soundly engineered construction can be accomplished without the evaluation of the engineering properties of the material [5].

Volcanic tuffs are currently widely used in buildings all over the world. These new varieties display highly fascinating colors, such as green, yellow, beige and gray. Thus their decorative applications are widespread worldwide. Among nations, new producers of pyroclastic stone are Armenia and Turkey [6]. The volcanic tuff industry has received its due share of development in recent years. This development has not only been due to the physical demands of construction, but also to the aesthetic and environmental aspects of the construction industry. Volcanic tuffs are used as ornamental stone and facing stones, which are relatively thin slabs, cemented or mechanically anchored to a building's face to enhance its appearance and protect it from weathering processes.

At present, there are many operational dimension stone quarries of volcanic tuff in the western part of Yemen, from which raw blocks are extracted and processed as building stone and ornamental stone. The reserves are virtually unlimited. Therefore, it is very important to evaluate the rock quality and to determine the engineering properties of such volcanic tuff. The information could help the present or the future engineering projects using volcanic tuffs in or around the quarry areas. Tuffs dealt with in the present study belong to the Yemen Tertiary Volcanic Group of Oligocene-Miocene age [7]. Despite their widespread occurrence in the country, there is a lack of studies of the engineering properties of these volcaniclastics and their commercial uses as building stone.

For local housing and construction, easily workable rocks are required in preference to rocks with attractive aesthetic qualities. The stone is shaped and worked to finished products (slabs and building blocks). The large scale economically viable use of rocks for various building purposes requires that cheap and simple technology can be employed to reduce the cost. In Yemen, the use of Tertiary volcanics has a long history.

The aim of this paper is to investigate the engineering and physical properties of volcanic tuffs and ignimbrites that were collected from six different sites within the Yemen volcanic series.

## 2. Study Area

The quarries selected for the current study are located in the western part of Yemen between Sana'a City in the north and Taiz City in the south (Figure 1). The six selected quarries are: one in Jabal Al-Mislamah, Manakha in Sana'a Governorate which is situated around 93 km to the southwest of Sana'a City, four sites in Dhamar Governorate: Jahran area (25 km to the northwest of Dhamar City), Bakhran area (13 km southwest of Dhamar City), Dar Al-Hanash area (13 km southeast of Dhamar city) and Abaser area (17 km southeast of Dhamar City). The sixth site is in Soraifa area in Taiz Governorate, and is located about 20 km east of Taiz City (Figure 1). The selected quarries occur in mountainous terrain with sparse vegetation.

## 3. Materials and Method

Building stones have been produced from volcanic tuff and ignimbrite rocks using hand tools, blasting and motorized machines. A geological map of the volcanic tuffs located in the western part of Yemen was explored. Forty two specimens of $10\times10\times10$ cm³ dimensions were collected from quarries in six different areas where tuff and ignimbrite are processed, and they were subjected to standard physical and mechanical experiments for rock, namely void ratio, porosity, density, specific gravity, water absorption according to ASTM-C97 [8], and uniaxial compressive strength according to ASTM-C170 [9] where the shape correction is expressed by the equation $\sigma = \sigma c\ [0.778 + 0222\ (l/h)]$, where $\sigma$ is corrected compressive strength to ASTM, $\sigma c$ is measured compressive strength and (l/h) the lateral dimension to height ratio which is equal to 1 in the present studied cube case [10] .

In addition specimens of $20\times10\times6$ cm³ dimensions were used to determine tensile strength according to ASTM-C99 [11, 12]. Each experiment was conducted on at least three specimens and the average of the obtained values was recorded. These experiments were carried out in the Central Laboratories, Ministry of Public Works and Roads in Yemen.

## 4. Geological Features

The key for identifying a potential source of stone for exploitation as dimension stone is an understanding of the geology of the region (as mentioned in [13] for aggregate), focusing on a general study of the stratigraphy, origin and structural position of the area in question.

Widespread volcanic activity occurred in Yemen and adjacent areas during the Late Cretaceous and Early Tertiary and is believed to be associated with the vertical uplift of the Afar Plume and rifting of the Red Sea [7, 14-18]. As a result of this activity, tremendous numbers of fissure-erupted and caldera eruptive centers, dikes and volcanic flows were formed, particularly in the central highland of the country, covering almost 45,000 km$^2$ [19] (Figure 2). Al-Kadasi, [20] classified Tertiary volcanic outcrops in Yemen in two fields; Sana'a-Taiz and

Sheharah. Mattash *et al*, [7] divided the Yemen Volcanic province into the late Oligocene – early Miocene Yemen Trap Series (YTS) and the late Miocene – Recent Yemen Volcanic Series (TVS).

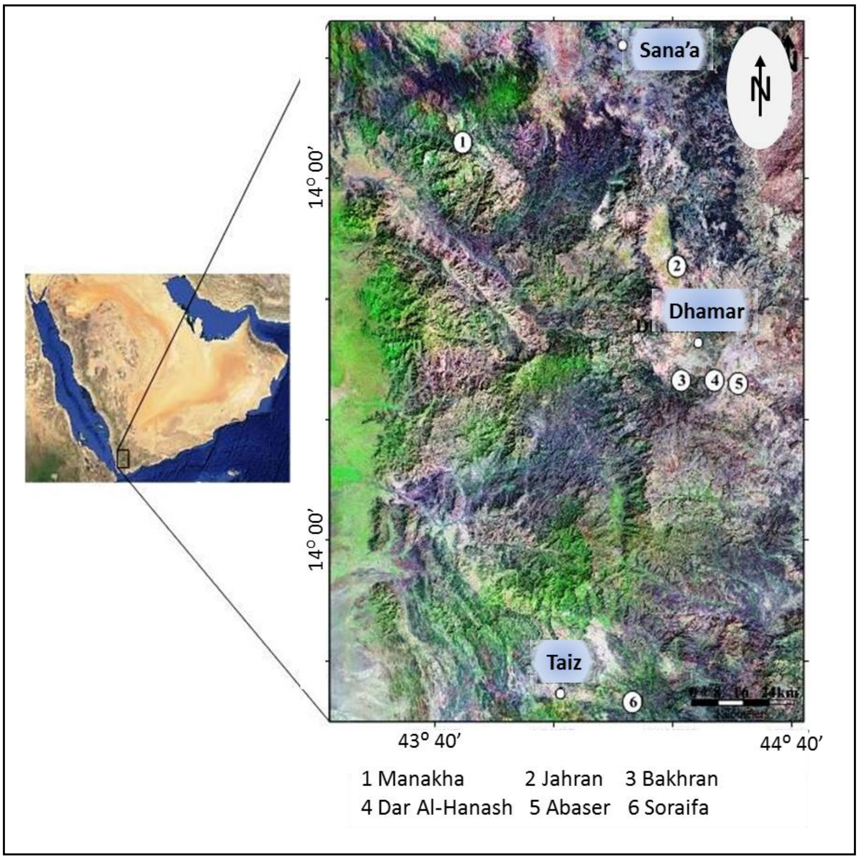


**Figure 1.** Location map of studied area

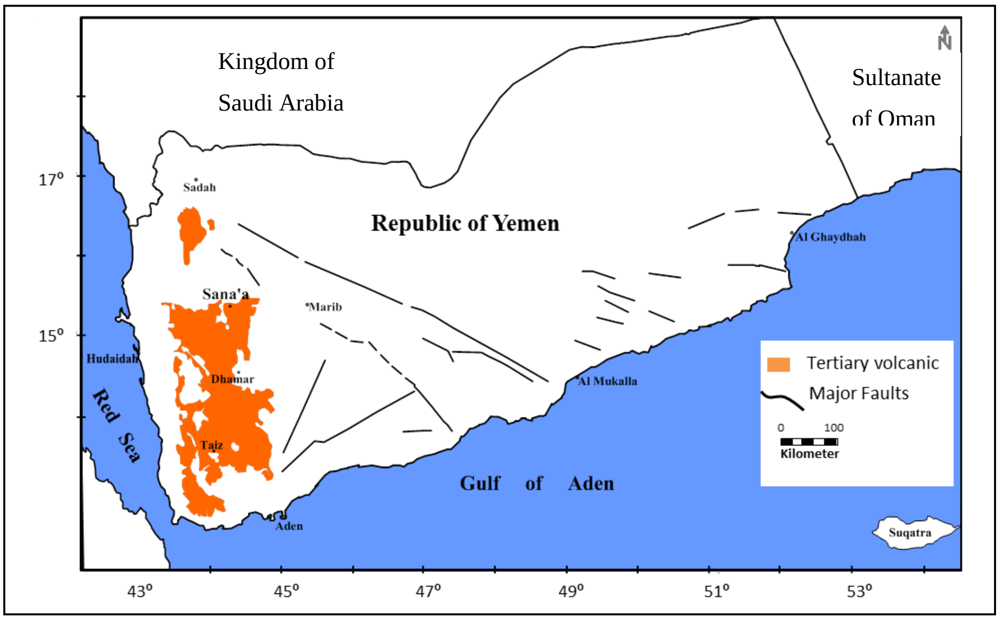


**Figure 2.** Simplified Tertary volcanic map of Yemen

The Tertiary volcanic represents the lowest part of the Cenozoic Yemen volcanic province, and mainly overlies the Cretaceous Tawilah Group sandstones and the Paleogene lateritic paleosols, and in some cases the Precambrian metamorphic basement rocks. These developed during the Oligocene-early Miocenic pre- and sin-rift phases. The Tertiary volcanic consists of thick, bimodal volcanics, including alkaline to transitional basalts and peralkaline rhyolites and their associated ignimbrites, tuffs and rhyolitic obsidian flows. The ratio of acidic to basic volcanic products is greater than 0.5. The thickness of the Tertiary volcanic varies from > 2000 m in the west down to hundreds to tens of meters in the east [7].

Tuffs and ignimbrites, which are the subject of this study, have rhyolitic composition and are widely found in the field. These represent a major episode of volcanic eruption widespread in the western part of Yemen.

Table 1 shows the volume of the reserves, which exceeds 44,500,000 m² in total [21] and gives a simple description of the volcanic tuff and ignimbrite in the studied quarries, whereas Figure 3 shows cubes of the studied samples.

**Table 1.** Simple description of volcanic tuffs in studied quarries

| Governorate | Quarry location | *Quarry reserve ($m^2$) | Local name | Rock name | Color | Texture |
|---|---|---|---|---|---|---|
| Sana'a | Manakha | 16,000,000 | Manakhi | Tuff | Light green | Fine |
| Dhamar | Jahran | 6,000,000 | Jahrani | Tuff | Beige | Fine |
| Dhamar | Bakhran | 1,500,000 | Bakhrani | Tuff | Light grey | Fine |
| Dhamar | Dar Al-Hanash | 12,000,000 | Hanashi | Ignimbrite | Pink | Medium to coarse with flow texture |
| Dhamar | Abaser | 5,600,000 | Abaseri | Ignimbrite | Pink | Medium to coarse |
| Taiz | Soraifa | 3,400,000 | Soraifi | Tuff | Light grey with reddish patterns | Fine |

* From [21].


**Figure 3.** Samples cut into 10×10×10 cm³ from six quarries used for various tests

## 5. Laboratory tests and results

Tuff and ignimbrite in the region have been used extensively for many years for a variety of purposes, for example as building, coating, outside covering and decorative stones (Figures 4a, b and c). Determination of their physical and mechanical properties is therefore crucial as these properties play an important role in the selection of these rocks to meet their various usages.


**Figure 4.** Examples of usage of tuff as (a, b) outside covering stone; (c) Decorative stone.

A number of laboratory tests were conducted on cube and slab specimens of volcanic tuff and ignimbrite (from Manakha, Jahran, Bakhran, Abaser, Dar Al-Hanash and Soraifa quaries) to determine their physical and mechanical properties. The tests were performed in accordance with the American Society for Testing and Material (ASTM) standards.

These tests, which included the determination of void ratio, porosity, density, specific gravity, water absorption, uniaxial compressive strength (UCS) and tensile strength were carried out on at least three samples from each site. The results are presented in Table 2.

**Table 2.** Physical and mechanical properties of the studied volcanic tuff and ignimbrite

| **Local Name** | **Void ratio** | **Effective Porosity (%)** | **Density (gm/cm$^3$)** | | | **Specific gravity** | **Water absorption (%)** | **Uniaxial compressive strength, UCS** (MPa) | **Tensile strength, T** (MPa) | **Brittleness ratio T/ UCS** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Dry** | **sat** | **sub** | | | | | |
| **Normal range*** | 0.001 - 0.25 | 0.1- 20 | 1.8 - 3.0 | - | - | - | - | > 10 MPa | 10-30% of UCS | 10-30 |
| **Manakhi** | 0.15 | 12.71 | 2.13 | 2.26 | 1.03 | 1.74 | 5.96 | 60 | 10 | 16.73 |
| **Jahrani** | 0.12 | 10.57 | 2.25 | 2.36 | 1.2 | 1.94 | 4.69 | 68 | 9 | 12.92 |
| **Bakhrani** | 0.24 | 19.62 | 1.81 | 2.01 | 0.93 | 1.68 | 10.82 | 56 | 8 | 13.45 |
| Hanishi | 0.37 | 27.12 | 1.66 | 1.93 | 0.79 | 1.45 | 16.39 | 24 | 4 | 17.58 |
| **Abasiri** | 0.25 | 20.25 | 1.81 | 2.02 | 0.85 | 1.56 | 11.16 | 35 | 5 | 13.10 |
| **Soraifi** | 0.26 | 20.36 | 1.89 | 2.1 | 0.94 | 1.64 | 10.75 | 34 | 5 | 13.34 |

* From [2] .

The average value of void ratio of tuff samples in the studied quarries ranges between 0.12 and 0.37 (Hanishi), the porosity ranged from 10.57% to 27.12%, and the dry density ranged between 1.66 and 2.25 gm/cm$^3$. Their measured uniaxial compressive strength is from 24 to 68 MPa and their tensile strength (flexural test, T) ranges between 4 to 10 MPa. The brittleness ratio (T/UCS) was calculated and ranged between 13.10% and 17.58%.

The correlations between UCS and water absorption, porosity, specific gravity and density are shown in Figures 5a, b, c and d. Figure 5e indicates the relationship between water absorption and porosity.

## 6. Discussion

Previous geological studies in the area have revealed that a vast area in the western part of Yemen is underlain by tuff, ignimbrite and other pyroclastic rocks representing the last volcanic eruption [7].

In the present investigation the UCS test has been carried out according to routine procedures for dimension stone. Our studies show that as per ISRM specification [22, 23] Jahrani, Manakhi and Bakhrani have strong compressive strength, while Abasiri and Soraifi are of medium strength and Hanashi is of weak to medium strength.

These average values are compatible with their use as dimension stone [2]. The high density values of samples from Jahran tuff indicate the basic textural characteristics of the rock. The high void ratio and porosity in samples from Hanashi indicate low density values.

Comparisons of void ratio, porosity and water absorption of the studied samples reveal that Hanashi Ignimbrite has high water absorption, while Jahrani Tuff samples with the lowest void ratio and porosity values have the lowest water absorption rate (Table 2). In this study the UCSs for Jahrani, Bakhrani, Hanashi, Abasiri and Soraifi have higher values compared with those in Al-Dery's study [24] and similar results have been found for Manakhi Tuff. On the other hand, Alssabri [21] found similar results for UCS for Hanashi, Abasiri and Manakhi, and higher values for Soraifi and noticably smaller values for Bakhrani (Table 3). The variation in test values obtained by these three studies might be due to changes in sample location within the quarries, or to subtle differences in the lithological and textural aspects of the rocks. However, all the results lie within the permitted range for use as dimension stone.

Furthermore, the regression analysis and correlations between the above physical and mechanical properties show that there are good correlations between UCS and water absorption, UCS and porosity, UCS and specific gravity, UCS and density, and porosity and water absorption. As can be seen from Figures 5a, b, c and d, UCS decreases with increasing water absorption (Figure 5a) and porosity (Figure 5b), whereas increasing UCS increases specific gravity and density (Figures 5 c and d), and water absorption increases with increasing porosity (Figure 5e). From these comparisons, UCS was found to follow a decreasing linear relation with water absorption and porosity, and an increasing linear relation with specific gravity and density. Also water absorption has an increasing linear relation with porosity. Tensile strength increases with increasing density (Figure 5f). Figure 5g shows an inverse relationship between density and porosity, whereas Figure 5h shows a direct correlation between UCS and tensile strength.

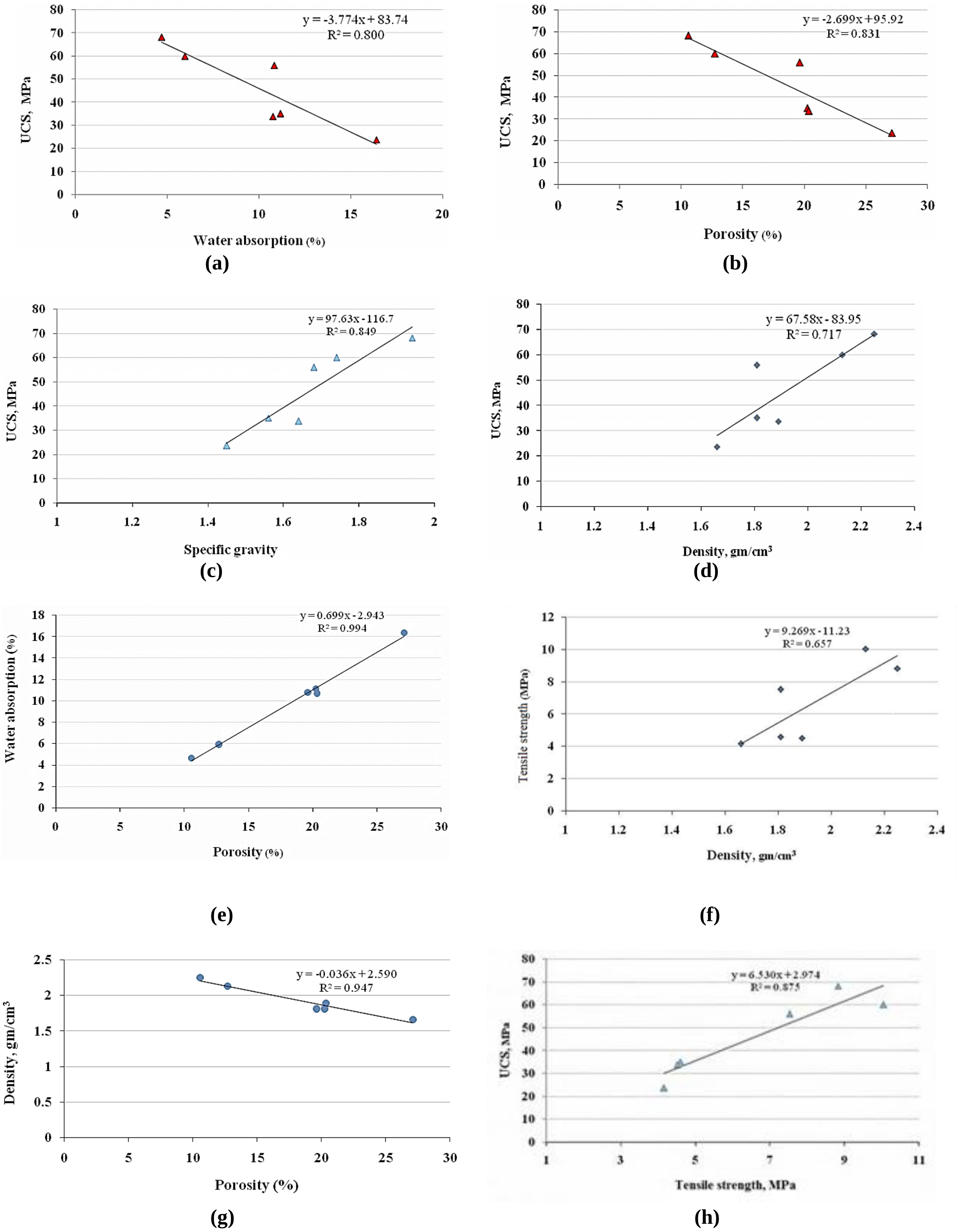


**Figure 5.** Linear relationships representing comparative analysis of physical and mechanical properties of tuffs and ignimbrites. a) between UCS and water absorption. b) between UCS and porosity. c) between UCS and specific gravity. d) between UCS and density. e) water absorption-porosity Relationship. f) tensile strength-density Relationship. g) between density and porosity. h) between UCS and tensile strength.

The medium porous structure of tuff is reflected in its density and therefore Yemeni volcanic tuff is generally defined as a lightweight rock type. In addition, its water absorption due to its void ratio was also found to be high. Figure 6 shows the comparison between porosity, water absorption and UCS for tuff and ignimbrite rocks in the studied area. The results show that Jahrani tuff represents the best quality stone for constructional purposes, whereas Hanashi ignimbrite is the worst. Jahrani tuff has low porosity, low water absorption, but strong compressive strength and tensile strength. Consequently, it is a good quality dimension stone, and so is Manakhi tuff due to its high brittleness ratio. The studied volcanic tuffs and ignimbrites can be easily cut and processed and, in addition, their color and engineering properties play an important role in their uses as building, cladding, and decorative stones.

**Table 3.**Water absorption, uniaxial compressive strength and tensile strength properties of the studied volcanic tuff and ignimbrite compared with Alssabri's study [21].

| Local Name | Studied by | Water absorption (%) | Uniaxial compressive strength, UCS (MPa) | Tensile strength, T (MPa) | Brittleness ratio T/ UCS |
|---|---|---|---|---|---|
| **Normal range*** | | - | > 10 MPa | 10-30% of UCS | 10-30 |
| **Manakhi** | Resent | 5.96 | 60 | 10 | 16.73 |
| | Alssabri | 0.38- 7.34 | 47- 84 (475- 864 Kg/cm²) | - | - |
| **Jahrani** | Resent | 4.69 | 68 | 9 | 12.92 |
| | Alssabri | - | - | - | - |
| **Bakhrani** | Resent | 10.82 | 56 | 8 | 13.45 |
| | Alssabri | 19.41 | 17 (170 Kg/cm²) | 4 (40 Kg/cm²) | - |
| Hanishi | Resent | 16.39 | 24 | 4 | 17.58 |
| | Alssabri | 13.48 | 37 (375 Kg/cm²) | - | - |
| **Abasiri** | Resent | 11.16 | 35 | 5 | 13.10 |
| | Alssabri | 16.26 | 27 (270 Kg/cm²) | 7 (72 Kg/cm²) | - |
| **Soraifi** | Resent | 10.75 | 34 | 5 | 13.34 |
| | Alssabri | 12.10 | 60 (609 Kg/cm²) | - | - |

The brittleness ratio (T/UCS) ranges between 13.10% and 17.58%, which means the tensile strength is equal to 13.10 to 17.58 of UCS, and lies within the typical range (10-30 of UCS) for dimension stone applications according to [2].

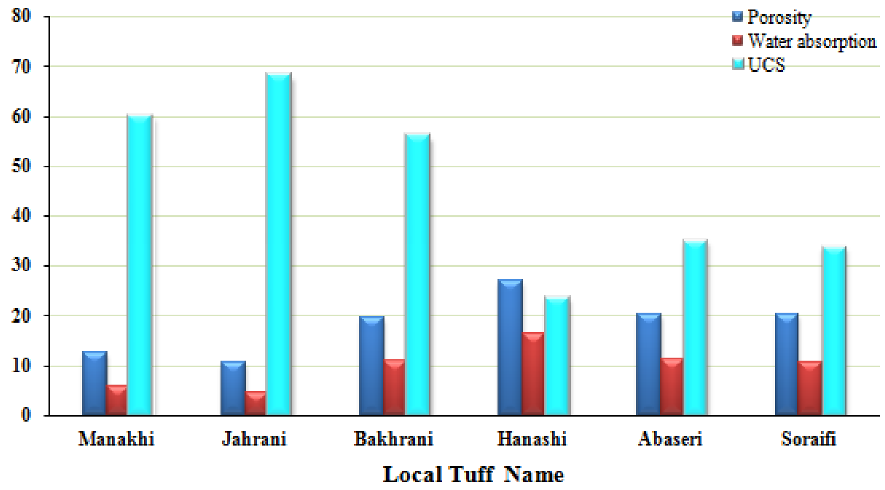


**Figure 6.** Comparison between porosity, water absorption and UCS for tuff rocks in the studied quarries.

## 7. Conclusion

The volcanic tuffs and ignimbrite, in the studied quarries, have suitable physical and mechanical properties as well as a fascinating variety of colors for architectural stone in the local commercial market. These stones have high aesthetic value and lend a prestigious appearance for a long service period, and hence have commercial viability.The present study shows that Jahrani tuff is of the best quality as dimension stone, whereas Hanashi ignimbrite is the worst and the other tuffs and ignimbrite, having similar physical and mechanical properties, are of medium quality as dimensionstones.

Soraifi tuff has attractive colors, but it has high porosity and water absorption making it less suitable as dimension stone, so it is recommended for use as a decorative and internal cladding stone in areas of low moisture content. Bakhrani, Hanishi, Abasiri and Soraifi tuffs can be classified as lightweight rock types (< 2.0gm/$cm^3$) according to their low densities.

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Received 6 November 2016
Accepted 9 April 2017