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Original Article

Assessment of the basaltic rocks in Yemen for the basalt fibers production

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Abstract

Representative samples were collected from 22 sites across Yemen. The geochemical analysis found that the SiO_2 content ranges from 40.40 to 55.60%, the Al_2O_3 content ranges from 12.70 to 16.10%, the Fe_2O_3 content ranges from 8.41 to 15.80%, the CaO content ranges from 3.66 to 11.05%, and the MgO content ranges from 1.30 to 11.40%. TiO_2 content ranges from 1.11 to 5.56%, NaO_2 content from 1.88 to 4.88%, and K2O content from 0.67 to 3.25%. The calculations of the acidity, viscosity modules and fusibility constant of the investigated rocks showed the suitability of the basaltic rocks locations for the production of basalt fiber, except the Hajda, Mafraq Al Makha, Karish, Wadi Al Jima, and Wadi Qaradh locations, as a result of the high acidity module The results of the geochemical analysis of the studied samples were compared with the geochemical analyses of similar rocks from different countries used in basalt fiber production. The comparison showed significant similarities in the results, indicating that the studied rocks are suitable for basalt fiber production. A petrographically study on basalt rocks after they melted at temperatures ranging between 1190 and 1240 °C, and it was found that they consist mainly of basalt glass. Melting experiments were carried out, which showed that the beginning of the fusion was at a temperature ranging between 1030 and 1150 °C, and the fusion was completed at a temperature ranging between 1200 and 1220 °C, while the temperature at which the crystallization process began was at a temperature ranging between 1190 and 1200 °C. The study concluded that the studied basalt rock sites are suitable for manufacturing basalt fiber.

Keywords: Basalt; Fiber basal; Geochemical analysis; Yemen.

1. Introduction

Basalt is an extrusive igneous rock that forms from the rapid cooling of lava flows. It is characterized by its fine-grained texture and mafic mineral composition. Basaltic rocks are among the most common, forming lava plateaus and volcanic cones. Chemically, these rocks are considered very stable and inert [1, 2].

Basalt rocks are used in many constructions and industrial applications, the most important of which is the manufacture of basalt fibers [3]. Basalt is the raw material necessary to produce basalt fiber, which currently makes up one-third of the igneous rocks that make up the Earth's crust [4]. Basalt is environmentally friendly and non-hazardous and can be used for multiple industrial applications [5].

The lower the amount of remaining olivine in the basaltic melt, the higher the consistency of the melt, its fabric-forming ability, and its ability to form fibers [6, 7]. This offers the prospect of a completely new range of composite materials and products. Low-cost, high-performance fibers offer the potential to solve the largest problem in the cement and concrete industry: cracking and structural failure of concrete [8, 9].

2. General Geological Setting

Continental flood basalts (CFBs) form part of large igneous provinces (LIPs) that erupt onto continental crust. Continental plateau basalt covers large areas with thicknesses reaching thousands of meters. It is found in continental regions, forming plateaus such as the Deccan Plateau in India, the Columbia River Plateau in northwest America, the Parana Basin in southern America, the Karoo Basin in Africa, Australia, Siberia, Ethiopia, Yemen, Saudi Arabia and the Qatrani basalt in Egypt (Figure 1) [6, 10-12].

Basalt rocks are found in Yemen within the rocks of the Yemen Volcanic Group (YVG) in the form of plateaus within the Yemeni Trap Series (YTS) and volcanic cones within the Yemen Volcanic Series (YVS) [1, 12]. The basalt rocks found within the Yemeni Trap Series are distinguished by their compact structure and fine-grained texture and are widespread throughout the various governorates of Yemen (Figure 2). The total estimated reserves of basaltic rocks in Yemen are about 142 million cubic meters [3].

3. Materials and methods

Fieldwork involved collecting 22 representative samples of basaltic rocks from various governorates in Yemen (Figures 3 and 4). Petrographic analysis was conducted on 22 samples at the Yemeni Geological Survey laboratories using a Nikon optical polarizing microscope. The melting experiments were performed in the same laboratory's smelting furnaces. Geochemical analysis was carried out at the Saudi Geological Survey laboratories using X-ray fluorescence spectrometry (XRFS) on a fully automatic Philips PW2440 MagiX PRO wavelength-dispersive spectrometer equipped with a 66 kV generator and a 4 kW rhodium end-window X-ray tube.

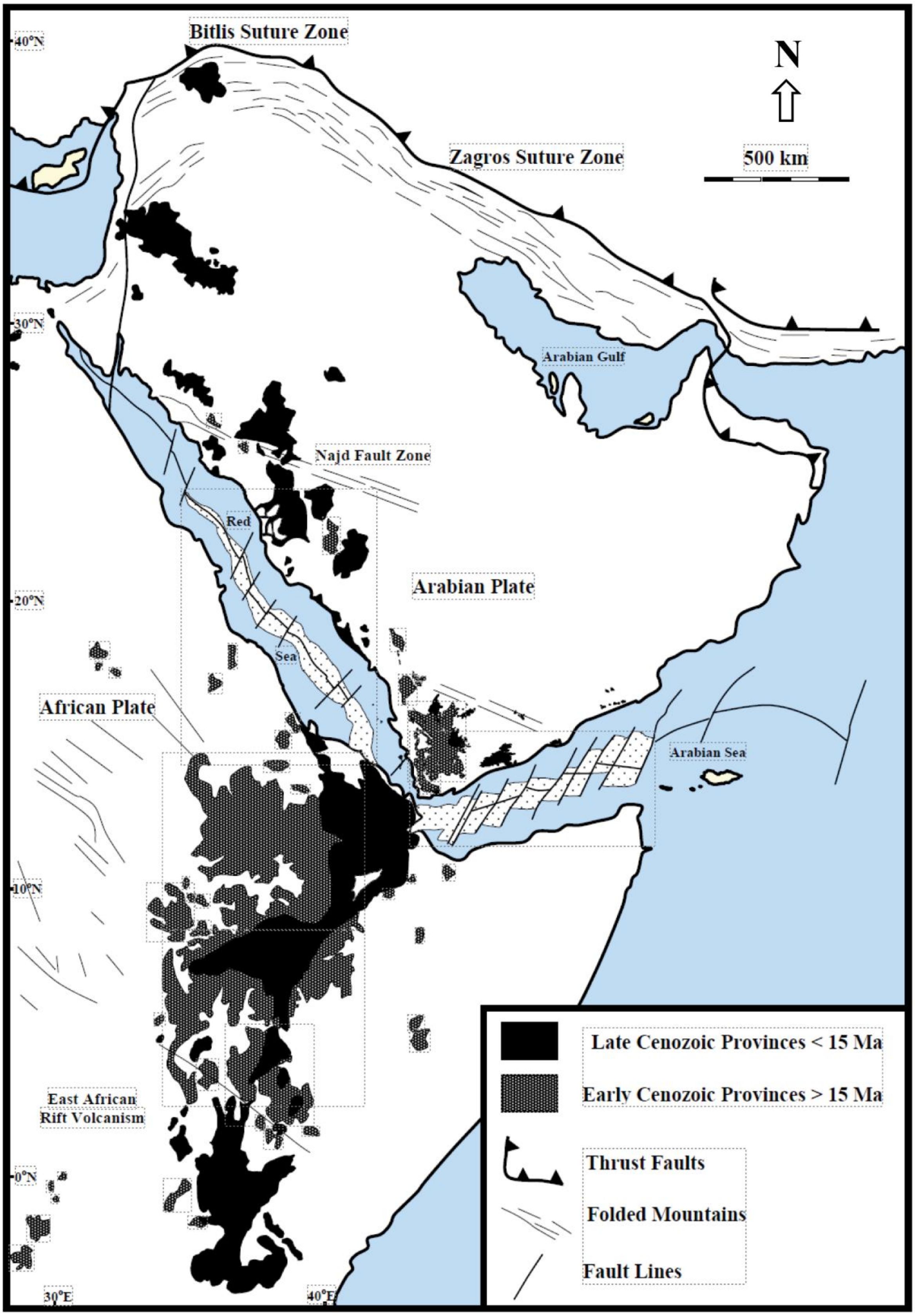

Figure 1: Simplified Geological map showing the distribution structure and Cenozoic volcanism around the Red Sea, Gulf of Aden, Afar, and adjacent areas [1]. Copyright 2009 Sana'a University.

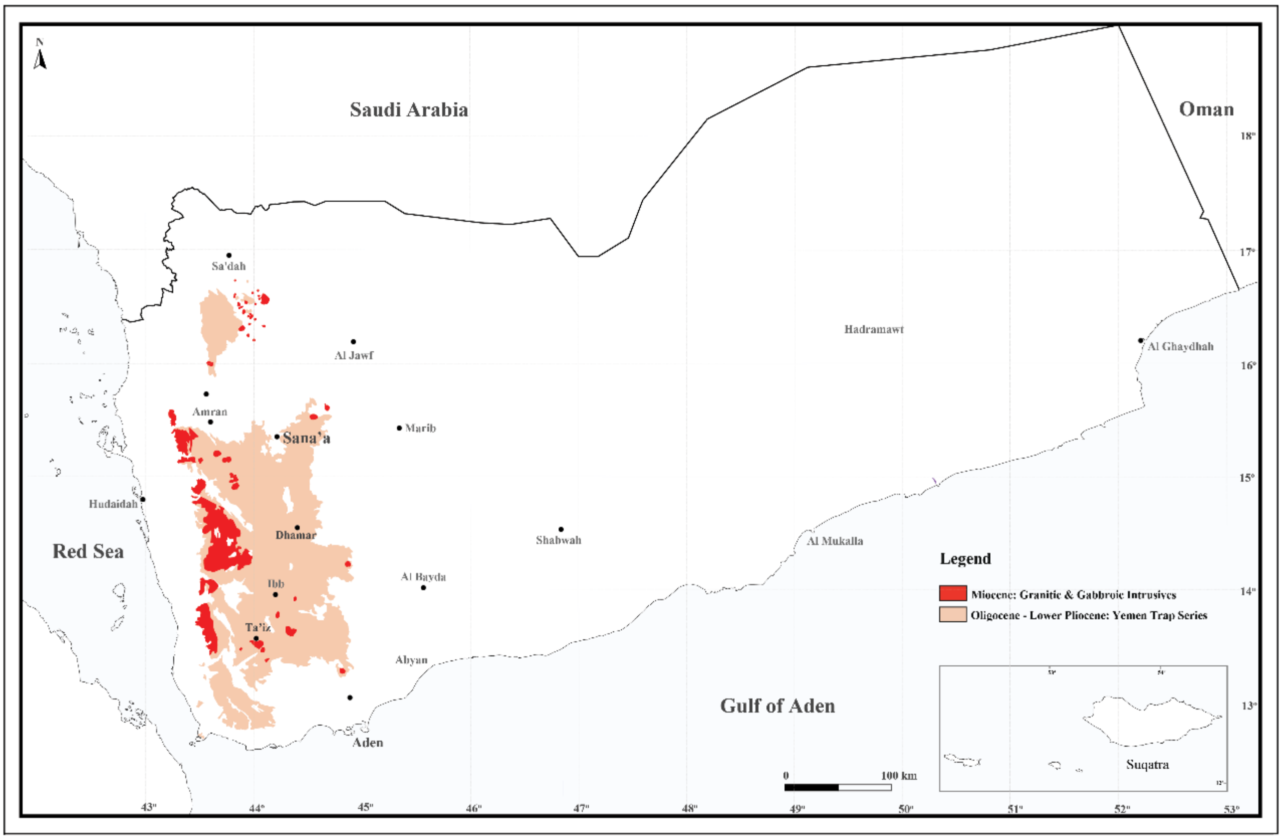

Figure 2: Geological map of Yemen Volcanic Series (Modified by Al-Sabri, 2020). Copyright 2020 Geological Survey & Mineral Resources, Sana'a, Yemen.

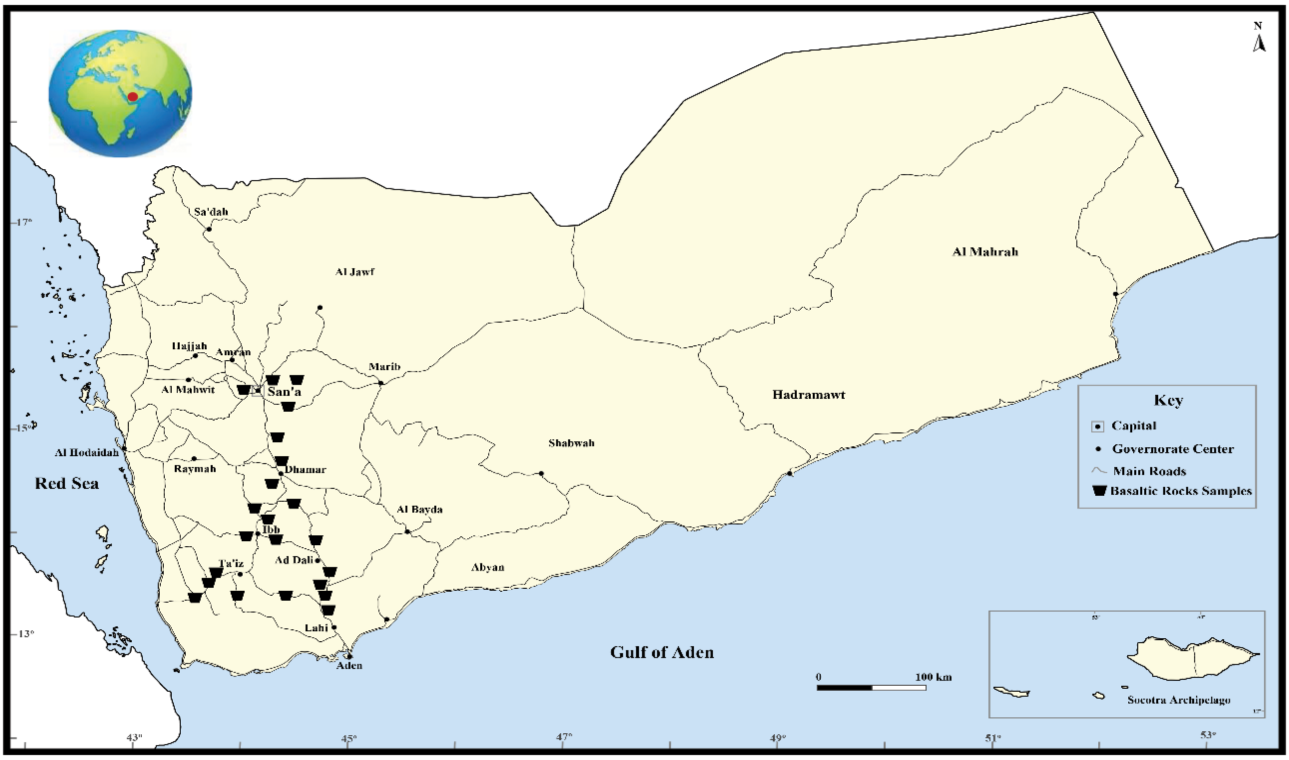

Figure 3: A location map of the study area showing the sites of collected samples.

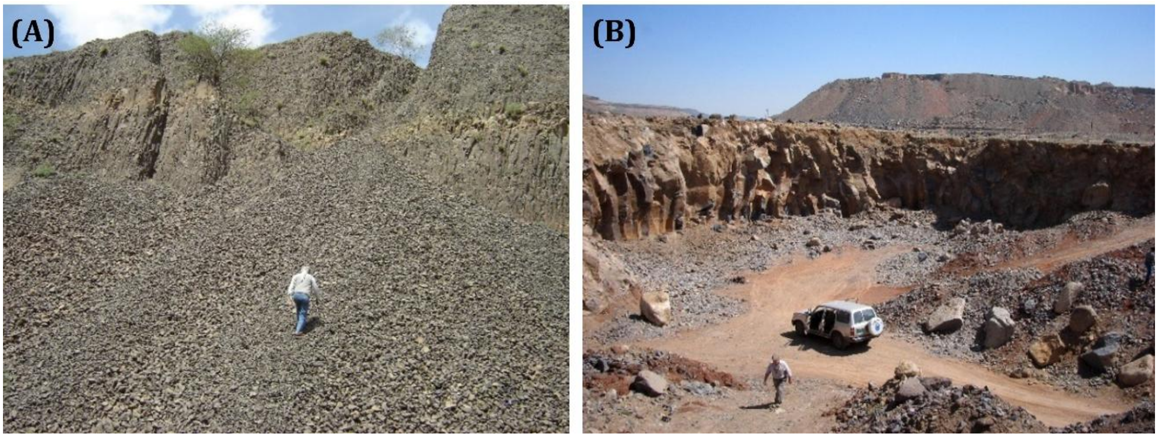

Figure 4: Outcrops of basaltic rocks (A) East of Ma'bar. (B) Al Subahah.

4. Results and Discussion

4.1 Results

4.1.1 Geochemistry

Geochemical analysis was carried out on twenty-two samples. The analysis included oxides of the major elements, SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O, K_2O, and TiO. It was found that the SiO_2 content ranges from 40.40 to 55.60%, the Al_2O_3 content ranges from 12.70 to 16.10%, the Fe_2O_3 content ranges from 8.41 to 15.80%, the CaO content ranges from 3.66 to 11.05%, and the MgO content ranges from 1.30 to 11.40%. TiO_2 content ranges from 1.11 to 5.56%, NaO_2 content from 1.88 to 4.88%, and K_2O content from 0.67 to 3.25% (Table 1).

4.1.2 Petrographically study

Petrography was carried out on basalt rocks after they melted at temperatures ranging between 1190 and 1240 °C, and it was found that they consist mainly of glass, in addition to plagioclase and olivine (Figure 5A). The basalt rocks before the melting showed augite phenocrysts (Figure 5B).

The basaltic rock samples of the study area are dark and fine-grained. The main components of basaltic rocks are as follows:

Plagioclase: Plagioclase crystals are the predominant minerals in thin sections of all samples and occur in a lath-like, subhedral to euhedral tabular shape (Figure 6A).

Pyroxene: Pyroxene occurs as colorless to grayish brown in color with euhedral to subhedral pyroxene phenocryst crystals, forming ~22% of the rocks (Figure 6B).

Olivine: Olivine phenocrysts occur as single or clustered euhedral to anhedral crystals, forming ~12% of the rocks (Figure 5A).

Based on the petrographic study, it was found that the studied rocks are composed of basalt glass. Melting experiments were examined, which showed that the beginning of the fusion was at a temperature ranging between 1030 and 1150 °C, and the fusion was completed at a temperature ranging between 1200 and 1220 °C, while the temperature at which the crystallization process began was at a temperature ranging between 1190 and 1200 °C (Table 2), which are good indicators of the suitability of using basalt rocks in Yemen to form basalt. fibers for multiple construction and industrial applications.

Table 1: Geochemical composition of basaltic rocks in Yemen.

Localities	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O
Jihanah	46.18	3.20	13.79	14.74	4.80	11.30	2.58	0.58
Bani Hushaish	44.50	5.56	13.40	15.53	4.89	10.40	2.22	0.84
W. Al Rawnah	46.85	4.14	12.80	15.97	4.75	8.94	3.90	1.25
Al Subahah	48.80	2.20	14.20	11.60	7.27	9.00	4.60	1.07
East of Ma'bar	44.03	3.86	15.80	7.41	8.97	10.50	2.20	1.12
Rusabah	47.80	3.75	13.90	11.60	4.12	7.70	4.53	1.40
A'med	48.10	2.67	14.60	12.82	6.23	9.60	3.24	0.83
Al Qawfa'ah	40.40	5.18	12.70	15.44	8.50	11.05	2.82	1.44
Al Dalil	49.15	4.29	13.40	13.72	4.56	8.60	2.77	1.12
Manwaz	48.00	2.49	15.40	11.20	7.68	9.70	3.17	1.02
Negd Al Juma'y	46.06	4.68	13.95	15.80	4.72	9.16	2.90	0.67
Al Udayn	50.30	4.07	14.30	11.98	4.26	8.75	2.42	1.05
Hajdah	52.00	3.20	14.88	11.01	3.59	6.22	3.46	1.85
Khuzaigah	45.50	3.22	15.00	13.31	6.41	10.60	2.56	0.90
Mafraq Al Makha	52.60	1.95	15.90	10.78	3.00	6.78	3.31	1.55
Al Nashamah	48.60	4.68	14.40	13.36	4.98	8.70	2.82	1.14
Karish	52.06	2.77	14.50	12.46	3.98	8.20	3.00	0.76
Al Anad	44.40	2.19	14.20	11.40	3.55	9.50	2.86	1.03
W. Al Jima	54.30	1.11	15.80	9.18	1.30	5.70	4.88	1.52
Al Ghayl	46.26	2.74	12.76	12.11	11.40	9.80	1.88	0.70
W .Qaradh	55.60	1.51	16.00	8.41	2.36	3.66	3.91	3.25
Al Erfaf	47.80	3.29	16.10	13.54	4.99	7.52	3.00	1.21

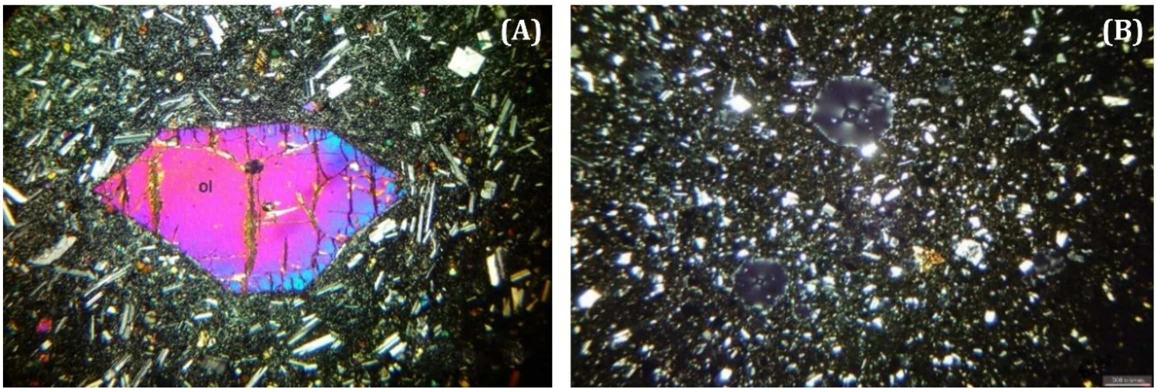

Figure 5: (A) Microphotographs of basalt rocks before the smelting showing the appearance of ol. phenocrysts. (B) Microphotographs of basalt rocks after the melting show the glassy structure.

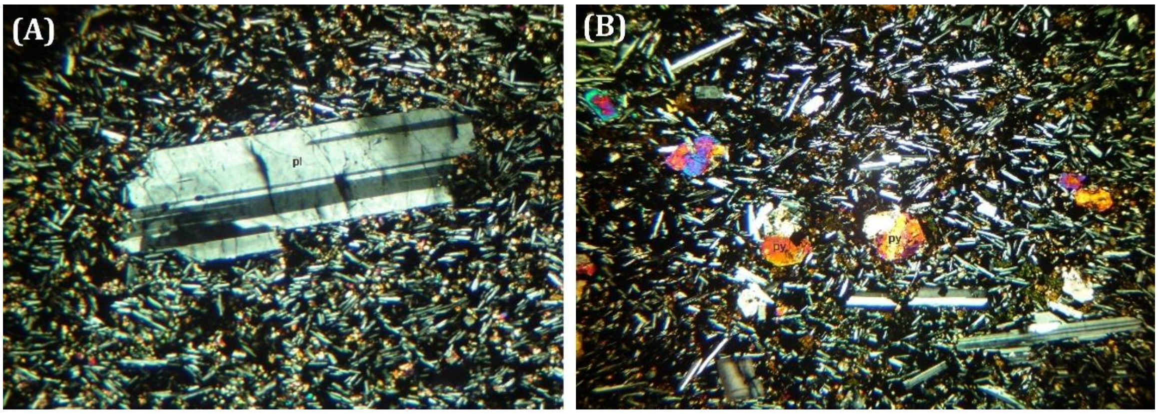

Figure 6: (A) Microphotographs of basalt rocks before the smelting showing the appearance of pla. phenocrysts. (B) Microphotographs of basalt rocks before the smelting showing the appearance of py. phenocrysts.

Table 2: Melting experiments results of basaltic rocks in Yemen.

Localities	Temperature (°C)		
	Initial Fusion	Total Fusion	Initial Crystallization
Jihanah	1165	1220	1200
Bani Hushaish	1150	1190	1180
W. Al Rawnah	1150	1195	1185
Al Subahah	1160	1200	1190
East of Ma'bar	1150	1190	1180
Rusabah	1165	1210	1195
A'med	1160	1195	1185
Al Qawfa'ah	1160	1195	1185
Al Dalil	1100	1190	1180
Manwaz	1155	1195	1185
Negd Al Juma'y	1155	1195	1185
Al Udayn	1140	1200	1190
Hajdah	1100	1200	1195
Khuzaigah	1150	1200	1190
Mafraq Al Makha	1100	1220	1200
Al Nashamah	1150	1200	1190
Karish	1050	1190	1180
Al Anad	1030	1200	1190
W. Al Jima	1030	1240	1220
Al Ghayl	1100	1220	1200
W .Qaradh	1030	1200	1190
Al Erfaf	1150	1220	1200

According to the Geochemical analysis result, the TAS diagram was plotted; it was found that most of the basalt rocks were in the area of the basalt type (Figure 7) [13, 14]. Based on the oxide values, a number of standards were calculated, which included the acidity module (Ma), which ranges between 2.72 and 11.89, the viscosity module (Mv), which ranges from 0.79 to 2.39, in addition to calculating the fusibility constant (R), which ranges from 3.10 to 6.19 (Table 3).

Table 3: Assessment Modules of basaltic rocks in Yemen.

Localities	Temperature (°C)		
	Viscosity Module (Mv)	Acidity Module (Ma)	Fusibility Constant (R)
Jihanah	1.8	3.72	4.05
Bani Hushaish	1.8	3.79	4.30
W. Al Rawnah	1.8	4.36	4.23
Al Subahah	1.6	3.87	3.50
East of Ma'bar	1.6	3.07	3.12
Rusabah	2.1	5.22	4.34
A'med	1.8	3.96	3.93
Al Qawfa'ah	1.2	2.72	3.10
Al Dalil	2.1	4.75	4.72
Manwaz	1.6	3.65	3.57
Negd Al Juma'y	1.8	4.32	4.61
Al Udayn	2.4	4.97	4.89
Hajdah	2.6	6.82	5.36
Khuzaigah	1.7	3.56	3.76
Mafraq Al Makha	2.9	7.00	5.55
Al Nashamah	2.0	4.61	4.59
Karish	2.4	5.46	5.13
Al Anad	2.3	4.49	4.26
W. Al Jima	3.8	10.01	6.00
Al Ghayl	1.2	2.78	3.11
W .Qaradh	3.6	11.89	6.19
Al Erfaf	2.0	5.11	4.83

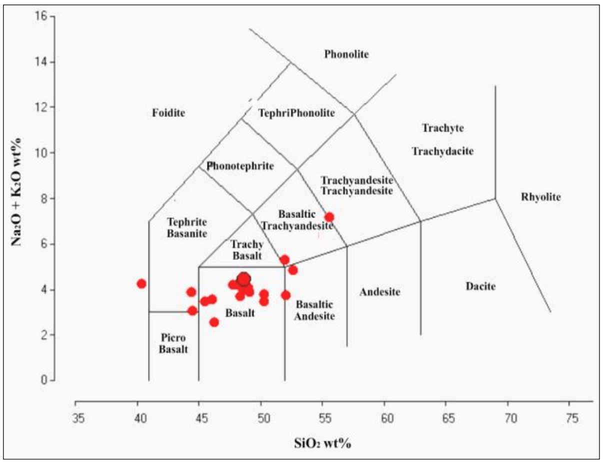

Figure 7: Total alkali-silica classification diagram [14]. Copyright 1992 Springer Nature.

The lower the remnant olivine in the basaltic melt, the higher the melt consistency and fabricability, and the better the fiber quality as well. The acidity modulus (Ma) for the raw basalt samples is calculated to evaluate the quality of the basaltic melt. The calculated acidity modulus (Ma) values would help predict the wool quality [6]. The acidity module (Ma), viscosity module (Mv), and fusibility constant (R) are calculated (Table 3) according to the following equations:

$$Ma = mSiO_2+mAl_2O_3 /mCaO+mMgO \quad (1)$$

$$Mv = xSiO_2+xAl_2O_3 /2xFe_2O_3+xFeO+xCaO+xMgO+xNa_2O \quad (2)$$

$$R=mSiO_2+mAl_2O_3+mTiO_2+mFe_2O_3+mFeO/mCaO+mMgO+mNa_2O+mK_2O \quad (3)$$

where m: mass content of oxides (wt.%) and x = molar content of oxides in mineral rocks (%).

4.2 Discussion

Geochemical analysis of basalt rocks in Yemen was compared with the Chemical composition of rocks for fiber production, which showed a similar composition with rocks for producing fibers (Table 4). The chemical composition of the rocks for producing fibers showed that the percentage of SiO_2 ranges from 39.0 to 55%, Al_2O_3 ranges from 10.0 to 20.0%, $FeO+Fe_2O_3$ ranges from 7.0 to 18.0%, MgO ranges from 3.0 to 12.0%, CaO ranges from 7.0 to 13.0%, K_2O+Na_2O ranges from 2.0 to 7.5%, TiO_2 ranges from 0.2 to 5.0%.

Geochemical analysis of basalt rocks in Yemen was compared with international analyses of basalt rocks from different countries, which are used to manufacture basalt fiber for all oxides that make up basalt rocks in Yemen (Table 5).

Based on oxide analysis, several standards were calculated. These include the acidity module (Ma), which ranges from 2.72 to 11.89; the viscosity module (Mv), which varies from 1.2 to 3.8; and the fusibility constant (R), which ranges from 3.10 to 6.19. The calculations of the acidity, viscosity modules, and fusibility constant of the basaltic rocks in Yemen showed the suitability of the basaltic rocks locations for the production of basalt fiber, except the Hajda, Mafraq Al Makha, Karish, Wadi Al Jima, and Wadi Qaradh locations, as a result of the high acidity module The high content of CaO and MgO in the andesitic basalt increases its crystallizing capacity and the smaller content of Al_2O_3 and a similar content of SiO_2 decrease the values of the acidic and viscosity modules. The basalt raw material's acidity modulus (Ma) is the main parameter defining the final fiber product quality [4, 15]. When the acidity modulus (Ma) value ranges between 2 and 2.7, the viscosity modulus (Mv) value ranges between 3.7 and 6, and the fusibility constant (R) value ranges between 2.3 and 4.4, the fiber is considered to be mineral wool [7].

The geochemical analysis of basalt rocks in Yemen was compared with the chemical composition of rocks used for fiber production (Table 5) and analyses of basalt rocks from different countries, which are used for the purpose of manufacturing basalt fiber [10]. The results showed similar compositions for all oxides that make up basalt rocks in Yemen.

The study concluded that the studied basalt rock sites are suitable for manufacturing basalt fiber, except the Hajda, Mafraq Al Makha, Wadi Al Jima, and Wadi Qaradh sites due to their high acidity standard.

Table 4. Chemical composition of rocks for fiber production [10].

Basic oxides	Content, wt. %	
	continuous fiber	staple fiber
SiO_2	47.0 - 55.0	39.0 - 51.0
Al_2O_3	14.0 - 20.0	10.0 - 19.0
$FeO+Fe_2O_3$	7.0 - 13.5	10.0 - 18.0
MgO	3.0 - 8.5	4.0 - 12.0
CaO	7.0 - 11.0	8.0 - 13.0
K_2O+Na_2O	2.5 - 7.5	2.0 - 5.0
TiO_2	0.2	2.0 - 5.0

Table 5. Chemical composition of basalts of different deposits [10].

Localities	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O+K_2O	TiO_2
Ukraine	49.03	12.58	14.03	5.47	9.53	3.00	2.85
	47.60	17.50	24.40	5.10	9.50	4.70	1.50
Georgia	50.61	16.75	10.26	4.65	9.07	4.88	1.81
Uzbekistan	48.54	14.40	11.65	7.18	9.88	3.99	2.14
	43.85	15.10	10.71	5.1	17.71	5.32	1.06
	47.05	15.74	8.71	5.44	8.45	4.99	-
	44.01	6.99	19.65	6.95	13.35	-	-
Kyrgyzstan	44.00	14.80	10.95	6.30	8.33	4.84	2.30
China	55.17	15.57	9.10	12.23	12.23	5.89	-
Russia	50.42	11.82	12.25	10.58	8.84	2.52	1.04
	49.92	15.96	9.39	8.22	10.52	2.85	0.68
	53.54	14.12	10.44	6.70	6.60	4.84	1.52
	51.70	17.00	12.90	5.29	7.00	3.81	2.20
	48.42	18.82	12.60	4.56	9.76	3.99	1.33
	48.70	15.90	20.80	5.40	12.90	3.50	0.80
	48.43	14.23	12.36	3.58	8.58	5.56	-
Indonesia	50.60	16.00	22.90	5.10	9.80	3.20	0.90
Buryatia-Russia	48.60	16.70	11.69	4.47	6.25	7.40	2.12
	44.28	15.21	13.92	8.58	9.61	5.24	2.08
	47.98	16.04	10.60	4.82	7.69	6.72	1.93

5. Conclusion

Based on the geochemical analysis of basalt rocks in Yemen and the oxide values, several standards were calculated, including the acidity module (Ma) and the viscosity module (Mv), in addition to calculating the fusibility constant (R). The study concluded that the studied basalt rock sites are suitable for manufacturing basalt fiber except the Hajda, Mafraq Al Makha, Wadi Al Jima, and Wadi Qaradh sites due to their high acidity standard.

Data Availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

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