geosciences

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Petrographic and Geotechnical Features of Dir Volcanics as Dimension Stone, Upper Dir, North Pakistan

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Abstract: The utilization of dimension stone in construction has been prevalent since ancient times; however, its application in modern construction has gained significant attention over the last few decades. This research aimed to assess the physical and strength properties of volcanic rocks from the Kohistan Island Arc for their potential use as dimension stone. Five types of andesites (MMA, PMA-1, PMA-2, CMA, and FMA) and two types of agglomerates (AG-1 and AG-2) were identified based on their composition, color, and texture. The samples were characterized in terms of their petrography (compositional and textural), physical properties (specific gravity, water absorption, and porosity), and strength properties (unconfined compressive strength and unconfined tensile strength). Two non-destructive tests (ultrasonic pulse velocity test and Schmidt hammer) were conducted, and the degree of polishing was evaluated. Correlation analyses were carried out to establish possible relationships among these parameters. The presence of chlorite, epidote, sericite, and recrystallized quartz indicated signs of low-grade metamorphism in andesites. The study revealed that feldspar, amphibole, and quartz imparted good physical and strength properties to samples MMA, CMA, FMA, AG1, and AG2. On the other hand, PMA-1 and PMA-2 exhibited reduced physical and strength properties due to the abundance of alteration products like chlorite, sericite, and epidote. The unconfined compressive strength exhibited a strong correlation with ultrasonic pulse velocity, skeletal density, porosity, and water absorption. Weathering grade considerably affected the values of ultrasonic pulse velocity and Schmidt hammer. Consequently, samples PMA-1 and PMA-2 are not recommended for load-bearing masonry units and outdoor applications due to their high water absorption and low strength values. On the other hand, samples FMA and MMA exhibited excellent properties like high strength and good polishing, indicating their potential use as decorative and facing stones, external pavement, ashlar, rubbles, and load-bearing masonry units.

Keywords: dimension stone; volcanic rocks; physical properties; strength properties; petrography; non-destructive testing

Citation: Nawaz, M.; Ahmed, W.; Yasir, M.; Islam, I.; Janjuhah, H.T.; Kontakiotis, G.; Antonarakou, A.; Stouraiti, C. Petrographic and Geotechnical Features of Dir Volcanics as Dimension Stone, Upper Dir, North Pakistan. *Geosciences* **2023**, *13*, 224. https://doi.org/10.3390/geosciences13080224

Academic Editors: Agust Gudmundsson and Jesus Martinez-Frias

Received: 20 June 2023
Revised: 20 July 2023
Accepted: 25 July 2023
Published: 27 July 2023

1. Introduction

Dimension stones, such as granite, marble, limestone, and sandstone, have been used in construction since the foundation of human history [1–3]. However, with the production and development of modern cement and bricks, their use in megastructures has decreased. Nonetheless, they are still used in the building of foundation materials, retaining walls, armor stone, and dams. Dimension stone must meet the requirements of durability, strength, porosity, and attractiveness, in addition to being easy to quarry and accessible. These properties are determined by the composition, texture, weathering grade, and tectonically produced rock fabric [4–8]. The petrographic characteristics of a rock specimen must be precisely investigated to determine its overall performance for usage as a building stone in a specific environmental condition of a region [9–13]. Petrography not only determines the origin of rocks, but also their resistance to weathering, durability, and strength [14]. Studies have shown that texture and alteration have a significant influence on rock strength [15–18]. Grain size variation, recrystallization at grain boundaries, low porosity, a low quantity of micaceous minerals, and low water absorption all contribute to increased strength, and vice versa. Similarly, a rock's physical and strength properties are critical in the design, construction, and maintenance of engineering projects. According to De Vallejo and Ferrer [19], the composition and texture of rocks determine their physical properties. Durable rocks have high mechanical properties, low porosity, and are chemically inert. The evaluation of rock response to applied weight, temperature fluctuations, and moisture content is a critical aspect in determining the durability and performance of rocks in various applications. Likewise, achieving the required degree of polish is of utmost importance for decorative stones intended for use in interior applications such as flooring, tabletops, and wall cladding.

Heap and Violay [20] showed how the mechanical properties of volcanic rocks are complex because of the complexities and variety in minerology and texture. Pola, et al. [21] investigated the influence of alteration on the mechanical properties of several volcanic rocks and discovered that alteration caused a 45–85% loss in strength and ultrasonic pulse velocity (V_p). Korkanç and Solak [22] evaluated the engineering properties of tuffs using grain-to-mass ratios and found that samples with a high degree of welding (well compacted) have strong geotechnical properties. Similarly, Ündül [23] investigated the impact of mineralogy and petrography on the petrophysical, strength, and cracking processes of Turkish volcanic rocks. The results revealed that mineral masses influenced specific gravity and loss of ignition (LOI). Unconfined compressive strength and elastic characteristics, on the other hand, were shown to be related to mineral content. Furthermore, the fraction of phenocrysts and groundmass had a considerable influence on fracture propagation.

The geotechnical characteristics of Dir volcanics have not been extensively studied, resulting in a dearth of data in this area. This study focuses on evaluating the potential of Dir volcanics as dimension stones, given their attractive volcanic textures, such as porphyritic texture. The rocks are classified by their use as load-bearing masonry units, coping, ashlars, cladding, and wall faces, among others. The primary objective of this research is to assess the petrographic and geotechnical properties of Dir volcanics for use as dimension stones. To establish mineralogical and textural relationships, a comprehensive petrographic analysis was conducted. Furthermore, the physical and strength characteristics of the rocks were evaluated. The study investigated the relationship between the petrographic, physical, and strength properties of Dir volcanics to determine their suitability as dimension stones. In addition, the degree of polish required for decorative purposes, such as internal floors, worktops, tabletops, and internal wall facing, was determined.

2. Study Area

The study area is situated between latitudes 35°16′06.9″ and 35°19′45.0″ and longitudes 71°57′21.6″ and 72°02′80.3″ in the vicinity of Sheringal town in District Upper Dir and can be easily accessed via the Peshawar-Dir metalled road (Figure 1). The Dir-Utror metavolcanics are composed of andesites, basaltic andesites, dacite, and rhyolite, which are mainly characterized by a porphyritic texture dominated by abundant phenocrysts of plagioclase, K-feldspar, and quartz, while carbonate and opaque minerals are scarce. The primary metamorphic phases present in the metavolcanics include chlorite, epidote, and actinolite. Geochemical analysis indicates that the study area has undergone low-grade metamorphism under the greenschist facies (epidote-amphibolite facies). The bulk rock geochemistry of metavolcanics suggests a calc-alkaline trend, like subduction-related magmatism. The presence of a significant amount of mafic lava suggests that these volcanic rocks originated from the older continental crust [24].

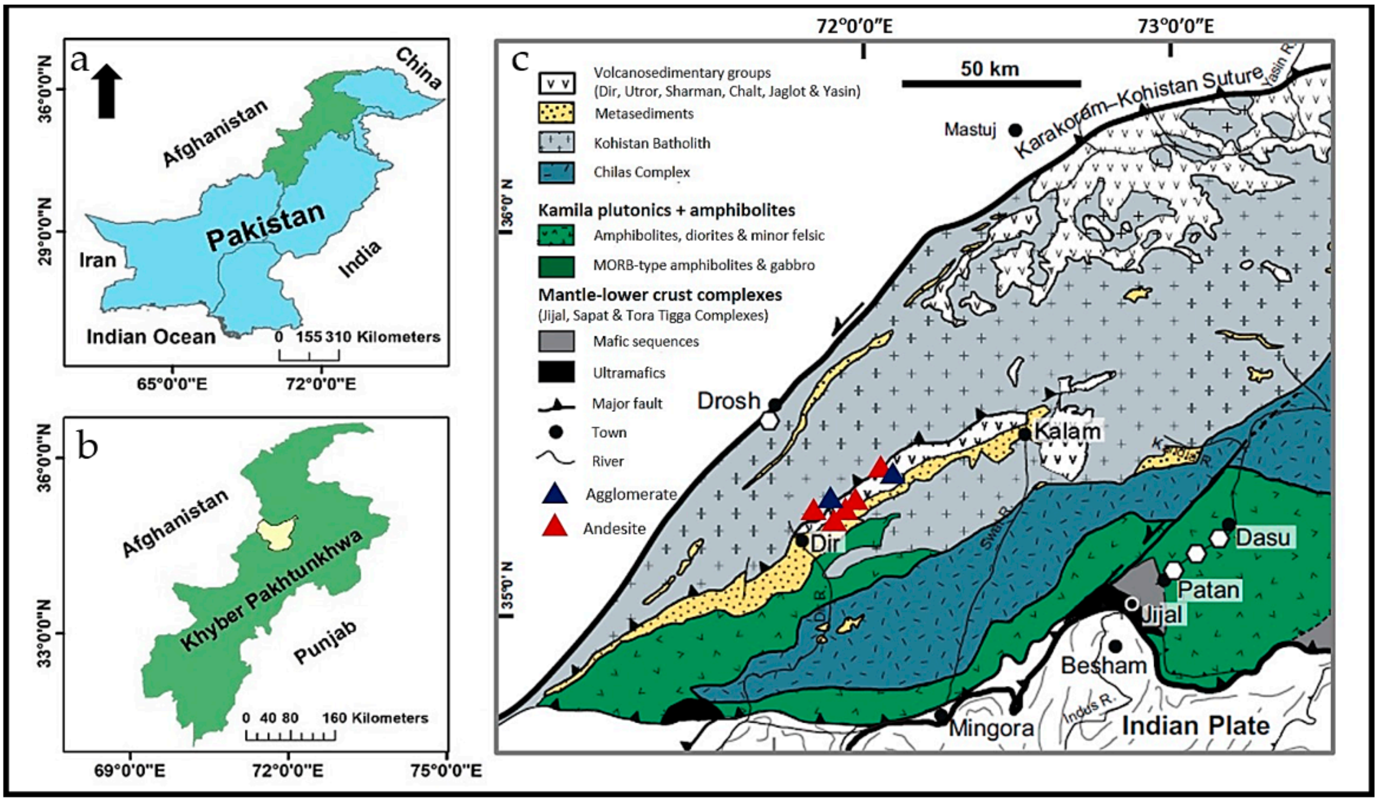

Figure 1. Map showing the study area and location of the investigated samples: (**a**) geographic map of Pakistan; (**b**) geographic map of Khyber Pakhtunkhwa province; (**c**) geological map of the study area.

3. Materials and Methods

3.1. Sample Collection

The fieldwork was conducted in Sharingle, Dir Upper, where a total of seven (7) bulk samples were collected (Figure 1). The samples were divided into two groups based on their texture and composition: andesite MMA (medium-grained meta-andesite), FMA (fine-grained meta-andesites), PMA-2 (porphyritic meta-andesite-2), CMA (coarse-grained meta-andesite), PMA-1 (porphyritic meta-andesite-1), and agglomerate AG-1 (hard and compacted agglomerate-1), AG-2 (comparatively soft agglomerate-2) (Figure 2). Table 1 shows detailed information about the collected samples and the weathering grades, as proposed by Borrelli, et al. [25]. The samples were chosen based on their textural and compositional variations, and they were carefully selected to ensure homogeneity and the absence of cracks and fissures for accurate interpretation. The rocks exhibited a porphyritic texture, with phenocrysts visible to the naked eye.

WGI: No discoloration was observed in these samples; the original volcanic texture was preserved; when struck with a hammer, they produced a ringing sound; and a geological pick scratched with difficulty.

WGII: Slight discoloration was observed in these samples; the volcanic texture was preserved; when struck with a hammer, they produced a ringing sound; and a geologic pick scratched with difficulty.

WGIII: Discoloration was observed in these samples; the volcanic texture was preserved; when struck with a hammer, they produced an intermediate sound; and a geologic pick made scratches on the surface.

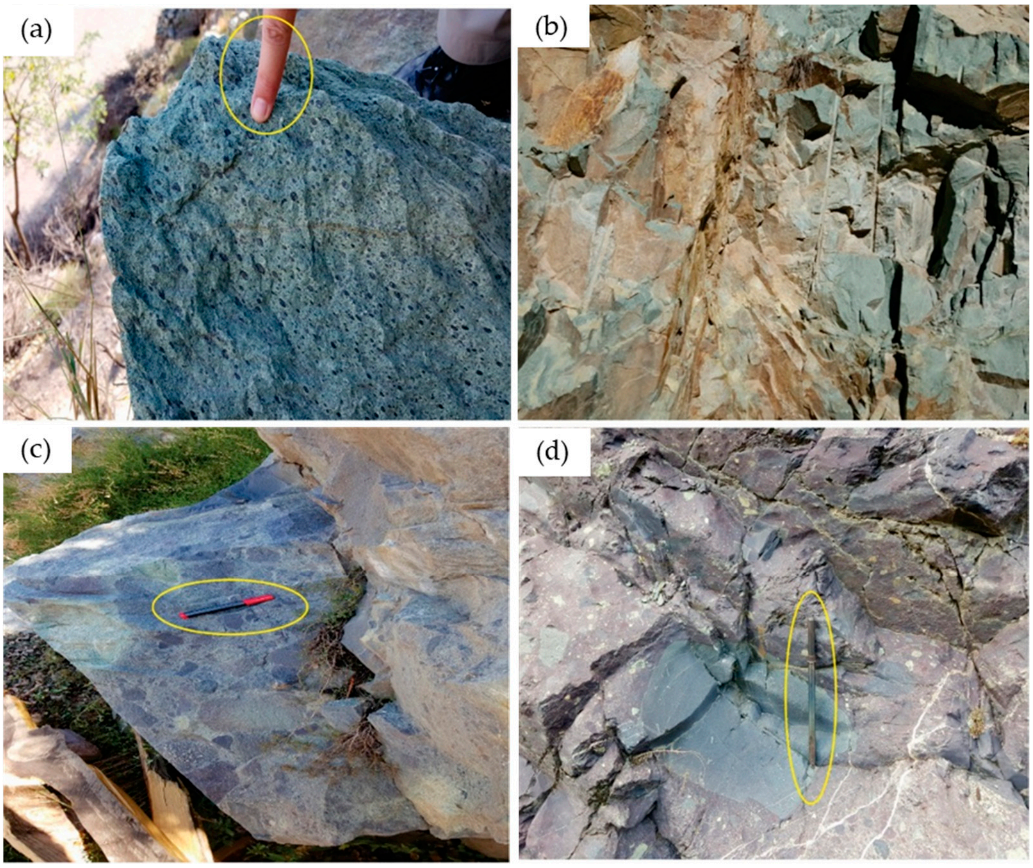

Figure 2. Field photographs of the volcanic rocks investigated in this study, showcasing their distinct compositions, textures, and colors. Yellow circles highlight a finger (7 cm) and a pen (14 cm) for scale: (**a**) phenocrysts in PMA-1; (**b**) outcrop view of porphyritic meta-andesites PMA-2; (**c**) small size clasts in AG-1; (**d**) large size clasts of MMA in AG-1.

Table 1. Details of the collected rock samples and weathering grades according to Borrelli, Greco and Gullà [25].

S.No	Rock Type	Specimen Designation	Texture	Descriptive Term	Weathering Grade
1 2	Andesite	MMA FMA	Fine Very fine	Fresh	WG-I
3 4		PMA-2 CMA	Porphyritic Coarse	Slightly weathered	WG-II
5		PMA-1	Porphyritic	Moderately weathered	WG-III
6	Agglomerate	AG-1	Clastic	Fresh	WG-I
7		AG-2		Slightly weathered	WG-II

3.2. Experimental Program

To investigate the mineralogy, texture, and microfractures of the bulk samples, three core samples of NX size (54.75 mm) were obtained from each variety in accordance with ASTM C170/C170M [26]. The core samples were then used to prepare thin sections for petrographic studies, which were analyzed under the Nikon LV 100 ND polarizing microscope. Physical tests, including specific gravity, water absorption, and porosity, were performed using ASTM standards [27] and Franklin [28] saturation and buoyancy methods. The p-wave velocity (V_p) was measured on oven dry (for 24 h at 100 °C) samples and saturated samples (after immersing in water for 24 h, under a saturated surface dry condition) using MS Controls, Italy's ultrasonic pulse velocity equipment [29]. Strength tests, including the unconfined compressive strength test (UCS) [26] and unconfined tensile strength test [30], were conducted on the oven dry core samples. A Schmidt hammer test [31] was also performed using the rebound hammer from MS Control, Italy, with an impact energy of 2.207 Nm. To determine the grade of polishing, rock samples in the form of blocks were examined underneath a stereomicroscope and scanning electron microscope (SEM) after being homogenously polished with different abrasives (400 grit, 600 grit, 800 grit, and 1000 grit) of silicon carbide powder. The surface morphology, microfractures, veins, cavities, general appearance, mineral alteration, and smoothness of the surface were observed under the stereomicroscope before studying the same features under the SEM.

To establish the relationship between the petrographic, physical, and strength parameters, a simple regression analysis was carried out. Additionally, a Pearson bivariate statistical correlation was also established separately among the various parameters of andesites and agglomerates. For this purpose, the statistical software Stat/14 MP version was used to develop bivariate correlation. The values of the correlation fluctuate between 0, +1, and −1, where the positive and negative signs indicate whether the relationship between the two properties is direct or inverse. A stronger relationship is indicated when the value is closer to one (1), and vice versa. Additionally, there are significant figures; the significant values of 0.01 and 0.05 fall within these limits and indicate an effective relationship.

4. Results and Discussion

4.1. Petrography

4.1.1. Andesites

Figure 3 shows five distinct types of andesites, characterized based on their texture and color: medium-grained meta-andesite (MMA), coarse-grained meta-andesite (CMA), fine-grained meta-andesite (FMA), and two types of porphyritic meta-andesite (PMA-1 and PMA-2). Except for FMA, which falls within the quartz andesite range, all samples were located within the andesite range. These samples ranged in color from dark gray to green and maroon. The texture of these andesites was porphyritic and seriate. Table 2 shows the modal mineralogy and the phenocryst-to-groundmass ratio that varied among the different andesites. Alkali feldspar, plagioclase, and amphibole were the primary minerals and phenocrysts, with chlorite, quartz, epidote, opaque minerals, and calcite contributing as accessory minerals.

Table 2. The modal mineralogy of the investigated samples.

Rock Type	S. No.	Plg	Alkf	Qtz	Amp	Ep	Car	Op	Cl	Gm	Pc: Gm
Andesite	MMA	37.08	8.01	5.98		2.60	2.00			45.00	1.26
	PMA-1	18.87	5.00	3.90	4.67	1.90	1.67	1.63	3.83	59.13	0.70
	PMA-2	27.67	5.00	11.97	4.40	1.00	1.00	1.50	1.73	45.23	1.33
	CMA	33.97	7.00	6.83	1.70	1.67		10.00		34.43	1.87
	FMA	6.00		7.40	15.80		6.67	1.33	1.00	62.13	0.62
Agglomerate	AG-1	50.97	2.00	3.47	2.00	2.87	2.17	6.60		31.27	2.23
	AG-2	29.00		14.33	1.00		19.67	1.33		35.33	2.14

Alkf = alkali feldspar, Amp = amphibole, Car = carbonates, Cl = chlorite, Ep = epidote, Gm = groundmass, Op = opaque minerals, Plg = plagioclase, Qtz = quartz, Pc:Gm = phenocrysts to groundmass ratio.

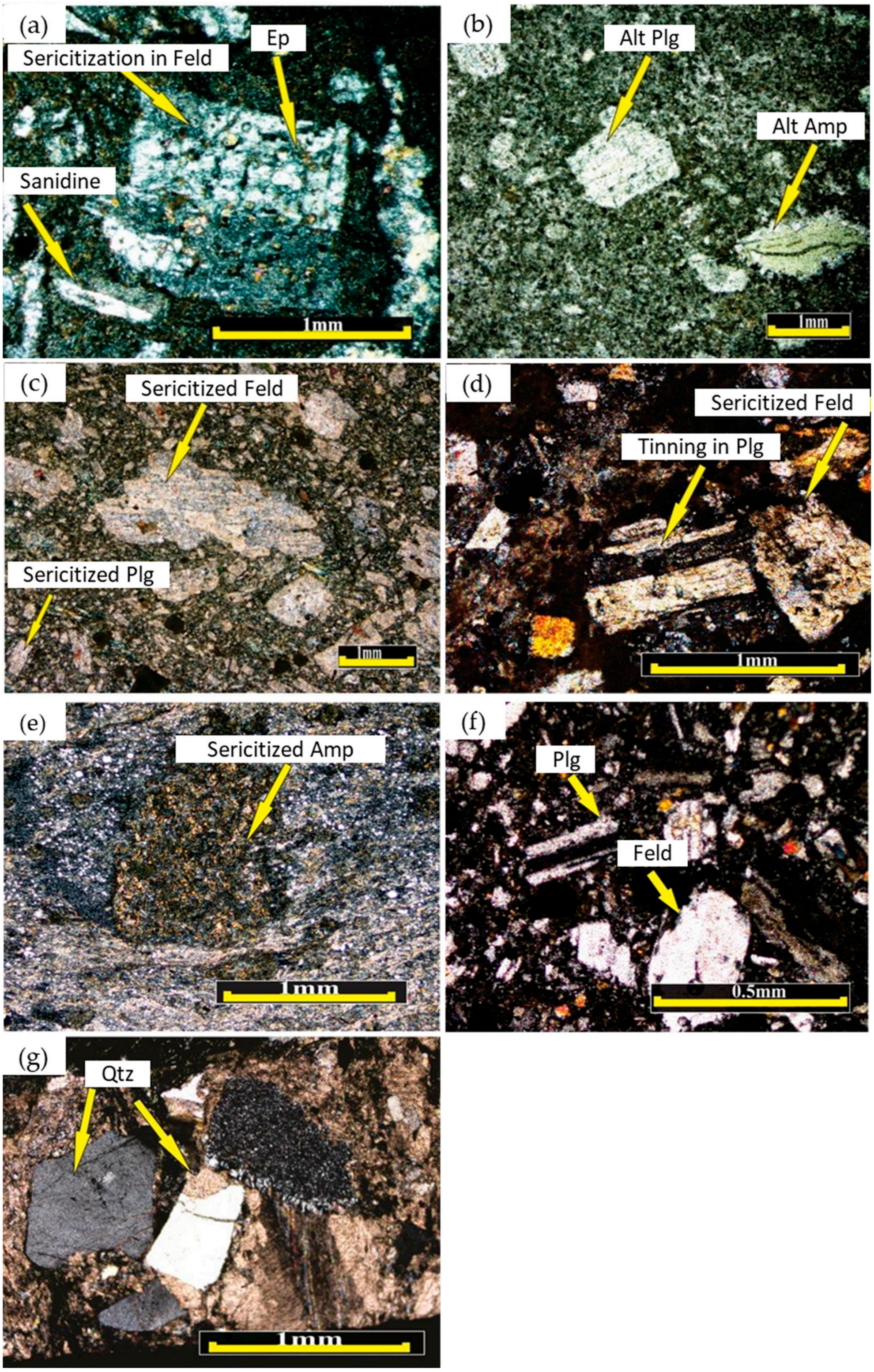

Figure 3. Photomicrographs of the thin sections of the studied volcanic rocks: (**a**) MMA (XPL) sericitization and epidote in feldspar; (**b**) PMA-1 (PPL) chloritization and alteration of plagioclase and amphibole; (**c**) PMA-2 (PPL) sericitization in feldspar and plagioclase; (**d**) CMA (XPL) twinning and sericitization in plagioclase and feldspar; (**e**) FMA (PPL) sericitization of amphibole; (**f**) AG-1 (XPL) twinning in plagioclase and feldspar; (**g**) AG-2 (XPL) fractures in quartz.

4.1.2. Agglomerate

The samples consist of two different types of agglomerates, AG-1 and AG-2, which are distinguishable from one another by their texture and composition. AG-1 appears maroon-pinkish and compacted, while AG-2 is greenish in color. Both agglomerates are formed from welded clasts, ranging in size from inches to feet. The modal mineralogy of the samples includes alkali feldspar, plagioclase, quartz, epidote, amphibole, carbonates, and opaque minerals. They exhibit a porphyritic and seriate texture, with a dirty and fine-grained ground mass consisting of small plagioclase grains and some quartz.

4.2. Physical Properties

4.2.1. Specific Gravity, Water Absorption, and Porosity

Table 3 presents the average physical properties of the rock samples analyzed in this study. The specific gravity of the samples ranged from 2.76 to 2.92 g/cm^3, falling within the high to very high range according to [32]. Andesites had an average water absorption ranging from 0.10 to 0.28%, while agglomerates had an average water absorption ranging from 0.10 to 0.11%. The porosity values of the andesites ranged from 0.39 to 0.77%, while the agglomerates ranged from 0.28 to 0.30%. The higher specific gravity of agglomerates in comparison to andesites can be attributed to their compact nature and lower degree of weathering. According to [32], rocks with specific gravity values of 2.55 or higher are suitable for heavy construction. The andesites' higher water absorption values can be attributed to their greater degree of alteration and higher porosity compared to the agglomerates. The porosity values for all samples were found to be very low, i.e., less than 1%, indicating their suitability for construction purposes.

Table 3. Average values of physical and strength properties of investigated rocks.

Sample	Specific Gravity (g/cm^3)	Water Absorption (%)	Skeletal Density (g/cm^3)	Porosity (%)	Ultrasonic Pulse Velocity (m/s) Oven Dry		Saturated		R-Value	UTS (MPa)	UCS (MPa)
					Value	S.D	Value	S.D			
MMA	2.86	0.13	2.85	0.39	5121.83	256.09	5275.56	248.95	53.0	16.13	117.87
PMA-1	2.76	0.28	2.74	0.77	4465.03	223.25	4667.33	228.59	44.6	12.06	44.45
PMA-2	2.76	0.26	2.74	0.72	4522.66	226.13	4726.66	232.56	50.2	14.59	47.97
CMA	2.81	0.23	2.79	0.66	4650.00	232.50	4810.00	238.48	50.8	12.25	62.73
FMA	2.86	0.17	2.84	0.50	4905.00	239.11	5154.66	245.15	54.2	16.89	102.94
AG-1	2.92	0.10	2.91	0.28	4782.23	295.25	5060.90	308.79	58.2	11.26	77.05
AG-2	2.77	0.11	2.76	0.30	4624.80	301.72	4854.33	309.14	50.0	10.32	56.95

4.2.2. Ultrasonic Pulse Velocity (V_p)

The ultrasonic pulse test was conducted under both dry and fully saturated conditions. The average V_p ranged from 4465 to 5121 m/s (Table 3). These results are comparable to those for granites reported by Karaman and Kesimal [33] and Sousa [9], but higher than the values reported by Korkanç and Solak [22] for a tuff stone from Turkey. The Vp for andesites ranged from 4465 to 5121 m/s, while the values for agglomerates ranged from 4782 m/s to 4624 m/s for AG-1 and AG-2, respectively. The FMA and MMA average values ranged from 4905 to 5121 m/s, which is classified as high, while the PMA-1, PMA-2, and CMA average values ranged from 4465 to 4650 m/s. The results indicate that the core samples exhibited lower V_p in the dry condition compared to the fully saturated condition. This is explicable by the fact that V_p is directly proportional to the ratio of the solid skeleton to the fluid velocity, and the proportion is higher for water than for air in the pore spaces, leading to an increase in V_p. The V_p also showed a significant decrease with an increase in weathering grade.

4.3. Strength Properties

4.3.1. Unconfined Compressive Strength Test (UCS)

The average values of UCS obtained from the samples ranged from 44.4 MPa (PMA-1) to 117.87 MPa (MMA) (Table 3). The results indicated that the samples can be classified as moderately weak, strong, or very strong. The strength values of volcanic rocks were found to be higher than those of ignimbrites and lava flows from Italy, as reported by Pola, Crosta, Fusi and Castellanza [21], but lower than those of volcanic lava flows from Turkey, as reported by Ündül [23]. Furthermore, it was observed that the fine- and medium-grained andesites had higher strength than their coarse-grained counterparts. However, among the meta-andesites, the coarser-grained samples exhibited higher strength than the porphyritic ones, likely due to their higher porosity, water absorption, weathering grade, and alteration. The samples MMA and FMA also displayed comparatively higher strength values, which could be attributed to their low alteration and fine-grained texture. Similarly, AG-1 and CMA samples lacking veins and fractures also demonstrated higher strength values. On the other hand, PMA-1 and PMA-2 (porphyritic meta-andesites) showed moderate strength values due to the high degree of alteration of primary minerals into weak, flaky minerals such as chlorite and sericite. Additionally, a higher number of fractures and veins were observed in these samples, which could have further weakened their strength.

4.3.2. Uniaxial Tensile Strength (UTS)

The average UTS values ranged from 10.32 MPa (AG-2) to 16.89 MPa (FMA). MMA and FMA had higher UTS values that ranged from 12.47 to 21.02 MPa and 14.92 to 19.37 MPa, respectively. On the other hand, PMA-1, PMA-2, and CMA showed moderate values ranging from 11.45 to 13.07 MPA, 14.02 to 15.46 MPA, and 12.08 to 12.51 MPa, respectively. The values of AG-1 exhibited some uniformity, ranging from 10 to 13.64 MPa, while AG-2 showed variation from 5 to 13.87 MPa (Table 3).

4.3.3. Schmidt Hammer Rebound Hardness

The average R-values obtained from the Schmidt hammer test ranged from 44.6 (PMA-1) to 58.2 (AG-1). The test was conducted on the bulk samples rather than the core samples, resulting in relatively higher R-values. The high value of AG-1 is attributed to the compact nature of these rock samples, which produce a ringing sound when struck with a hammer. Additionally, since weathering has a direct impact on the strength of rock samples, the R-values exhibited a negative correlation with increasing grades of weathering. The values of PMA-2, CMA, and AG-2 were found to be similar, with a value of 50, while the values of MMA and FMA were also similar, with values of 53 and 54.2, respectively (Table 3).

4.4. Correlation among Petrographic, Physical, and Strength Properties

The objective of this study was to investigate the relationship between the mineralogical composition and strength of andesite and agglomerate rocks (Figure 4). To this end, the UCS values were plotted against the phenocrysts to groundmass ratio (Pc:Gm) to examine the correlation between the two parameters (Figure 4a). The results demonstrated a statistically significant negative relationship between the two parameters in both andesites (R^2 = 0.76) and agglomerates (R^2 = 0.76), indicating that an increase in the Pc:Gm ratio leads to a decrease in the UCS values. Table 4 shows the Pearson correlation coefficients for andesites and agglomerate. The results show a weak negative correlation between the Pc:Gm ratio and UCS in the studied samples, with coefficients of −0.32 and −0.45, respectively. The Sig. (2-tailed) values were high for both andesites (0.25) and agglomerates (0.37), suggesting that there is no clear evidence of a significant correlation between Pc:Gm and UCS in the investigated samples. The results indicate that the presence of larger phenocrysts or clasts in the rock's texture reduces its overall strength, while a finer-grained groundmass with a higher degree of mineral interlocking enhances its strength. The observed relationship between texture and strength is likely due to increased porosity and decreased grain-to-grain contact in samples with a higher Pc:Gm ratio, resulting in a weaker mechanical response under load. In comparison, agglomerate samples showed a higher Pc:Gm ratio, resulting in weaker rock strength, as larger clasts can create a more porous and less connected matrix. These results highlight the importance of understanding the textural and mineralogical characteristics of rocks for predicting their strength and deformation behavior. The alteration of primary minerals in andesites is accompanied by a significant decrease in the mechanical strength of the investigated rocks, as reported in this study. Karakaş and Güçtekin [34] also reported that the andesites' strength was compromised due to the extensive transformation of plagioclase and amphibole into platy minerals, such as chlorite and sericite. Likewise, the agglomerate samples display strong strength properties, which can be attributed to the presence of quartz-healed veins, reduced alteration, low carbonates, and porosity. However, the presence of opaque minerals may diminish their ornamental stone properties.

To evaluate the strength of the samples indirectly, the skeletal density, porosity, and water absorption were measured and correlated with the UCS (Figure 4b–d). Skeletal density was found to have a strong positive relationship with UCS for both andesites and agglomerates, with R^2 values of 0.82 and 0.84, respectively, and Pearson correlation coefficients of 0.91 and 0.86, respectively. The study found that there is a strong negative correlation between UCS and both porosity and water absorption values in the studied samples. The Pearson correlation coefficients show a high degree of correlation between UCS and these properties. Specifically, the R^2 values and Pearson correlation coefficients for porosity were 0.97 and −0.81, respectively, for andesites, and 0.80 and −0.89, respectively, for agglomerates. Similarly, the R^2 values and Pearson correlation coefficients for water absorption were 0.91 and −0.78, respectively, for andesites, and 0.84 and −0.92, respectively, for agglomerates. These results suggest that higher porosity and water absorption may lead to decreased strength and mechanical properties in both andesites and agglomerates. The relatively high values of water absorption and porosity in andesites corresponded to higher weathering and fracturing.

The correlation between UCS and V_p (Figure 4e) indicates a strong relationship between the two parameters, with high R^2 values of 0.91 and 0.81 for andesites and agglomerates, respectively, and Pearson correlation coefficients of 0.93 and 0.90, respectively. This can be attributed to the fact that both parameters are related to the elastic properties of rocks, which tend to increase with increasing rock density and stiffness. This finding contrasts with earlier studies by Tandon and Gupta [35], who examined limestone, sandstone, marble, and granite and found no correlation between UCS and V_p. The difference in rock types and associated mineralogy may have contributed to the observed discrepancies in the results. The linear graph between UCS and UTS also showed a positive trend (Figure 4f), with R^2 values of 0.78 for andesites and 0.78 agglomerates, respectively, and Pearson correlation coefficients of 0.79 and 0.71, respectively. This agrees with previous studies by Pola, Crosta, Fusi and Castellanza [21], and Sajid, Arif and Shah [16], which have also reported a positive correlation between UCS and UTS for various rock types. The relationship between the average Schmidt hammer rebound values (R-values) and UCS was analyzed (Figure 4g), and a positive correlation was observed. The R^2 values were found to be 0.76 for andesites and 0.94 for agglomerates. The Pearson correlation coefficient was found to be 0.77 and the Sig (2-tailed) value 0.00 for both types of samples, indicating that the correlation is statistically significant. This suggests that the Schmidt hammer rebound test can be used as a reliable method to estimate the strength of andesites and agglomerates.

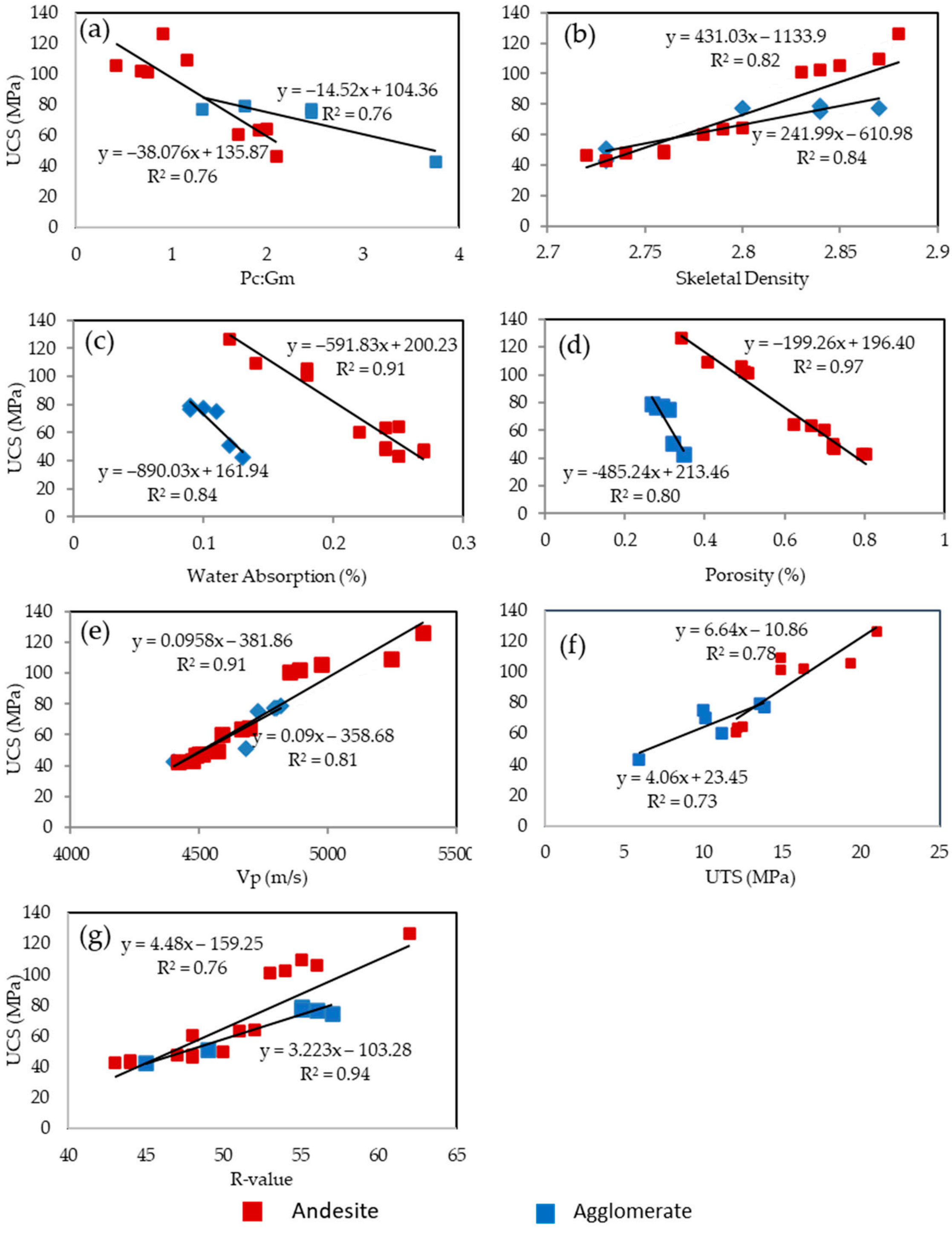

Figure 4. Correlation of compressive strength (UCS) with physical and strength properties of the investigated rocks: (**a**) UCS vs. Pc:Gm; (**b**) UCS vs. skeletal density; (**c**) UCS vs. water absorption; (**d**) UCS vs. porosity; (**e**) UCS vs. Vp; (**f**) UCS vs. UTS; (**g**) UCS vs. R-value.

Table 4. Correlation matrix of Pearson correlation coefficients among the strength and physical properties for andesite (N = 15) and agglomerate (N = 6).

		Pc:Gm	**Skeletal Density**	**Porosity**	**W.A**	**Vp**	**UTS**	**R-Value**	**UCS**
Pc:Gm	Pearson correlation	1	−0.17	0.07	0.20	−0.17	−0.42	0.27	−0.32
	Sig. (2-tailed)		0.55	0.80	0.47	0.55	0.12	0.32	0.25
Skeletal Density	Pearson correlation	−0.12	1	−0.94 *	−0.90 *	0.95 *	0.68 *	0.55	0.91 *
	Sig. (2-tailed)	0.82		0.00	0.00	0.00	0.01	0.04	0.00
Porosity	Pearson correlation	0.68	−0.71	1	0.94 *	−0.92 *	−0.66 *	−0.66	0.81 *
	Sig. (2-tailed)	0.14	0.11		0	0	0.01	0	0.00
W.A	Pearson correlation	0.61	−0.70	0.98 *	1	−0.90 *		−0.46	−0.78 *
	Sig. (2-tailed)	0.20	0.12	0.00		0	0.02	0.07	0.00
Vp	Pearson correlation	−0.76	0.71	−0.92 **	−0.88 **	1	0.75 *	0.37	0.92 *
	Sig. (2-tailed)	0.08	0.11	0.01	0.02		0.00	0.16	0.00
UTS	Pearson correlation	−0.91 **	0.42	−0.91 **	−0.86 **	0.87 **	1	0.62	0.79 *
	Sig. (2-tailed)	0.01	0.40	0.01	0.03	0.02		0.02	0.00
R-value	Pearson correlation	0.27	0.55	−0.66	−0.46	0.40	0.62	1	0.77
	Sig. (2-tailed)	0.32	0.04	0.00	0.07	0.13	0.02		0.00
UCS	Pearson correlation	−0.45	0.8 6**	0.89 **	0.92 *	0.90 **	0.71	0.77	1
	Sig. (2-tailed)	0.37	0.03	0.02	0.01	0.01	0.11	0.00	

Andesite = non-shaded, agglomerate = shaded. * Correlation is significant at the 0.01 level (2-tailed). ** Correlation is significant at the 0.05 level (2-tailed).

4.5. Degree of Polishing

The presence of opaque minerals, fractures, and veins on the surface of decorative stones can degrade their polishing properties and increase the likelihood of rusting and staining. Figures 5 and 6 show the stereomicroscope and scanning electron microscope (SEM) images of the studied samples, respectively. The surfaces of samples MMA and FMA were found to be homogenous and smooth, with no visible fractures and a medium-to-fine grain size. This resulted in a higher polishing degree compared to other samples. Specifically, sample FMA exhibited better polishing and smoothness due to its finer grain size. However, sample PMA-1 displayed a fracture on the surface and had signs of weathering, resulting in a lower polishing degree. Similarly, sample PMA-2 showed fractures and filled veins, but the porphyritic texture may still make it suitable for decorative purposes. Sample CMA, on the other hand, displayed a rough and dull appearance due to the abundance of opaque minerals, indicating a lower potential for use as a decorative stone. The samples AG-1 and AG-2, which contained clasts, also exhibited rusty and dull surfaces under the stereomicroscope and rough and heterogeneous surfaces under SEM analysis, but the presence of phenocrysts may increase their decorative value. Based on the qualitative assessment of polished surfaces, samples MMA and FMA can be classified as excellent, PMA-1 and PMA-2 as good, AG-1 and AG-2 as fair, and CMA as poor.

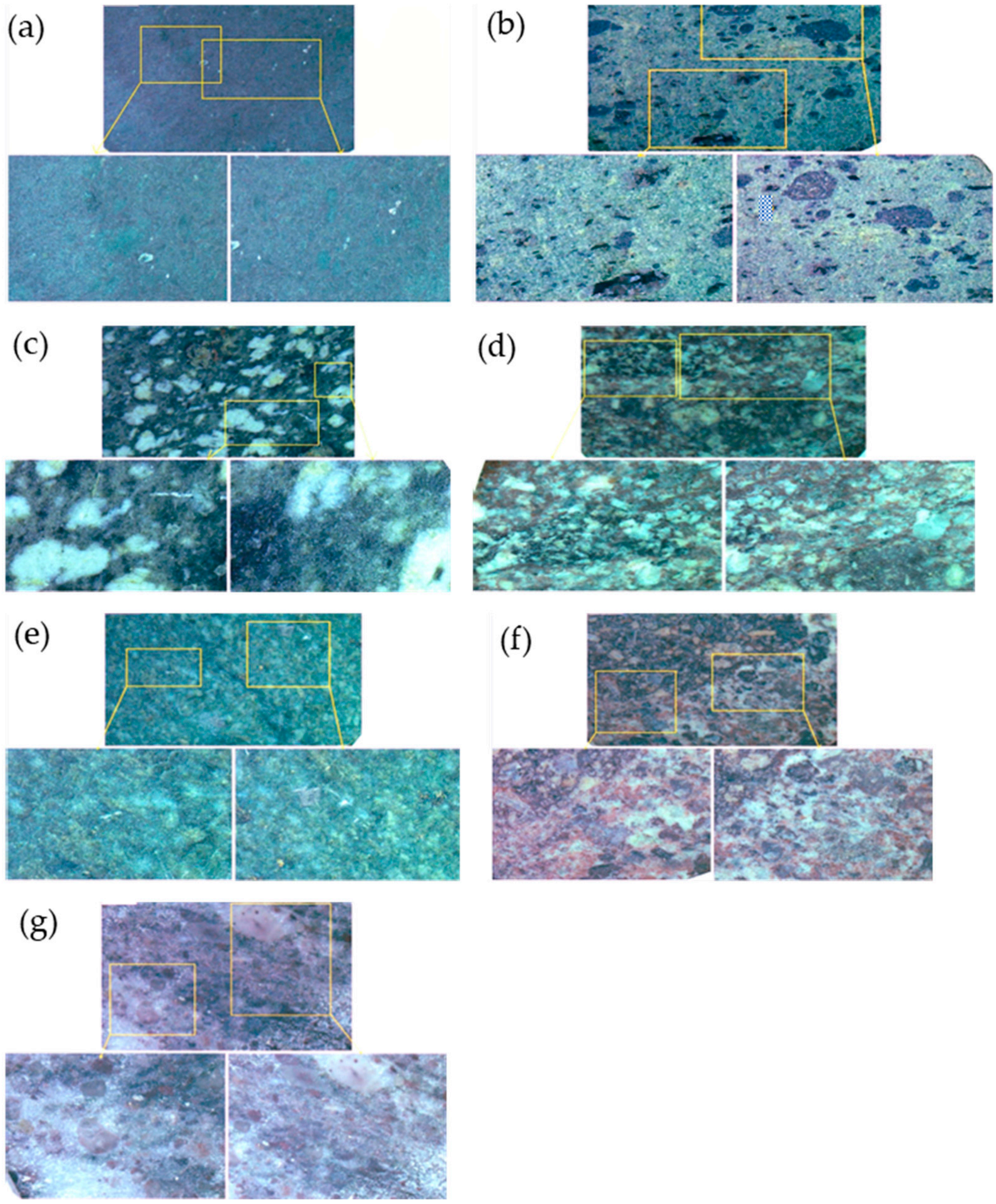

Figure 5. Polished surfaces of the studied volcanic rocks for their use as dimension stone. Yellow rectangles highlight two areas enlarged in insets.: (**a**) MMA; (**b**) PMA-1 (**c**) PMA-2; (**d**) CMA; (**e**) FMA; (**f**) AG-1; (**g**) AG-2.

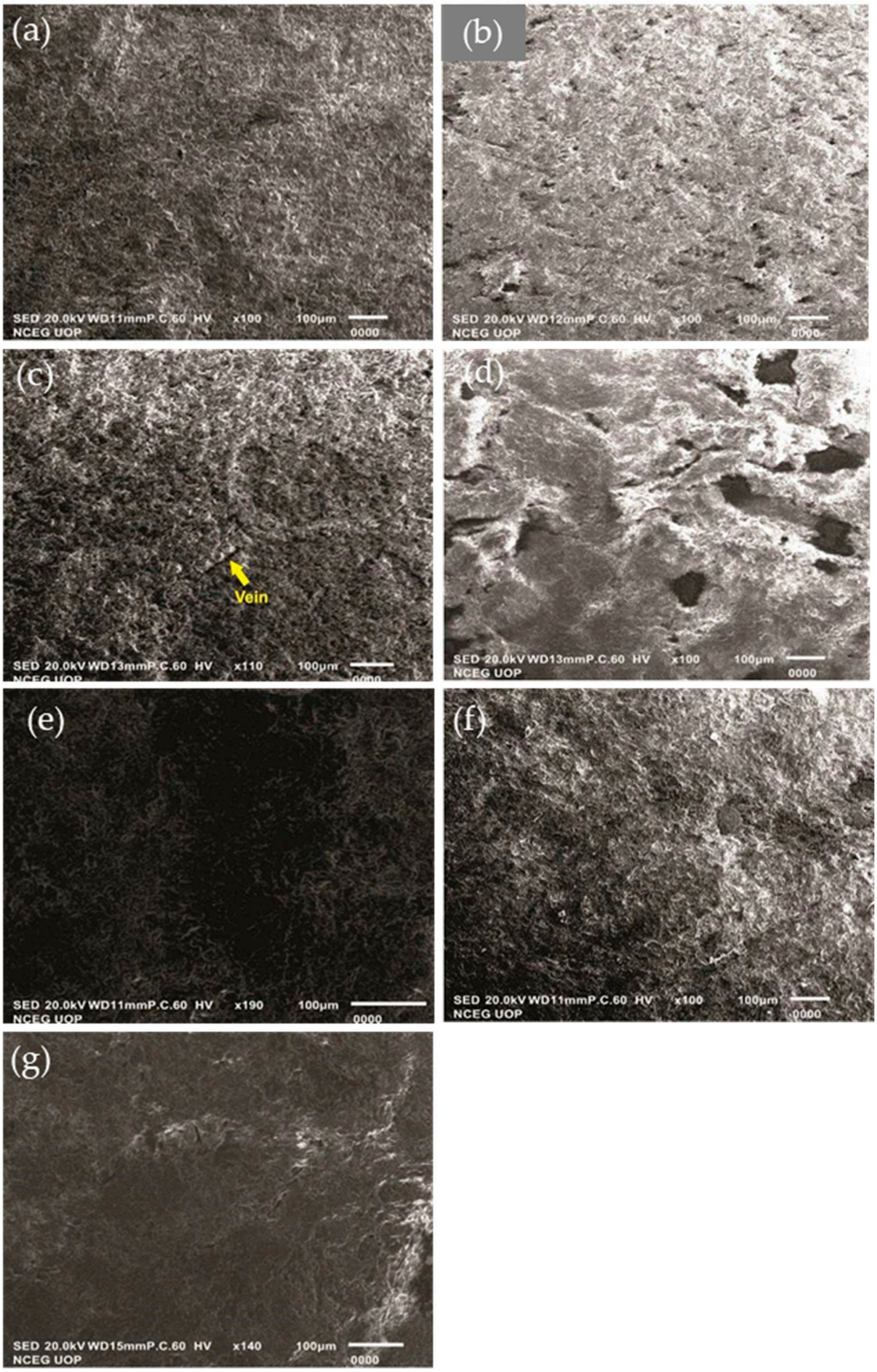

Figure 6. SEM images of the polished surfaces of the investigated volcanic rocks: (**a**) MMA; (**b**) PMA-1; (**c**) PMA-2, vein can be seen; (**d**) CMA; (**e**) FMA; (**f**) AG-1; (**g**) AG-2.

5. Conclusions

The present study focused on the classification and evaluation of various types of rocks from the Dir volcanics. The analyzed rocks include andesites and agglomerates, which were further classified into five varieties of andesites (MMA, PMA-1, PMA-2, CMA, and FMA) and two varieties of agglomerates (AG-1 and AG-2). The main conclusions are provided as follows:

- The rocks from the Dir volcanics, including andesites and agglomerates, possess physical and strength properties suitable for use as building and decorative stones. The presence of plagioclase, amphibole, and quartz contributes to good physical and strength properties in most samples.
- Low-grade metamorphism in andesites resulted in the presence of alteration products such as chlorite, epidote, sericite, and recrystallized quartz. The abundance of these alteration products negatively affected the physical and strength properties of certain andesite varieties (PMA-1 and PMA-2).
- Samples CMA, AG-1, and AG-2 exhibited high strength due to their interlocking grain pattern and low alteration. However, their strength was relatively lower than FMA and MMA due to factors such as coarse grain size and the presence of clasts.
- FMA and MMA showed high strength and low water absorption due to their fine-to-medium grain size and low alteration. These factors positively influenced their physical and strength properties.
- Strong correlations were observed between unconfined compressive strength (UCS) and variables such as ultrasonic pulse velocity (Vp), skeletal density, porosity, and water absorption. Conversely, the phenocryst to groundmass ratio (Pc:GM) demonstrated a weak correlation with UCS for the studied samples.

6. Recommendations

The results in Table 3 are compared to the recommended values of ASTM C170 [26] and ASTM C615 [36] to assess the suitability of the studied samples for decorative and construction purposes. ASTM C615 recommends that specific gravity be $\geq$2.4, water absorption < 0.4%, and porosity be between 0.5% and 1.5% for use as building stone and dimension stone. According to various rock strength classifications based on UCS values, the samples are classified as moderately strong to strong ISRM [37], IAEG [32], Geological Society [38]. However, the UCS values were lower than the recommended ASTM C615 value of greater than 131 MPa.

Based on the study's findings, it is recommended that PMA-1 and PMA-2 be avoided in load-bearing masonry units and outdoor applications due to their high-water absorption and low strength values. However, they may be used in indoor applications such as internal flooring due to their good polishing character. AG-1 and AG-2 may not be suitable for use as decorative stones due to their low degree of polishing. However, their good strength values and low water absorption make them suitable for use as load-bearing masonry units, such as foundation and armor stone. CMA's high strength favors its use as a foundation stone, but its high-water absorption and poor polishing properties limit its use as a decorative stone. FMA and MMA showed excellent properties, i.e., high strength and good polishing, and could be used as decorative and facing stones in the external pavement, ashlar, rubbles, and load-bearing masonry units, among others.

This study is limited in its coverage of Dir volcanics and requires further investigation to expand its scope. Additionally, the potential use of these rocks for concrete and asphalt aggregates must be further explored. To provide a comprehensive assessment of the rocks' physico-mechanical properties, additional tests such as triaxial compressive strength, shear strength, modulus of elasticity, fracture analysis, and the measurement of the degree of polishing using a gloss meter or a spectrophotometer with gloss measure should be conducted. Moreover, chemical tests are necessary to determine alkali–silica reactivity (ASR) and evaluate the rocks' suitability for concrete use. These additional investigations will enhance our understanding of the rocks and their applicability in various large-scale projects such as tunnels and dams.

Author Contributions: Conceptualization, M.N. and W.A.; methodology, M.N., W.A., I.I. and M.Y; software, M.N.; validation, W.A., M.N., I.I. and M.Y.; formal analysis, M.N., W.A. and I.I.; investigation, M.N., W.A., M.Y., I.I., H.T.J., A.A., C.S. and G.K.; resources, M.N.; data curation, W.A. and M.N.; writing—original draft preparation, W.A. and M.Y; writing—review and editing, M.N., W.A., M.Y., I.I., H.T.J., A.A., C.S. and G.K.; visualization, W.A., M.Y., M.N., I.I., H.T.J. and G.K.; supervision, W.A.; funding acquisition, G.K. and C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data used in this research work are available upon request from the corresponding authors.

Acknowledgments: The National Centre of Excellence in Geology is acknowledged for providing laboratory facilities during this research work.

Conflicts of Interest: The authors declare no conflict of interest.

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