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Characterization of Buner marble from Pakistan for construction purposes

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ABSTRACT

The exploration and management of abundant economic mineral resources of Pakistan, particularly the vast marble deposits in the northwestern region, hold immense potential for driving economic growth. The use of marble in the construction industry faces extensive challenges, such as undeveloped mining processing methods, incomplete understanding of marble qualities, undefined selection criteria for suitable varieties, and the environmentally harmful consequences of excessive waste production. This research developed a laboratory investigation protocol to characterize distinct marble deposits in Buner, Pakistan, each offering unique compositions and petrographic features. Three marble varieties were identified including pure calcitic (over 90% calcite) with low silica content (0.1% to 2.5%); impure calcitic (non-carbonate minerals up to 20%) with 19.8% silica and 31% lime; and pure dolomite (over 20% dolomite) with 29% lime and 23% magnesium oxide. The distinctive petrographic features of the marble deposits, such as equigranular structures, subhedral to anhedral grains, granuloblastic textures, and schistosity in impure calcitic, as well as luster-displaying dolomite in pure dolomite, provide valuable insights into their geological characteristics. Furthermore, the physical properties of the marble types exhibit correlations with their compressive and tensile strengths. Notably, the low specific gravity, water absorption, and porosity of the investigated marble result in high strength values. The average compressive strength was found to be 31 MPa for pure calcitic, 35 MPa for impure calcitic, and 59 MPa for pure dolomite marble. Likewise, the tensile strengths measured 6 MPa, 7 MPa, and 9 MPa, respectively. While the investigated marble types prove to be excellent choices for dimension stone applications, it is crucial to note that they do not meet the standards required for cement production and paint manufacturing. This research contributes to the understanding of Pakistan's marble resources, refined processing methods, and sustainable construction practices.

Keywords: *Geochemical characteristics, Marble deposits, Mechanical properties, Petrographic features.*

1. Introduction

Marble is the preferred material of construction in Pakistan, used for buildings (dimension stone), concrete (gravel/sand replacement), and asphalt (powder form). The low heat conduction of marble tiles helps reduce temperature in summer, saving energy in residential and commercial facilities [1]. For concrete, marble chips have been shown to increase compressive strength by up to 25% [2], while marble sand can decrease porosity by up to 100% [3]. Similarly, marble dust has been found to improve plastic deformations by 7% in asphalt mixes [4-6]. Given the increasing demand for construction materials in Pakistan, there is an exigent need to investigate the properties of new marble deposits.

The suitability of different rock types for a dimension stone is assessed based on a number of factors, including the possibility of extracting large blocks, the physical and mechanical properties of the stone, the appearance of the stone when cut and polished, and the accessibility of the site [7-10]. Rock mass fractures make it difficult to cut commercially viable blocks, resulting in waste. Therefore, it is crucial to evaluate fractures during the exploratory stage [11, 12]. Likewise, physical properties, such as porosity, water absorption, and saturation coefficient determine the rock's durability. Petrographic and mineralogical studies provide valuable insights into the textural characteristics (grain size, grain distribution, and grain orientation) and mineralogical composition of a rock, revealing its provenance and geological history [13, 14]. The effects of petrographic and textural features on these properties have been studied by several researchers [15-18]. These studies highlight the predominant role of textural features over mineralogy, emphasizing the intricate interplay between texture, geological conditions, and petrographic properties in determining the durability of dimension stones [18, 19]. Salmi and Sellers [20] demonstrated the synergistic integration of physical and strength measurements with rock mass data, specifically incorporating discontinuity information. This approach facilitates the identification of

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optimal methods for extracting dimension stones. The adoption of recent advancements in dimension stone assessment, including 3D imaging [21, 22] and digital rock modelling [23], has proven instrumental in predicting fractures during exploration, optimizing block extraction, and minimizing waste. The integration of these advancements into the existing framework will significantly improve our understanding of marble deposits for construction applications in Pakistan.

Pakistan boasts an abundance of economic mineral resources, with its northwestern region holding a 10.14 billion tonnes of marble deposits, representing over 70% of the country's marble reserves [24, 25]. However, the country's marble mining industry uses primitive, uncontrolled blasting methods that are not well established. Likewise, the inherent characteristics of marble are not well known, and the selection criteria for acceptable marble types are not clearly defined. Excessive waste production is also hazardous to the environment. The objective of this research is to characterize marble deposits from Buner, Pakistan. The innovative aspects of this research are to understand marble quality from a geological engineering perspective and to aid in the selection of regional-scale marble for construction. For this purpose, a comprehensive laboratory investigation program was enacted. The petrographic, geochemical, physical, and strength properties were determined for the selected samples from a local quarry.

2. Regional Geology

The northwestern areas of Pakistan possess some of the most extensive marble deposits in the country [26]. The various marble varieties found in the region include Ziarat marble, super-white, White grey, Badal, Zebra, Nowshera pink, Jet-black, Bampokha and golden marble. Figure 1 shows the distribution of the primary marble belts in the area. The main marble belts (Swabi-Nowshera, Mardan-Buner, and Swat-Kohistan) are categorized as internal metamorphosed zones. They constitute a part of the northwestern Indo-Pakistan Plate and lie approximately 25 km south of the Main Mantle Thrust (MMT) [27]. The MMT is the leading northern edge of the Indian plate. It is extensively deformed in the form of folding, thrusting, and regional metamorphism. This fault is still active and has produced multiple deformations in the cover sequence of the Indian plate which is metamorphosed up to amphibolite facie [28, 29]. The Nikanai Ghar Formation (Late Triassic) in the Mardan-Buner belt is mainly composed of crystalline and dolomitic marble. It also contains thin beds of calcareous schist, schistose marble and calcareous quartzite [30]. Despite the widespread use of marble from this region in the construction industry, limited studies have focused on investigating its properties. For example, Din and Rafiq [31] determined the compressive and tensile strengths of granite and limestone, while Fahad [24] studied the geochemical and mechanical properties of marble. The unique geological settings (rock provenance, extensive deformations, regional metamorphism) provide an opportunity to classify marbles in distinct varieties based on lithological, geochemical, physical, and strength properties.

3. Material and Methods

The study area is located in the Nikanai Ghar Formation of Late Triassic age, between 34°28'51"N – 34°32'44"N latitude and 72°16'1" E – 72°28'39"E longitude. The formation is mainly composed of crystalline and dolomitic marble, with thin beds of calcareous schist, schistose marble, and calcareous quartzite [30]. The marble deposits at the site are present in the form of a huge 1200 m thick lens-shaped body. Figure 2 shows the flow chart of the research methodology.

A detailed fieldwork was carried out to select and retrieve samples of ten distinct marble varieties (BM1-BM10). The chain saw cutting method was also adopted for the retrieval of approximately 3 m in height square blocks (Figure 3a). Representative bulk samples were collected based on physical appearance, including homogeneity and low fracturing (Figure 3b).

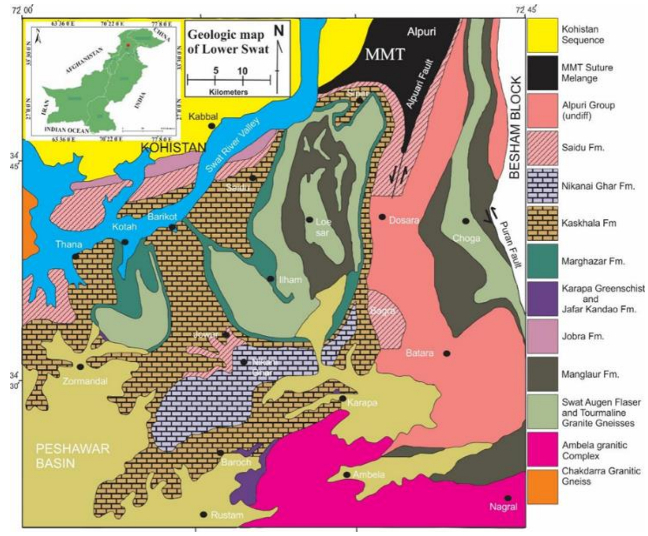


Figure 1. The location map of the study area (modified after Hussain [48].

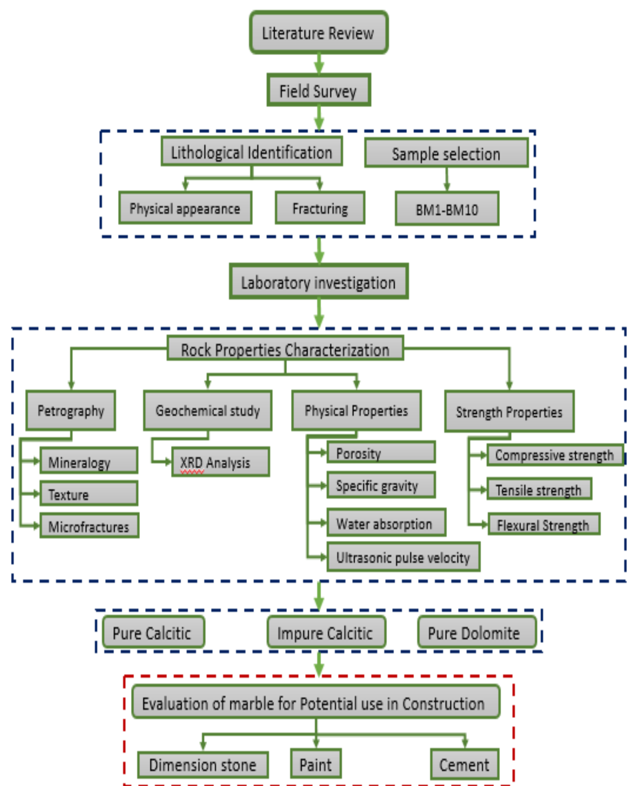


Figure 2. The flow chart of the research methodology.

The petrographic features, such as mineralogy, texture, and microfractures were observed using a polarized light microscope (Model Olympus BX51). Three thin sections (40 mm x 20 mm) were prepared from each variety by cutting the samples with a diamond saw. The samples were mounted on a glass slide and smoothened using progressively finer abrasive grit to achieve a thickness of about 30 µm. This ensured that the light could pass through most of the minerals, facilitating the study of their plane and cross-polarized light properties.

The major element composition was determined using the wavelength-dispersive X-ray fluorescence spectrometry (WDXRF) [32]. The analysis was performed on powdered samples (maximum size of 120 µm) that were obtained in a tungsten carbide ring mill and subsequently pressed into pellets of 37 mm diameter. The following

Figure 3. Sampling at a typical marble quarry in the investigated area; a) Chain saw cutting method, b) Collected bulk samples.

major elements were obtained from the samples: SiO_2, Al_2O_3, Na_2O, CaO, MnO, MgO, K_2O, TiO_2, P_2O_5, and Fe_2O_3 (Total Fe). The geochemical classification of the rocks was made based on the analysis.

The physical properties, such as specific gravity, porosity, and water absorption were determined in accordance with ASTM C97/C97M [33]. The unconfined compressive strength (UCS) and unconfined tensile strength (UTS) were determined according to ASTM C170/C170M [34]. Flexural strength tests (ASTM C-880-18) [35] were also conducted by applying loads by two rollers at the top of the specimen at a distance of L/2, which produced a uniform moment in the central half of the specimen. The ultrasonic pulse velocity (UPV) was measured to assess the strength of the samples [36]. For all of the tests, core samples with a diameter of 50 mm and a length-to-diameter ratio of 2.0–2.5 to 1.0 were prepared. Based on grain size, the marble was categorized into fine, medium, and coarse-grained, and the relationship between grain size and mechanical properties was established.

4. Results and Discussion

This section presents the detailed results of the study on ten Buner marble varieties. The petrographic analysis revealed their mineralogical composition, grain size, and color patterns. The geochemical assessment highlighted variations in their chemical composition, providing insights into their formation. The physical and strength property testing showed significant correlations between calcite content, specific gravity, water absorption, and strength parameters. These findings have wide-ranging implications for the commercial applications of Buner marble in various industries.

4.1. Petrographic Features

Table 1 shows the modal mineralogical composition of ten marble varieties. At the outcrop level, all of the varieties are medium-thick bedded with medium-close fracture spacing (Figure 3). After polishing, the varieties show a variety of colors and patterns (Table 1). Based on grain size, the investigated samples were generally classified into fine, medium, or coarse types. Furthermore, the samples were classified into three types: pure calcitic (more than 90% calcite, including BM2, BM3, BM4, BM5, BM7, BM8, BM9, and BM10), impure calcitic (non-carbonate minerals of up to 20%, that is, BM1), and pure dolomite (more than 20% dolomite, that is, BM6).

Figure 4 provides the typical petrographic features in the investigated marble varieties. Generally, the grains were equigranular, subhedral to anhedral, and displayed granoblastic texture grains of calcite with traces of dolomite, quartz, muscovite, and ore minerals. The calcite grains were found to be interlocking and exhibited polysynthetic twinning having curved and embayed grain boundaries (Figure 4a). In the impure calcitic marble, quartz was identified from undulose extinction (Figure 4b and Figure 4c). Muscovite in these varieties was occasionally present in trace amounts along grain alignment showing schistosity (Figure 4d and Figure 4e). Finally, dolomite was identified from its lustre, as confirmed through the staining technique [37], whereby the colourless calcite grains changed to red or orange (Figure 4f). The petrographic features observed in the studied marble varieties closely correspond to the findings in previous research [38], highlighting consistent patterns of calcite dominance, granular texture, and the occurrence of trace minerals.

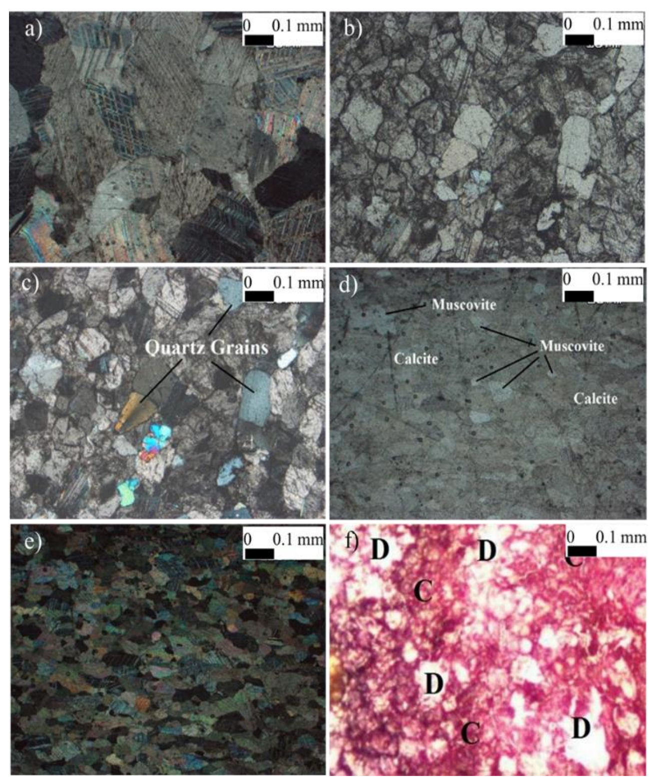
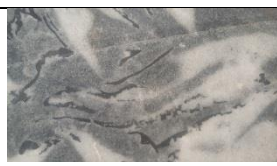
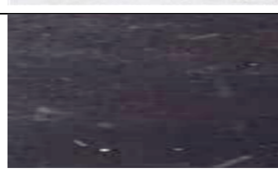
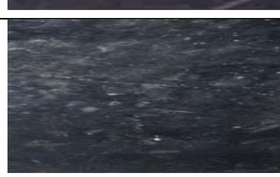
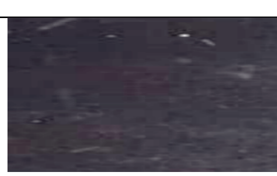


Figure 4- Typical petrographic features in the investigated marbles; a) (plane polarized light view-PPL) pure calcitic marble showing twinning of calcite grains, b) (PPL) impure calcitic marble having granoblastic texture, c) (cross polarized light view-XPL) impure calcitic marble showing undulose extinction, d) (PPL) impure calcitic marble with muscovite grains, e) (XPL) impure calcitic marble showing schistosity, f) (PPL) pure dolomite marble having dolomite grains after staining

Table 1. The summary of modal mineralogical composition of the investigated marble.

Symbol & Grain Size	Appearance	Calcite (%)	Dolomite (%)	Quartz (%)	Muscovite (%)	Other (%)
Pure Calcitic						
BM7 (Fine)		93	2	-	-	5
		94	-	-	3	3
		96	-	-	-	4
BM8 (Fine)		92	-	2	2	4
		93	2	-	2	3
		95	-	-	-	5
BM3 (Medium)		94	-	-	3	3
		96	4	-	-	-
		97	-	-	-	3
BM4 (Medium)		95	-	-	-	5
		97	-	-	-	5
		93	-	-	-	3
BM5 (Medium)		93	-	-	-	-
		95	-	-	-	-
		92	-	-	-	-
BM9 (Medium)		97	-	-	-	3
		96	-	-	-	4
		97	-	-	-	3
BM2 (Coarse)		96	2	2	-	-
		95	3	2	-	-
		94	3	-	-	3
BM10 (Coarse)		92	-	-	4	4
		92	-	3	-	5
		95	-	-	3	2
Impure Calcitic						
BM1 (Coarse)		65	2	18	9	6
		70	-	20	8	2
		72	3	20	5	-
Pure Dolomite						
BM6 (Fine)		64	23	5	5	3

4.2. Geochemical Characteristics

Table 2 shows the major elemental composition of the investigated samples. In pure calcitic marble, the silica content was found to be low, ranging from 0.1% to 2.5%. Impure calcitic marble showed a relatively high concentration of silica (19.8%) and low CaO (31%) that was collected from the formation base in contact with schistose rocks. Likewise, pure dolomite marble showed low CaO (29%) and high MgO (23%). Following the above pattern, loss on ignition (LOI) varied between 42% and 46% for pure calcitic samples, 36% for impure calcitic sample, and 47% for pure dolomitic marble. The high LOI values are due to the loss of water from muscovite and the loss of CO_2 from carbonate minerals. Figure 5 gives the elemental compositions on the ternary diagram (Carr and Rooney [39]). Based on the combined content of ($CaCO_3$ + $MgCO_3$ + non-carbonate), the investigated marble varieties plotted as follows: pure calcitic in zone E, impure calcitic in zone C, and pure dolomitic marbles in zone P. The elemental compositions of the studied marble closely align with Fahad [24] and Bukhari [39], where Fahad [24] reported SiO_2 (4.2%-20.5%), CaO (34.6%-56.57%), and LOI (27%-45.7%), and Bukhari [39] reported SiO_2 (1.03%-2.16%), CaO (51.53%-55.02%), and LOI (39.26%-41.8%). This concordance with established findings strengthens the reliability of results reported in this study.

4.1. Physical and Strength Properties

Table 3 gives the physical and strength properties of the investigated samples. The average specific gravity was found to be 2.7 for pure calcitic marble, 2.8 for impure calcitic marble, and 3.0 for pure dolomite marble. The increase in the specific gravity with the decrease in calcite content is due to the replacement of calcite with quartz and muscovite (in impure calcitic marble) and dolomite (in pure dolomite marble). With the exception of sample BM2, water absorption increased with a decrease in calcite content from 0.14 (pure calcitic), 0.17 (impure calcitic), to 0.24 (pure dolomite). The corresponding values of porosity measured 0.36, 0.45, and 0.71, respectively. The specific gravity values obtained (2.7–3.0 g/cm^3) are in line with those of Fahad [24] (2.64–2.90 g/cm^3), whereas water absorption (0.14-0.24%) is similar to Ur Rehman [40] (0.05-0.16%) but slightly exceeds Fahad [24] (0.20-0.52%). Likewise, porosity (0.36-0.71%) corresponds with Ur Rehman [40] (~0.42%) and exceeds Fahad [24] (0.20-0.45%). The bulk density (2.7–2.8 g/cm^3) is consistent with the findings of Fahad [24] and Ur Rehman [40] (2.57–2.89 g/cm^3). Figure 6 shows the diverse fracture patterns observed in marble samples subjected to the compressive strength testing. These patterns can be categorized into three distinct modes: multiple fracturing planes, single plane, and axial splitting. The average compressive strength was found to be 31 MPa for pure calcitic marble, 35 MPa for impure calcitic marble, and 59 MPa for pure dolomite marble. The corresponding values of tensile strength were 6 MPa, 7 MPa, and 9 MPa, respectively. The flexural strength is about twice the tensile strength, as also reported in the earlier studies [41, 42]. These data correlate well with the above data, indicating that low water absorption and low porosity means high strength and vice versa [43-45]. This research validates previous findings, showing that the highest compressive and tensile strength are exhibited by pure dolomite marble, followed by impure calcitic marble and pure calcitic marble. Compressive strength ranges for marble samples from Buner and Chitral, respectively, were reported by Fahad [24] to be 15.72–61.91 MPa and by Ur Rehman [40] to be 53–68 MPa.

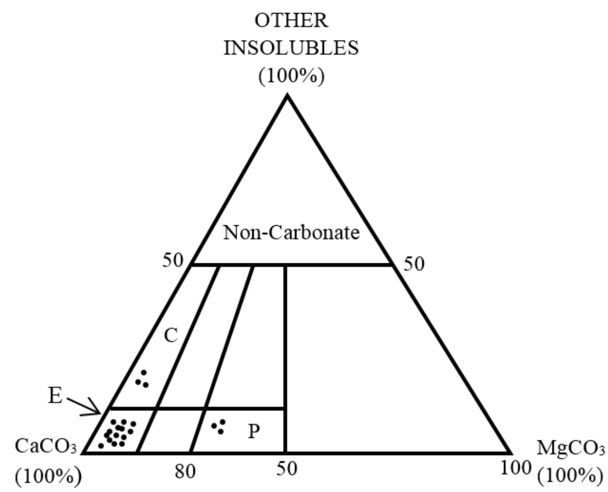


Figure 5. The geochemical classification of the investigated marble using the ternary diagram (after Carr and Rooney, 1983): pure calcite (E), impure calcite (C), and pure dolomite (P)

4.1. Commercial Applications

In addition to the desirable physical and chemical properties, the use of marble in the cement and paint industries relies on its purity, which is defined by the percentage of Lime (Cao), Al_2O_3 and SiO_2. The attractive colours and patterns of marble can further add value to pricing and marketing. Coloured marbles are used as pigments in the paint industry. Similarly, pure white marbles act as a good filler in the paper industry. The suitability of Buner marbles is discussed in this section for their use in the dimension stone, cement production, and paint manufacturing.

Table 2. The summary of elemental composition of the investigated marble.

Symbol and Grain Size	SiO_2(%)	CaO (%)	MgO (%)	Al_2O_3(%)	Fe_2O_3(%)	LOI (%)	$CaCO_3$(%)	$MgCO_3$(%)
Pure Calcitic								
(BM7) Fine	0.1	53	0.2	0.2	0.1	44.9	94.6	0.4
(BM8) Fine	0.1	53	0.3	0.2	0.2	45.5	95.2	0.7
(BM3) Medium	0.1	53	1.8	0.3	0.0	44.0	94.4	3.7
(BM4) Medium	0.9	54	2.1	0.6	0.3	42.3	95.8	4.5
(BM5) Medium	0.9	53	1.5	1.0	0.2	43.1	94.9	3.1
(BM9) Medium	0.1	53	0.5	0.2	0.1	45.9	94.6	1.1
(BM2) Coarse	2.5	51	1.5	1.2	0.7	42.6	91.4	3.2
(BM10) Coarse	0.3	52	0.3	0.3	0.1	46.5	93.6	0.7
Impure Calcitic								
(BM1) Coarse	19.8	31	0.0	7.6	5.4	36.1	54.6	0.0
Pure Dolomite								
(BM6) Fine	0.1	29	23	0.3	0.1	47.3	52.0	47.8

Table 3. The physical and Mechanical properties of the investigated marble.

Type and Symbol	Specific Gravity	Water Absorption (%)	Porosity (%)	UCS (MPa)	UTS (MPa)	UPV (km/sec)	Flexural strength (MPa)
Pure Calcitic							
(BM7) Fine	2.61	0.09	0.24	23.26	3.94	1.3	8.63
(BM8) Fine	2.73	0.10	0.26	58.41	9.37	6.19	13.42
(BM3) Medium	2.72	0.10	0.26	54.45	8.39	5.08	12.87
(BM4) Medium	2.63	0.15	0.39	20.29	6.24	1.01	11.62
(BM5) Medium	2.69	0.21	0.55	21.78	6.21	1.10	7.12
(BM9) Medium	2.53	0.16	0.41	27.72	2.96	1.69	7.21
(BM2) Coarse	2.75	0.48	1.31	23.76	6.17	1.33	5.49
(BM10) Coarse	2.53	0.17	0.43	20.79	1.97	1.08	4.67
Impure Calcitic							
(BM1) Coarse	2.78	0.17	0.45	34.65	6.91	1.81	12.48
Pure Dolomite							
(BM6) Fine	2.96	0.24	0.71	59.40	8.88	6.35	14.68
min	2.53	0.09	0.24	20.29	1.97	1.01	4.67
max	2.96	0.48	1.31	59.4	9.37	6.35	14.68
mean	2.69	0.19	0.50	34.45	6.10	2.69	9.82
SD	0.13	0.11	0.32	16.43	2.49	2.23	3.61

The use of a rock as dimension stone primarily depends on its physical and strength properties. The results of all the varieties of the studied marble showed favorable physical properties and moderately high strength, and they can be used as dimension stone for both internal and external usages as well as floor tiles. In particular, the medium grain varieties (BM3, BM4, BM5, BM 9) and coarse grain verities (BM2, BM10) of pure calcitic marble and the coarse grain variety (BM6) of impure calcitic are weather resistant and suited for external use, such as wall cladding. Whereas, the varieties of pure calcitic marble (BM3, BM8) with high compressive strength (54.45 and 54.45 MPa) and flexural strength (13.42 and 12.87 MPa) and low porosity (0.26%) and water absorption (0.10%) are suitable for their use in floor tiles and countertops. Mixing of the raw materials (CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO) in a specific proportion is required to produce cement. The desired proportion of lime (CaO ≥ 63%) and silica (SiO_2 = 22%) govern strength and setting time, respectively. A comparison of the geochemical data of the investigated marble with the standard values for cement manufacturing (Table 4), shows the values of oxides are generally below the required standard [46]. The maximum CaO is low (54% in pure calcitic marble, 31% in impure calcitic marble, and 29% in pure dolomitic marble). Likewise, SiO_2 in pure calcitic marble and pure dolomite is way below the required standard (0.1 to 2.5%). Whereas, in calcitic marble SiO_2 is maximum, i.e., 20%, however still below the requirement for cement production.

Similarly, the Lime saturation factor (LSF) of most of the samples lie outside the range of 66-102. Based on these observations, all of the varieties of the Buner marble are rendered unsuitable for cement production. The physical properties of marble, such as white or pink colour, fine sized particles (98% passing through No. 325 mesh) and absence of hard particles are necessary for the production of quality paint (Table 4). The physical properties of the studied marble varieties satisfy these requirements of paint manufacturing, The chemical standards (Boynton [47]) require that Al_2O_3 ≥ 2%, LOl in the range of 4-8% and MgO + SiO_2 > 75%. The investigated marble varieties do not satisfy the minimum requirement and make Buner marble unsuitable for paint manufacturing.

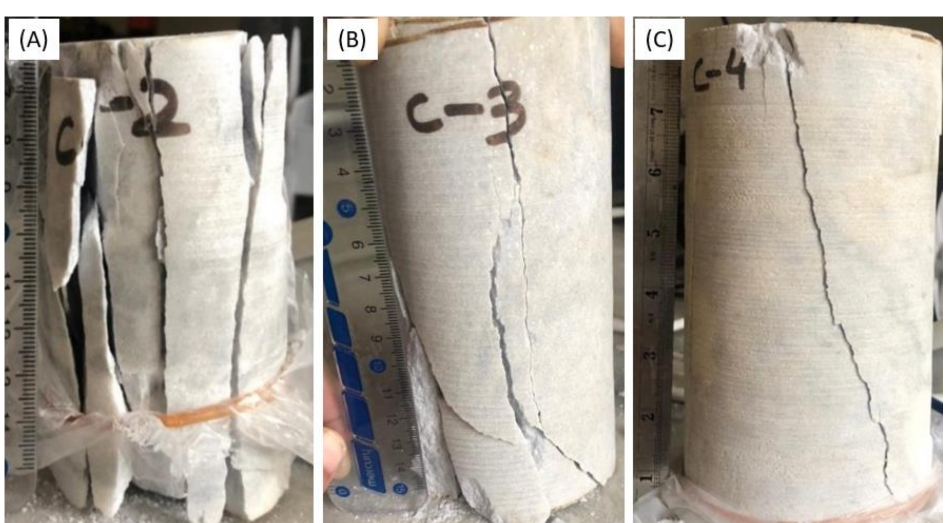


Figure 6. Fracture patterns in the marble samples following the compressive strength testing: (A) the multiple-fracturing plane mode of failure; (B) the single plane mode of failure; (C) the axial splitting mode of failure (Note: C on the samples represents core and not the sample numbers).

Table 4. The comparison of Buner marbles with chemical standards for the cement production and paint manufacturing.

Symbol and Grain Size	SiO_2 (%)	CaO (%)	MgO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	LOI (%)	LSF	Al_2O_3+ Fe_2O_3 (%)	MgO+SiO_2 (%)
Pure Calcitic									
(BM7) Fine	0.1	53	0.2	0.2	0.1	44.9	132.5	0.3	0.3
(BM8) Fine	0.1	53	0.3	0.2	0.2	45.5	106	0.4	0.4
(BM3) Medium	0.1	53	1.8	0.3	0	44	132.5	0.3	1.9
(BM4) Medium	0.9	54	2.1	0.6	0.3	42.3	30	0.9	3
(BM5) Medium	0.9	53	1.5	1	0.2	43.1	25.24	1.2	2.4
(BM9) Medium	0.1	53	0.5	0.2	0.1	45.9	132.5	0.3	0.6
(BM2) Coarse	2.5	51	1.5	1.2	0.7	42.6	11.59	1.9	4
(BM10) Coarse	0.3	52	0.3	0.3	0.1	46.5	74.29	0.4	0.6
Impure Calcitic									
(BM1) Coarse	19.8	31	0	7.6	5.4	36.1	0.95	13	19.8
Pure Dolomite									
(BM6) Fine	0.1	29	23	0.3	0.1	47.3	58	0.4	23.1
Required Standards									
Cement Production (Rajput, 2008)	22	63	2.5	6	3	1.5	66-102	0.66	--
Paint Manufacturing (Boynton 1980)	--	--	--	> 2 %	--	4-8 %	--	--	> 75 %

5. Summary and Conclusions

Knowledge of the inherent properties of marble is critical for improving construction practices in Pakistan. Given the unique geological settings of the region, a comprehensive laboratory investigation protocol was developed to characterize distinct marble varieties. The detailed characterization employed petrography, geochemistry, physical, and strength properties. The following conclusions outline the various aspects of marble quality and provides a basis for making well-informed choices when choosing marble for construction applications on a regional scale.

- The investigated marbles classify as pure calcitic (more than 90% calcite), impure calcitic (non-carbonate minerals up to 20%), and pure dolomite (more than 20% dolomite). The distinctive petrographic features were found to be equigranular, subhedral to anhedral, and granoblastic with impure calcitic marble showed calcite along with deformed quartz, and muscovite with schistosity and pure dolomite marble indicated luster-displaying dolomite along with calcite and opaque minerals.
- The geochemical analyses indicated that the pure calcitic marble has low silica content (0.1% to 2.5%), impure calcitic marble has a relatively high concentration of silica (19.8%) and CaO (31%), and pure dolomite marble has CaO (29%) and MgO (23%).
- Finally, the physical properties correlated well with the strength; that is, low specific gravity, water absorption, and porosity resulted in high compressive and tensile strength. The average compressive strength was found to be 31 MPa for pure calcitic marble, 35 MPa for impure calcitic marble, and 59 MPa for pure dolomite marble. The corresponding values of tensile strength were 6 MPa, 7 MPa, and 9 MPa, respectively.
- The commercial use of the studied marble was assessed based on the physical, strength and geochemical properties. Because of favorable physical properties and moderately high strength, these marbles can be used as dimension stone for both internal and external usages, such as exterior wall cladding, floor tiles, and countertops. However, the geochemical data showed that due to the lack of desirable values of CaO, SiO_2 and LOI, all of the studied marble varieties are unsuitable for their use in the cement production and paint manufacturing.

6. Recommendations

To optimize production in dimension stone quarries, discontinuity modelling and rock block geometry identification should be carried out in the study area using image processing techniques, core drilling, and geophysical methods. In the marble industry, a large amount of marble waste (marble powder and marble sludge) is produced as a by-product during the extraction, sawing, polishing, and water treatments processes. The sustainable utilization of marble waste is required to ascertain its use in concrete and cement, as investigated in several studies. Similarly, the use of marble waste in bricks, soil stabilization, and in the paper, color, rubber, and tire industries can be investigated.

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Authors contributions

Mohsin Raza conducted laboratory testing and drafted the manuscript. Waqas Ahmed and Shahid Azam provided conceptual guidance, polished and revised the manuscript, and assisted with data analysis. Muhammad Sufyan Qazi and Muhammad Sajid provided conceptual guidance. All the authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests. No author has received funding or financial support for this research, and no author has any financial or personal relationships that could be perceived as influencing the results or interpretation of this study.

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