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Grain properties, grain-boundary interactions and their effects on the characteristics of marbles used as building stones

Zeki Karaca [a,*], Ramazan Hacımustafaoğlu [b], Mehmedi Vehbi Gökçe [c]

[a] Çanakkale Onsekiz Mart University, Department of Mining Engineering, Çanakkale, Turkey
[b] Dokuz Eylül University, Torbali Vocational School, Izmir, Turkey
[c] Niğde University, Faculty of Architecture, Department of Architecture, Niğde, Turkey

HIGHLIGHTS

- Calcite grains of large size are mostly euhedral.
- Porosity increases as the smoothness of the boundaries of grains disrupts.
- Single-coursed twinning decreases tensile strength of marbles.
- Böhme abrasion loss value increases as alteration and deformation does.

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ABSTRACT

In this study, the effects of relationships of micro-structure, grain size and grain boundary of 15 well-known worldwide marbles on some physical and mechanical properties (dry unit weight, porosity, uniaxial compressive strength, tensile strength) and on abrasion loss value were investigated in detail, being the first in terms of elaborateness in the literature considering the mentioned features. 10 different samples were tested for each marble in each test. Microscope images were grouped as intergranular properties (shape of grains, shape of grain aggregates, grain boundary type and pressure solution), intragranular properties (twinning and alteration) and deformation. All marbles which were tested were found to be of heteroblastic texture. Nine samples were monomineralic marble while six were polymineralic. It was determined that grain characteristics and grain boundary interaction affected dry unit weight, porosity, uniaxial compressive strength, tensile strength and abrasion loss value of each marble tested.

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1. Introduction

Marble is a metamorphic rock being used as natural building stone. Moreover, it is the most widely used one on the globe. The true marble is composed of calcite crystals. Dolomite grains might also be contained in marbles which are referred as dolomitic marbles. Dolomitic marble ($4\% \leqslant MgO < 10\%$) and dolomite ($MgO \geqslant 10\%$) contain dolomite grains besides calcite grains. In this study, marble rocks that contain minerals other than calcite grains are referred as polymineralic marbles while those composed of pure calcite minerals are named monomineralic marbles. Currently, the standard EN 12670 defined a terminology based upon the ratios of calcite and dolomite minerals within the body of marbles [1], which is a more relative approach compared to that of the study that prefers definitions based on the oxide ratios.

Most of the studies carried out on grain properties and grain-boundary interactions are on the effects of these interactions on the strengths, deformations and/or micro fractures in marbles or other types of stones. Wong and Einstein conducted a detailed study on Carrara marble [2]. Yılmaz et al. investigated the relationships between some petrographic characteristics of granites and their mechanical strengths [3]. Grain size and grain properties are of importance for micro fracture development and deformation in stones. Deformation and grain boundaries reduce the intergranular energy [2,4–7]. Bandini et al. reported that intra-grain micro fractures determine the mechanical behaviors of marbles. They determined that grain textures (granoblastic to xenoblastic), micro discontinuities (cleavage cracks, grain boundary cracks) and mineral composition (monomineralic, polymineralic) are of importance for micro fractures [6].

* Corresponding author. Tel.: +90 505 332 2805.
E-mail address: zeki@comu.edu.tr (Z. Karaca).

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On the other hand, grain properties and grain-boundary interactions are essential determinants in terms of engineering applications on a stone such as its drillability, sawability, polishability and in terms of parameters of use such as cost, preferability, material design, and service lifetime. In a drilling operation, it was observed that rock texture, grain boundaries and boundary characteristics are of significance in the disintegration process of granules [8]. Karaca reported that the grain boundary density increased and the surface roughness decreased as the grain size decreased [9]. It is a well-known fact that this case increases the glossiness and preferability of dimension marbles. In addition, Siegesmund et al. explained the effects of the grain size and form of grain boundary on physical weathering of marbles [10].

In this study, the effects of relationships of micro-structures, grain sizes and grain boundaries of 15 well-known worldwide commercial marbles on some physical and mechanical characteristics (dry unit weight, porosity, uniaxial compressive strength, tensile strength) and on abrasion loss values were investigated in detail. It should be noted that European Union requires these tests for natural building stones as initial type test standards [11,12]. In the construction industry, these characteristics have distinctive roles in determining the purpose and place of use of a given stone, its quality, fixing procedure and price. In addition, a scale was developed for pressure solution, alteration and deformation of grains, which are of great importance in deciding on the place of use of marbles and in predetermining their lifetimes of service. Also, microscopic parameters that affect the material properties of marbles and interactions between these properties were studied.

2. Materials and methods

Texture and characteristics of a stone are the corollaries of the properties of the grains that compose the stone, and of the interactions of the boundaries of grains. Marble is a metamorphic rock; and metamorphic conditions, mineralogical composition and grain characteristics are substantial features for the development of the mass of marbles. Only a few researchers studied the microscopic details of these features that affect the characteristics of stones [13]. This fewness resulted in the lack of comparative and comprehensive analyses on the issue. In this study, the effects of microstructures of grains, on some physical, mechanical and abrasion loss properties of metamorphic marbles were investigated in detail. These effects were not dealt with in previous researches.

Within the framework of the study, chemical and petrographic analyses of 15 marbles were carried out, and their dry unit weights, porosities, uniaxial compressive strengths, tensile strengths and abrasion loss values were determined. A polarized microscope, Olympus BX41TF model was used for petrographic analyses of the tested samples. Petrographic analyses were carried out according to the methods suggested by EN 12407 [14]. Petrographic examination of the all samples was carried out on cross-sections prepared normal to the apparent bedding planes. At least 50 crystals measurements were made from thin sections under the microscope. More than 100 countings were made in relatively microcrystalline samples. Chemical analyses of the samples were performed by the inductively coupled plasma mass spectroscopy (ICP-MS) technique. Dry unit weights and porosities of the samples were determined using cube samples of which dimensions were $7 \times 7 \times 7$ cm. Physical values were determined using Archimedes method. Uniaxial compressive strengths (UCS) of the studied marbles were determined from cores with diameters of 54 mm in accordance with the test procedure suggested by ASTM C170 [15], and with height to diameter ratios of 2. The tensile strength (indirect, TS) tests were carried out on cores which were 27 mm high and 54 mm in diameter [16]. The Böhme abrasion loss value (BALV) of the samples was determined using Böhme abrasion equipment. The values were measured according to the methods suggested by EN 14157 [17]. The mechanical tests were performed parallel to the anisotropy planes in dry conditions. Physico-mechanical and abrasion tests were performed on 10 samples for each marble.

Some chemical and physico-mechanical properties of the tested marbles are given in Tables 1 and 2.

Table 1
Chemical analyses of the tested marbles (in wt.%).

Sample	CaO	MgO	SiO_2	Fe_2O_3	Na_2O	K_2O
M1	55.52	0.17	0.13	0.02	<0.01	<0.01
M2	55.37	0.49	0.06	0.01	<0.01	<0.01
M3	32.76	19.78	0.11	0.43	0.01	0.04
M4	48.96	5.70	0.33	0.08	0.05	0.09
M5	55.44	0.40	0.08	0.02	0.06	<0.01
M6	55.52	0.30	0.01	0.01	0.01	<0.01
M7	55.12	0.50	0.16	0.01	0.02	<0.01
M8	53.24	0.93	1.42	0.03	0.01	0.03
M9	55.13	0.67	0.07	0.02	0.01	<0.01
M10	40.85	13.22	0.10	0.15	0.01	<0.01
M11	55.90	0.68	0.10	0.06	0.01	<0.01
M12	51.01	4.13	0.11	0.07	0.01	<0.01
M13	51.00	5.16	0.04	0.08	0.08	<0.01
M14	56.4	0.18	0.04	0.01	<0.01	0.03
M15	55.30	0.41	0.06	0.02	0.06	<0.01

Table 2
Physico-mechanical properties of the tested marbles.

Sample	Grain size (μm)	Dry unit weight (kN/m^3)	Porosity (%)	UCS (MPa)	TS (MPa)	BALV cm^3/50 cm^2
M1	222 ± 110	27.11	0.123	56.51	6.44	21.42
M2	772 ± 315	27.13	0.134	42.61	5.49	20.96
M3	426 ± 116	28.11	0.402	118.16	11.7	15.73
M4	429 ± 150	27.34	0.459	108.13	9.85	18.13
M5	980 ± 247	27.09	0.164	33.52	4.82	21.54
M6	978 ± 220	27.07	0.221	46.9	5.31	20.14
M7	1,075 ± 261	27.06	0.264	22.96	3.53	22.14
M8	369 ± 85	27.09	0.118	51.68	8.52	21.99
M9	377 ± 97	27.11	0.175	22.25	4.23	23.54
M10	676 ± 303	27.67	0.385	117.85	8.47	19.83
M11	1,392 ± 358	27.16	0.171	54.86	6.19	23.26
M12	1,080 ± 380	27.20	0.376	68.94	8.75	20.39
M13	598 ± 54	27.17	0.149	85.52	9.03	20.44
M14	942 ± 266	27.06	0.098	44.76	4.62	23.59
M15	875 ± 179	27.08	0.169	58.22	3.92	24.87

3. Results and discussion

Service lifetime of marbles and other natural building stones is an important feature. Characteristics of a given marble are required to be known for health and safety considerations besides economic reasons. The properties given in Table 2 are the most important characteristics for the performance and service lifetime of a stone in use. The basic detail here is the characteristics of calcite grains, and interactions of grains with each other and other minerals such as dolomite existing within the compositions of marbles. Micro characteristics of calcite, which is the main mineral in the composition, and interactions between calcite grains determine material characteristics of marbles. Taking this fact into consideration, Table 3 was developed. In one of the previous studies, Nasseri et al. made definitions similar to Table 3 to explain micro fractures [18]. The main difference of this study from those of Nasseri et al. and the other ones is that the definitions have been given in more detail and microscopic data have been used for material properties.

There are 3 groups in Table 3. These are (i) intergranular properties, (ii) intragranular properties, and (iii) deformation. Shapes of grains, shapes of grain aggregates, grain boundary types and pressure solution were investigated under the intergranular properties. Texture is also an intergranular property. The entire 15 samples tested for this research are of heteroblastic texture. Heteroblastic texture is a definition that means that grains are of different sizes. For this reason, texture was not included in Table 3. Under the intragranular properties, twinning and alteration were discussed. In fact, Table 3 could have contained five main groups instead of three, by adding two more columns for mineral types and dolomitization properties. However, mineral types and dolomitization were not included in the table to save from the size of the table and let it be more effective.

Table 3
Micro definitions affecting marble characteristics.

Sample	Intergranular properties				Intragranular properties		Deformation
	Shape of grains	Shape of grain aggregates	Grain boundary type	Pressure solution	Tiwinning	Alteration	
M1	Subhedral > anhedral	Ineq-interlobate	Monotype < polytype	Low	Single > double	Medium	Low
M2	Subhedral > anhedral	Ineq-interlobate	Monotype < polytype	Low	Single > double	Medium	Low
M3	Subhedral < anhedral	Seriate-interlobate	Monotype > polytype	Medium-high	–	High	High
M4	Subhedral > anhedral	Ineq-interlobate	Monotype > polytype	Low	Single > double	Medium	Low
M5	Euhedral > subhedral	Ineq-polygonal	Monotype > polytype	low	Single < double	Low-medium	Low
M6	Euhedral > subhedral	Ineq-polygonal	Monotype > polytype	Low	Single > double	Low	Low
M7	Euhedral > subhedral	Ineq-polygonal	Monotype > polytype	Low	Single < double	Medium-high	Low
M8	Subhedral < anhedral	Ineq-interlobate	Monotype < polytype	Medium	Single > double	Medium-high	Medium-high
M9	Subhedral > anhedral	Ineq-interlobate	Monotype < polytype	Low-medium	Single > double	Medium	Medium
M10	Subhedral > anhedral	Ineq-interlobate	Monotype > polytype	Low-medium	Single > double	Medium-high	Medium
M11	Euhedral > subhedral	Ineq-interlobate	Monotype > polytype	Low	Single < double	Medium	Low
M12	Euhedral > subhedral	Ineq-interlobate	Monotype > polytype	Low	Single > double	Medium	Low
M13	Euhedral > subhedral	Ineq-interlobate	Monotype > polytype	Low	Single > double	Medium	Low
M14	Subhedral < anhedral	Ineq-interlobate	Monotype < polytype	Medium-high	Single > double	Medium	Medium
M15	Euhedral > subhedral	Ineq-polygonal	Monotype > polytype	Low-medium	Single > double	Low-medium	Low

When microscopic images and Table 1 are studied, it will be seen that M1, M2, M5, M6, M7, M9, M11, M14 and M15 are monomineralic marbles and their CaO ratios are higher than 55%. M3, M4, M8, M10, M12 and M13 are polymineralic marbles. Except M8, the second mineral in polymineralic marbles is dolomite. Besides, M3 and M10 are metamorphosed dolomite. M4, M12 and M13 are dolomitic marbles. Albite, quartzite and opaque minerals are observed in M8 while it is composed at least, 94% of calcite grains.

Magnesium replaces calcium in a viscous medium which is rich in magnesium and this process is called dolomitization. In this case, grain volume decreases and porosity increases. Dolomite, which has a higher mineral hardness (4 Mohs) than calcite, does (3 Mohs) increase the hardness and water-holding ability of marbles [19]. Supported by the microscopic images, it is clear that dolomitization exists in polymineralic samples that contain dolomite. A small amount of dolomitization was also determined in microscopic images of M15, though it was not clearly apparent in Table 1.

Angles and forms of grain boundaries are related with the ratio between the surface energies and surface tensions of grains. Calcite grain boundaries are straight and crystals have 120° corner angles (euhedral) in rocks, especially in monomineralic marbles of which surface energy and surface tensions are in equilibrium. The rock has a stable structure in such a case. In case the surface energies of the grains differ, stability of the structure and grain boundaries gets disrupted. In this phase, grain boundaries have an indented form. Subhedral and anhedral boundary forms are the results of the high energy of the grain surface. During formation, rock or marble tries to decrease its total grain surface energy to the minimum to gain equilibrium. Smooth crystal surfaces (poligonal texture) as found in M15 are the signs of the realization of a high degree of stability in the environment of formation of rocks.

In Table 3, subhedral > anhedral means that subhedral grains are more than anhedral grains, euhedral > subhedral means that euhedral grains are more than subhedral grains. In this case, the marble is close to a low deformation and stable structure. Anhedral > subhedral means that anhedral grains are more than subhedral grains and the marble has a medium–high deformation and an unstable structure. Shape of grains of M1, M2, M4, M9 and M10 are subhedral > anhedral; of M3, M8 and M14 are anhedral > subhedral; of M5–7, M11–13 and M15 are euhedral > subhedral.

Shape of grain aggregates were explained by Passchier and Trouw in detail [20]. They classified shape of grain aggregates as equigranular-polygonal (granoblastic, foam structure), inequigranular-polygonal, seriate-polygonal, equigranular-interlobate (granoblastic), inequigranular-interlobate, seriate-interlobate, equigranular-amoeboid, inequigranular-amoeboid and seriate-amoeboid. In this study, inequigranular-polygonal (ineq-polygonal), inequigranular-interlobate (ineq-interlobate) and seriate-interlobate shapes were observed in microscope.

In inequigranular-polygonal aggregate, euhedral grains are in majority but subhedral grains were also found available. Large and small grains were found with together but small ones were in majority. Grain boundaries were smooth and the angle between three grain boundaries was observed to be 120°. Surface energies of the grains were generally found close to each other. The grains were determined to have developed in a stable or near-stable medium. The grains might exhibit low deformation or alterations. Large and small grains were found in inequigranular-interlobate aggregate. Regarding the distribution of grain sizes, it was not clearly detected whether small or large grains were in majority. Grain boundaries were irregular and indented while grain corners were roundish. In seriate-interlobate aggregate, grains which were of every size, irregular and indented were observed. M1, M2, M4, M8–14 and M15 were detected to have been of inequigranular-interlobate shape, M5–7 and M15 were inequigranular-polygonal, and M3 was seriate-interlobate.

Grain boundaries are classified as monotype and polytype. Calcite grains in monotype boundaries have either smooth or indented structure. On the other hand, a single calcite grain has more than one boundary in polytype grain boundaries. Monotype grain boundary > polytype grain boundary means that the grains that have either smooth or indented boundaries are more than those that have both smooth and indented boundaries. Monotype grain boundary < polytype grain boundary means that the grains that have both smooth and indented boundaries are more than those that have either smooth or indented boundaries. Grains that have both smooth and indented boundaries are in majority in M1, M2, M8, M9 and M14. In other marbles, the grains that have either smooth or indented boundaries are in majority. M1, M2, M4–7 and M11–13 do have low pressure solution while M3 and M14 have medium–high solution. M8 has medium pressure solution while M9, M10 and M15 have a low–medium one.

During metamorphism process, the fluid in the medium of normal, normal-high pressure and/or of high temperature dissolves the grains. The grains move from the region of high resolution to that of low resolution. Following this process called pressure solution; the dissolved material precipitates into appropriate spaces and re-forms. Pressure solution is an important deformation for grains. In Table 3, this group of deformation was classified into five

scales as low, medium–low, medium, medium–high and high. M1, M2, M4–7 and M11–13 do have low, M3 and M14 medium–high, M8 medium; M9, M10 and M15 have low–medium pressure solutions.

Multiple or polysynthetic twins are observed in the calcite grains that composed the marble. The main detail here is the relationship between the crystallization and twinning times of calcite grains. Primary twins are the twinning formations that has taken place at the same time with crystal development while the secondary is the one that has taken place either after the crystallization or together with deformation. Secondary twins were observed in all microscopic samples in this study. Additionally, single directional twins and double directional twins were found in thin sections. Single directional twins define the calcite grains developed in a single course while there are double-coursed twinning formations that intersect each other (diagonally or in frame) in double directional twins. In Table 3, single directional > double directional means that single directional twinning is more than double directional twinning. Single directional < double directional means that double directional twinning is more than single directional twinning. Single directional twinning was observed more than double directional twinning in M1, M2, M4, M6, M8–10 and M12–15. Double directional twinning was observed more than single directional twinning in M5, M7 and M11.

It should be noted that twin planes are the regions where alterations develop as well. Mica minerals can extensively be observed in these microscopic observations. In some samples, alterations were observed in calcite crystals along with and around the unidirectional and bidirectional twin lamellas. There are some samples in which the lamellar structures have totally disappeared as well. In Table 3, alteration was also classified in five scales as low, medium–low, medium, medium–high and high. Medium level alterations were observed in M1, M2, M4, M9 and M11–14, a high one in M3, low–medium in M5 and M15, a low one in M6. In M7, M8 and M10 medium–high level alterations were observed in the study.

In fact, the classification of deformation in Table 3 is a comprehensive definition and is the core of the other parameters defined in it. Each of the other classes is the product of this deformation. Other microscopic images were studied besides crystal shapes, inter-crystal structure and the deformations of the calcite and dolomite minerals in the marble samples, pressure solution on the grain boundaries. Furthermore, micro-fractures were investigated by means of thin sections [5]. Deformation levels of marble samples were defined as low, medium and high after microscopic observations (Table 3). There is little or no anhedral grains in low deformation. Very few pressure solutions might occur on the borders of the crystals and some deformations could be observed in the grains. In medium deformations, subhedral grains are dominant and anhedral grains are distinctive. Pressure solution on the borders of crystals and deformations of the grains are clear. Anhedral grains are in majority in high deformation. Seriate-interlobate aggregates and pressure solution on the borders of crystals are intense. Grain interior deformations are quite widespread in high deformation. Low deformations were observed in M1, M2, M4–7, M11–13 and M15, a high one observed in M3, a medium–high one in M8, and medium level deformations in M9, M10 and M14. An overview of Table 3 indicates that pressure solution is a formation quite similar to deformation.

Micro definitions that were made on the microscope images (Table 3) and physico-mechanical properties (Table 2) were analyzed together. Except M13, the first noticeable point here is that M5–7, M11, M12 and M15 are relatively of large grains of which the majority is euhedral grains. Basically, large grains are indicators of slow and stable metamorphism conditions. Dolomite marbles (M3, M10) have higher dry unit weights. This is a known situation and is a result of dolomite which is denser than calcite. For this reason, transportation costs and dead loads to be exerted to a building to be sourced from dolomite should be carefully considered when the marble and/or stone industry, their trade and building applications are in question.

Porosity values for polymineralic samples were generally found to be high. As in the grain size, porosity of M13 is not included within this finding. M8 exhibited a relatively low porosity though it is polymineralic type. In contrast to this, M6 and M7 which have relatively medium level porosity and other marbles that have high porosities have inequigranular-interlobate and seriate-interlobate grain aggregate forms. The porosities of the samples that have irregular, indented and roundish cornered grains were calculated to be high. On the other hand, monotype grain boundary is in majority in these marbles, that is, monotype grain boundary > polytype grain boundary. And, this was indeed found to have been interesting. The features explained in this section can be seen in Figs. 1 and 2.

In the industry and trade of stones, uniaxial compressive strength (UCS) is the first characteristics taken into consideration in determining the place of use and in choosing stones appropriate for a specific design purpose. It has clearly been seen that, dolomite mineral increases uniaxial compressive strength of marbles. Though each kind of detail was evaluated, neither an intergranular nor an intragranular feature could be found to have affected uniaxial compressive strength except for the mineral dolomite. Especially, pressure solution, alteration and deformation proved not to have affected the UCS on the contrary of the authors' expectations. On the other hand, grain boundary characteristics did not have any effects on tensile strengths except for dolomite. It is known in the literature that there is a relationship between UCS and TS. Within this context, a disparity is noticeable between the UCS and TS values of M2, M8, M10 and M15 when Tables 2 and 3 are reviewed. Common point of these samples in Table 3 is that single coursed twinning formations are more than double coursed. Thus it could be stated that single-coursed twinning formations decrease tensile strengths of marbles, which is a substantial mechanical characteristics in determining the application method (fixing or cementing) and in improving (filling, epoxy, polyester, mastic) the properties of stones.

Abrasion resistance and abrasion loss value are the most significant characteristics of marbles and other natural building stones

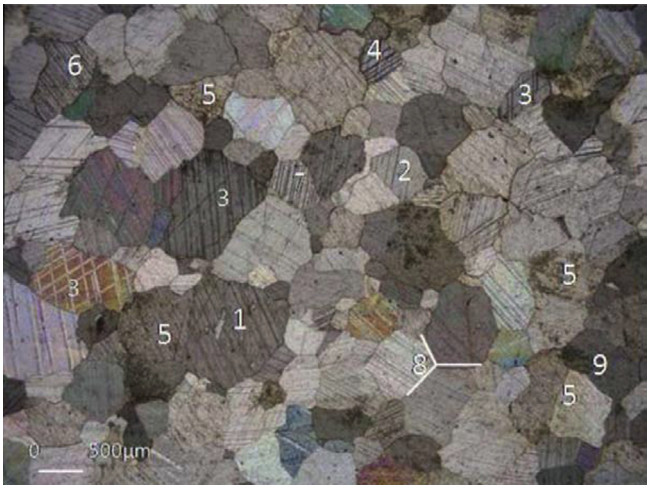


Fig. 1. Thin section from M5. Inequigranular (eg. 1–5), polygonal (eg. 8), euhedral (eg. 2–4), subhedral (eg. 5), alteration (eg. 2, 5), multiple twinning double directional (eg. 3, 4), multiple twinning single directional (eg. 1, 6, 7), deformation (eg. 2, 3).

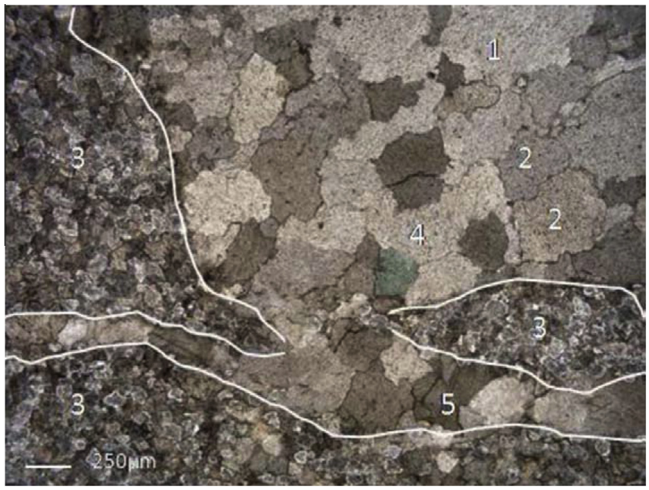


Fig. 2. Thin section from M10. Inequigranular (eg. 1–3), interlobate (eg. 1, 2), subhedral (eg. 1–4), unhedral (eg. 5), alteration (eg. 1–4), dolomitization (3).

to be used for flooring purposes. Within this context, tribology is a field which has not yet fully understood but in which extensive researches have continuously being done [21]. The first outstanding parameter related to the abrasion loss value of marbles is dolomite. In general, existence of dolomite, which has higher hardness value with regard to calcite, decreases abrasion loss value of marbles. However, a clear correlation could not be put forward between the amount of dolomite and BAL (Böhme abrasion loss) value. Characteristics of calcite grains are the reason for this case. According to the ratio of MgO (Table 1), the best BAL values were expected to be ranked as M3, M10, M4, M13 and M12. Yet, the ranking was obtained as M3, M4, M10, M12 and M13. When Tables 1 and 3 are carefully studied, the ranking mismatch between M12 and M13 could be regarded as acceptable. Here, the replacement between M4 and M10 is remarkable. When M4 and M10 are compared, it is seen that M4 has smaller grains. However, it would not be reasonable to state that grain size is effective on BAL values when grain sizes of M12 and M13, and the ranking between these two marbles are compared. On the other hand, the other two features that are noticeable and different between these two marbles are the levels of alteration and deformation. Alteration and deformation levels of M4 and M10 are low, medium and medium, medium–high respectively. Thus, it can be said that alteration and deformation increase BAL values. In fact, BAL value of M8 supports this conclusion. BAL value of M8 that contains quartzite and other minerals, which have higher mineral hardness (7 Mohs for quartzite) than calcite, was found to be relatively high. A careful review of the case would reveal that alteration and deformation levels of M8 were effective on the BAL values. The expected effect of grain size and mineral composition was not detected on M8 either. These results are compatible with previously reported importance of grain deformation [2,4–7]. But here in this study, it was not possible to clearly state the effects of grain sizes and boundaries though they were reported in previous studies. According to Table 1, minerals other than calcite did not affect BAL values in polymineralic marbles, except for dolomite (MgO $\geqslant$ 10%).

4. Conclusions

In this study, the effects of relationships of micro structures, grain sizes and boundaries of grains of 15 worldwide well-known commercial marbles on some physical and mechanical characteristics (dry unit weight, porosity, uniaxial compressive strength, tensile strength) and on abrasion loss properties were investigated. 10 different samples were tested for each type of marble for each test.

Microscopic images were classified as intergranular properties (shape of grains, shape of grain aggregates, grain boundary type and pressure solution), intragranular properties (twinning and alteration) and deformation. Pressure solution, alteration and deformation were classified into five scales as low, medium–low, medium, medium–high and high. M1, M2, M4–7 and M11–13 have low pressure solution; M3 and M14 have medium–high; M8 has medium, M9, M10 and M15 have low–medium pressure solution. In M1, M2, M4, M9 and M11–14 medium level alteration, in M3 high level, in M5 and M15 low–medium level, in M6 low; in M7, M8 and M10 medium–high level alterations were observed. In M1, M2, M4–7, M11–13 and M15 low level deformation, in M3 high, in M8 medium–high, in M9, M10 and M14 medium level deformations were observed. In general, pressure solution and deformation were found at similar levels.

Texture is an intergranular property and all 15 samples are of heteroblastic texture. On the other hand, M1, M2, M5, M6, M7, M9, M11, M14, M15 are monomineralic marbles while M3, M4, M8, M10, M12 and M13 are polymineralic. Except for M8, the secondary mineral in polymineralic marbles is dolomite. M3 and M10 are metamorphosed dolomites. M4, M12 and M13 are dolomitic marbles. Additionally, very few amount of dolomitization was detected in M15.

Having these general results, the following conclusions were made on the effects of grain properties and interaction of grain boundaries on the characteristics of marbles;

- Euhedral grains are mostly of large sizes.
- Dolomite increases dry unit weight and uniaxial compressive strength.
- Porosity increases as grain boundary smoothness fades.
- Single-coursed twinning decreases tensile strength of marbles.
- Böhme abrasion loss value increases as alteration and deformation does.
- Böhme abrasion loss value decreases in dolomites.

The authors hope that this research would be an in-depth contribution to the architects, designers, traders, miners and industrialists or whoever has a relationship with marbles, in their lifelong journeys with this noble stone.

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