TESTING JABAL FARASAN MARBLE DEPOSIT FOR MULTIPLE INDUSTRIAL APPLICATIONS: MINERALOGICAL, GEOCHEMICAL AND PHYSICO-MECHANICAL CONSTRAINTS

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الخلاصة:
رواسب الرخام بمنطقة جبل فراسان تمثل جزء من تركيب دسري بمربع رابغ. وراسب الرخام هناك يتواجد علي هيئة طبقات متوافقة مع صخور متورقة من الصوان المتحول والشست المافي الأخضر.

وبالاستعانة بتحاليل حيود الأشعة السينية والفحص المجهري، أمكن للمؤلف الحالي تصنيف صخور الرخام بمنطقة جبل فراسان الي أربعة أنواع بتروجرافية كالتالي: رخام أبيض نقي (مع قليل من الجرافيت)، رخام جرافيتي، رخام دايوبسيدي، ورخام تريموليتي. وتشير الدلائل المعدنية والنسيجية الي أن ظهور معدن الدايوبسيد يعتمد في الأساس علي اتاحية عنصر الماغنسيوم في صخور الحجر الجيري الأصلي قبل تعرضة الي التحول الأقليمي، بمعني أن يكون حجر جيري دولوميتي في الأساس. ويرتبط ظهور معدن التريموليت في أغلب العينات المدروسة بمستويات القص المجهرية والتي تتميز بنشاط ملحوظ للمحاليل الغنية بالسيليكا.

ومن أجل معرفة أنسب الاستخدامات الصناعية للرخام المدروس، تم تحديد الكثير من الخصائص الطبيعية وقيم الفقد عند الاحتراق وقياسات البريق. ووجد أن نسبة الفقد عند الاحتراق ممثلة في عينات رخام جبل فراسان لها مدي واسع حيث أنها تتراوح من ٦١و١٠ الي ٣٢و٤٢ % ، والمعروف أن لاقيمة المتعارف عليها عالميا تدور حول قيمة ٤٠ %. وبينت الدراسة الحالية انخفاض معامل البريق لمعظم عينات رخام جبل فراسان بسبب تواجد الجرافيت، سواء كان ردئ أو جيد التبلور. كما تبين الدراسة أن نوعية الرخام التريموليتي الأبيض اللون هي النوعية الوحيدة التي تتطابق مع المواصافات العالمية للاستخدام كمادة مالئة بعد طحنها في صناعات الورق وخلافة. وتوضح التخاليل الكيميائية للعينات المدروسة أن نسبة أكسيد الكالسيوم تتراوح من ٣٩و٢١ الي ٥٦ %، مع وجود شوائب من أكاسيد الحديد واللألمنيوم والماغنسيوم والسيليكا، علما بان الأكسيدين الاخيرين لا يتعدي تركيز أي منهما نسبة ١ %.

وتبين العينات المدروسة أيضا خصائص مرضية أخري مثل قوة التحمل وامتصاص المياة والكثافة النوعية المطلوبة للاستخدام كحجر زينة في صناعة البناء. وخلصت الدلراسة الي أن رخام جبل فراسان مناسب لتلبية أحتياجات السوق المحلي وصعوبة التصدير نظرا للمنافسة الضارية مع الرواسب العالمية الأخري.

ABSTRACT

The marble deposits at Jabal Farasan represent a part of a prominent nappe structure in Rabigh quadrangle in western Saudi Arabia. The marble deposit occurs in beds interbedded with foliated metachert and mafic green schists. The marble and the associating rocks are of late Neoproterozoic age.

Based on XRD analyses and microscopic investigation, the present author was able to classify the Jabal Farasan marble into four major petrographic types as follows: pure white marble (slightly graphitic), graphitic marble, diopside marble and tremolite marble. Mineralogical and textural evidence suggest that the appearance of diopside depends on the availability of Mg in the limestone precursor prior to regional metamorphism, i.e. dolomitic limestone. Tremolite in most cases is confined to micro-shear planes characterized by relative increase in silica activity.

The physical properties, loss on ignition and brightness measurements of the Jabal Farasan marble deposits were determined to establish its suitability for end-product use. The loss on ignition values vary from low to high (10.61 wt% to 42.32 wt%). The internationally recommended loss on ignition (L.O.I.) value is around 40 wt%. Most Jabal Farasan samples have a low brightness parameter due to common presence of both crypto- and well-crystalline graphite. The white tremolite marble is the only type at Jabal Farasan that fulfils the specifications for use as filler in paper and other industries. The chemical analysis of end products shows that CaO content varies from 21.39 to 56 wt%. Other impurities are Fe_2O_3, Al_2O_3, MgO and SiO_2. Only the contents of both MgO and SiO_2 are higher than 1%.

The bulk samples have shown satisfactory properties (good strength, water absorption and bulk specific gravity values) corresponding with the requirements of dimensional stones used in the building industry. Jabal Farasan marble deposits could provide the domestic market building industry but it might be difficult to supply for the international market because of acute competition from other world deposits.

Key words: marble, Jabal Farasan, mineralogy, geochemistry, physico-mechanical properties

1. INTRODUCTION

A. Nature of Jabal Farasan marble prospect

The Precambrian Jabal Farasan marble prospect is located within the Rabigh quadrangle in central western Saudi Arabia. The exact location of Jabal Farasan marble prospect that includes many quarries has a central point with the following geographic co-ordinates, latitude 22º 33’ 01’’ N and longitude 39º 25’ 01’’ E. It is located some 120 kilometres northeast of Jeddah city, and has been affected by a complicated series of structural events. Hence, most of the rocks are highly deformed. There are several types of marble, all are located in hills of different heights and the long narrow valley between these hills is called Wadi Farasan. The host rocks are principally ortho-schists, volcanic rocks and volcano-sedimentary rocks, in addition to a younger large intrusion of gabbro-diorite. The marble and the associating rocks are of late Neoproterozoic age. The collected samples were hand sorted, chipped from the broken rocks at its original place inside the quarries. The exact locations of the collected marble samples (expressed by their geographic co-ordinates) as determined by a Garmin GPS are given in Table 1.

B. What is marble?

Commercially, any rock that can take a polish, except granite, is called marble. Commercial deposits of marble in the world are mostly found in folded beds that have been subjected to regional metamorphism. There is no possibility to record fossils or trace any relict sedimentary features in most cases due to intense recrystallization. Geologically, marble is a monominerallic metamorphic rock with significant calcite content. Silicate minerals such as quartz, mica, chlorite and tremolite; where iron minerals such as hematite and limonite, are the common impurities in marble and

some of them (tremolite and diopside) indicating recrystallization at high temperatures. The most common rocks associated with marble are schists and gneisses. The result of the metamorphic process from limestones to marbles yields a stone that is re-crystallized and capable of being polished on cut surfaces.

Pure marble is apparently white but other colours can also result from the presence of non-opaque and opaque disseminations. For example, in marble, graphite shows grey colour, hematite shows red or pink colour and limonite shows yellow and cream colour. Very few marbles are principally dolomite [1]. The most pure marble is the one that has least contaminants while the least pure marble lacks whiteness [2]. Impurities that appear in the limestone during the recrystallization process might affect the mineral composition and consequently give the marble a wide range of colour varieties [3]. Commercial marble comprises true metamorphic marble, polished serpentine rock and crystalline limestones, suitable for polishing. For decorative purposes such as ornaments, sculptures and in building, gloss-polished marble is used in the form of slabs, while uniform marble fragments are used for the manufacture of floor tiles [4]. Streaks, bands or veins of dark silicate or graphite characterize most of the marbles. The interlocked calcite crystal lowers the porosity of marble making it less water absorbent [1].

According to [3], ground marble as calcium carbonate powder can contain talc, kaolin, mica and wallstonite as fillers, for example in paints, plastics, paper industry, carpet underlay and ceramic floor tiles. The nature of calcium carbonate grinding and crushing is relevant to its compressive strength value [5].

C. Major geological features for prospecting dimensional stones

Visual features

Consistent visual features are very important when evaluating the market potential of a stone. These visual features include colour, grain size, textures, flaws and irregularities. The grain size could be fine (individual grain size is less than 1 mm), medium (1-2 mm) or coarse (individual grain size larger than 2mm). Texture includes mixtures of larger and smaller crystals, regular or irregular banding, lineation and individual spots or grain clusters. The presence and the consistency of these features should be taken into account through a deposit because they are important points of sale features. Flaws and irregularities are represented by xenolithic enclaves, unusual mineral clusters, vugs or gas cavities etc. These features must be taken into account and carefully evaluated as their presence within the marble block could affect production [6].

Technical features

The technical features of a dimension stone include its mineralogy, petrology, brittle deformation, physico-mechanical properties and available volumes. Knowing the mineralogy and the petrology of a stone is very helpful in determining the extraction method and workability of that stone. Also, it is useful to understand the problem of alteration in a stone. Physico-mechanical properties are important in determining the limit of dimension stone usage under specific installation conditions. Tests following the requirements of the ASTM (American Society for Testing Materials) are used for evaluating the physico-mechanical properties of dimensional stones. Consistency is useful to give confidence in the supply of raw material to the market place. The blocks squaring must provide a minimum length to height ratio if a specific cut orientation is required [6].

D. Aim of study

The main aims of the present paper are the quality assessment and determination of the industrial potential of the Jabal Farasan marble deposit as a dimension stone, and testing its applicability as filler for some specific industries. It aims also to investigate the mineralogical and geochemical variations through representative areas at Jabal Farasan. In order to achieve such aims, representative samples of Jabal Farasan marble were collected from different exposures at the quarry areas. These samples were subjected to detailed laboratory investigations including mineralogy, petrography, geochemistry and determination of physico-chemical parameters.

2. GEOLOGICAl SETTING

The marble deposit of Jabal Farasan is a part of the oldest rocks in the Rabigh quadrangle. They are affiliated to the layered rocks of so-called “Birak Group” that is sub-divided into three formations, namely Suri, Qahah and Labunah [7]. The three formations are dominated by regionally metamorphosed mafic and subordinate felsic volcanics and volcaniclastics. The marble deposits of Jabal Farasan (Fig. 1) are members of the Labunah Formation that is dominated by metabasalt and subordinate metachert. A stratigraphic column showing the age relationships of the units is given in Fig. 2.

The marble comprises elongate irregular outcrops of marble and quartzite extending from Jabal Farasan to Wadi Ukaz at the core of synclinarium. The marble is intercalated with quartzite and metabasaltic greenschist (now quartz-sericite-chlorite schist).

All of the layered Precambrian rocks (including the Birak Group) were intensively deformed during the main tectonic episode (F_2) comprising three structural features: Khamrah anticlinarium flanked by the Farasan synclinarium in the north and the Samaran synclinarium in the south [8]. [9] stated that the axial plane of the Farasan synclinarium dips steeply northwest and the axis plung 30-40^o due SW.

[7] stated that the main tectonic event (F_2) was the main episode of deformation resulting in isoclinal to open folding and ended by intense compression that resulted in the development of recumbent folds, overthrusts and nappes at the Farasan-Labunah stretch. Figure 3 shows the Jabal Farasan nappe where four thrust sheets are present and each sheet is composed either of marble only or marble intercalated with the greenschist (metabasalt, now quartz-sericite-chlorite schist), both exhibiting S_2 foliation. Figure 3 also shows the megascopic recumbent folding of sheet number 3.

According to [10] and [11] and [12], the Jabal Farasan marble deposit is large and is estimated to have a volume in the magnitude of several million m^3.

3. GEOLOGY OF THE JABAL FARASAN MARBLE DEPOSIT

The geology of Jabal Farasan is characterized by a large syncline (or synclinarium) cut by faults. The syncline area contains parallel secondary folds marked by hills of marble. The faulted syncline contains schist (tuffaceous, siliceous and chlorite) and metamorphosed volcanic rocks or volcano-sedimentary beds in which are intercalated thick beds of marble that crop out in a discontinuous manner. This formation is cut by a large gabbro-diorite intrusion (Fig. 1).

According to [10], the colour and the texture of marbles at Jabal Farasan are based on their locations that have been divided into three divisions:

1-Eastern side: deep grey, banded white, grey marble (medium-grained stone)

2-Main body: white to very light grey with cloudy grey spots (medium-grained stone)

3-Western side: grey marble with small veinlets or spots (well crystalline, but fine-grained)

The geological map of the study area given in Fig. 1 shows the presence of common chert bands and green schists (highly foliated mafic metavolcanics) that are interbedded with the marble deposits. The marbles are found in different colours and are sometimes assigned by cherty bands, lenses of dolomite or quartz veinlets (siliceous marble). The grade of the metamorphism that caused deformation seems to range from greenschist to amphibolites facies. In the following section, field characterization of the marble deposit at different parts of Jabal Farasan is given.

A. West of Wadi Farasan

West of Jabal Farasan includes deep grey banded and white marbles, white to very light grey marble with cloudy grey spots and siliceous marble. The first marble type is mainly associated with volcanic-sedimentary rocks as thick beds and sometimes cut by a large intrusion of gabbro-diorite that sometimes grades to granodiorite composition in some few instances. The intrusion reaches a length of about one kilometre. The igneous body is highly weathered and exhibits porphyritic nature with the presence of prominent plagioclase phenocrysts up to 2.5 cm long. Siliceous marble and marble that has cloudy spots are associated with volcanics and schists. The siliceous marble is a bit stronger than the rest of the marbles because of its silica content. The strike of the schistosity of chlorite schist, siliceous marble and siliceous cherty tuff is mainly oriented to the northeast with northwest dipping beds. A part of the siliceous cherty tuff is highly fractured and jointed.

B. East of Wadi Farasan

Chlorite schist covers the northern part of east Jabal Farasan area. It is associated with volcanic rocks that have an orientation of N 30 ^{o} E and dip due 70 ^{o} NW.

The eastern edge of Wadi Farasan is characterized by a long exposure of black marble that is associated in some parts with talc schist and foliated talc-carbonates that are found along the contacts with the metavolcanics and ultramafic rocks. In comparison with the rest of marble varieties, the black marble is always highly schistose. The southern part of this black marble hill includes a small exposure of white to very light grey marble with cloudy spots.

C. North of the igneous intrusion

Most of the marble types have been found in this area. There is white pure marble, white to very light grey marble with deep grey spots, deep grey banded white marble and grey marble with very small veinlets. Two marble exposures are found close to each other in small scale in the eastern extremity. They all associated with foliated metavolcanics and soft talc-carbonate rocks. The exposures possess deep grey-banded white marble and it is located along the contact with the diorite and granodiorite. Volcanic rocks are widespread and cover a large part of the domain characterized by the igneous intrusion.

D. Northwest of Wadi Farasan

No marble exposures are found in this area. It basically consists of a mixture of metamorphosed mafic to intermediate volcanic rocks and chlorite schist that together extend for a length exceeding one kilometre.

4. MINERALOGY AND PETROGRAPHY

Three grams from each representative sample of each marble variety was taken for the X-ray diffraction runs (Table 1). They were put in a holder and pressed within a glass plate to the level of the rim, and then they were kept in a multiple holder. Samples pressed into the holder were run in a Siemens D5000 X-ray diffractometer using Cu k_{α} source.

Table 2 summarizes the main mineralogical characteristics of Jabal Farasan marbles. It is evident that all samples are rich in calcite as the dominant carbonate mineral, in addition to a variety of minor and trace phases in four petrographic classes of the studied marble deposit. Common minerals, other than calcite, are represented by nano- & well-crystalline graphite, quartz, diopside and tremolite, talc and dolomite. The nano-crystalline nature of some graphite-bearing samples was distinguished from the well-crystalline one both microscopically and by XRD runs. Dolomite is very scarce carbonate at the Jabal Farasan deposit indicating that the precursor limestone prior to regional metamorphism was Mg-poor.

The reduction of the marble purity is sometimes caused by the affect of the fluids that pass through areas rich in different minerals in an early stage of diagenesis. Calcium carbonate might be also impaired by the epigenetic mineralization and dolomitization. Some marble samples (JF6 & JF9) have calcite crystals with perfect cleavage and hence they are considered as good products for sculpture because they reflect light in shimmering pattern and make the sculpture material more attractive.

Microscopic investigation of Jabal Farasan samples revealed that four petrographic types of marble can be identified. Such classification is based essentially on the modal abundance of carbonates and accessory minerals (either minor or trace), and these petrographic types are: pure white marble, sometimes slightly graphitic

(samples JF4, JF9 & JF13), graphitic marble (sample JF10, JF12, JF17 & JF18), diopside marble (Sample JF 5) and tremolite marble (samples JF6 & JF20). The given petrographic subdivisions agree with the mineralogical composition indicated by XRD (Table 2).

Pure white marble is fine- to medium grained and it is either foliated or shows traces of obliterated foliation (S_2). From the mineralogical point of view, the white marble is entirely composed of calcite crystals but with occasional thin bands of graphite and microcrystalline silica in a few samples. In a single sample only (JF9), talc and chlorite flakes are encountered as scary traces corroding calcite. The white marble displays common microfolding on the microscopic scale. In parts, the rock is dissected by thin intersecting quartz and another generation of calcite. The size of both minerals in the veinlets is much coarser than the remainder of the rock.

Graphite marble is fine-grained and composed of calcite with variable amounts of graphite where the latter occurs as fine dust that shows some sort of segregation in micro- to mesobands. All investigated samples of graphite marble are foliated and contains occasional coarse calcite crystals set in a matrix dominated by fine calcite crystals. The rock is also dissected by thin sub-parallel veinlets made up of coarse calcite exhibiting ill-developed comb structure.

Diopside marble is not a common type at Jabal Farasan which indicates that the precursor limestone was Mg-poor and consequently magnesite and dolomite were uncommon. The diopside marble is composed mostly of calcite with appreciable amounts of diopside (up to 35 % modal). This variety is fine-grained, foliated and sometimes contains very minor amounts of fine tremolite laths.

Tremolite marble is either fine- or coarse-grained. The coarse-grained variety of this marble type exhibits traces of S_2 foliation and mosaic texture (e.g. sample JF

6), but not annealing with no evidence of thermal metamorphism. Tremolite coarse laths are observed only along micro-shear planes that are characterized by uncommon fine opaque disseminations. On the other hand, the fine-grained tremolite marble contains much finer tremolite laths that are non-segregated with no confinement to any shearing.

Some varieties of marble, particularly the graphitic ones, contain some intercalations of green to greenish black schist streaks or veneers (few millimetres thick). The schist is mostly less competent than the marble itself, so microfolding in the schist veneers is more pronounced than in the marble.

5. GEOCHEMISTRY

Ten different varieties of the Jabal Farasan marble were identified from representative samples analyzed by the X-ray fluorescence spectroscopy using a Philips PW 1400. Qualitative and quantitative analyses were conducted for determining the major oxides and a single trace element (barium) of the powdered samples of marble. Powders were used to make fusion bead for analysing the the following elements, Fe, Ti, Ca, K, Si, Al, Mg, Na, Mn, Ba, S, and P. Results are given in Table 3. L.O.I. (Loss on ignition) is given in a separate table later. Table 3 shows barium oxide as one of the major oxides because barium is known to be abundant in carbonate rocks. Table 3 shows that sample JF4 contains the highest CaO (57.32 wt%). The lowest CaO content is recorded in samples JF12 & JF13 (~ 21-25 wt%). Both samples are siliceous and contains considerable silica content (~ 23-52 wt%) that increases at the expense of the CaO content. Silica content in sample JF 10 is also considerably high (15.11 wt%). Highest MgO content in sample JF13 is connected to

common dolomite which is an exceptional case for Jabal Farasan. MgO content (2.87 wt%) in the latter sample is relatively high although the rock is very poor in diopside and dolomite. This suggests possible ionic substitution of Mg^{2+} for Ca^{2+} in the calcite structure. There is no existence for the MnO and Na_2O in any marble types. Dolomite, quartz, titanium and iron minerals are quite likely to be present in samples JF12 & JF13 and that because of the high portion of the MgO, SiO_2, TiO_2 and Fe_2O_3 in these marbles. K_2O only occurs in very small quantities in samples JF9, JF12 and JF20. Quartz or SiO_2 is the most common mineral that contaminates the marbles. The highest SiO_2 content is displayed by sample JF12 (52.04 wt%).

Generally, the identification of CaO, Fe_2O_3, MgO and SiO_2 is important to characterize the quality of the marble material. Iron and magnesium are admixed in the structural lattice of calcite as well as calc-silicate minerals. The theoretical composition of calcium carbonate is 56 wt% CaO and 44 wt% CO_2. The CaO of the marble of Jabal Farasan ranges from 21.39 wt% to 57.32 wt% and the CO_2 from 10.60 wt% to 42.32 wt%.

Evaluating chemical purity is important when assessing the marble's suitability for some specific uses. For example, very high chemical purity is required for filler applications. On the other hand, marble is widely used as a dimensional stone despite containing large amounts of fine grains of some sulphides (e.g. finely disseminated pyrite or marcasite). According to data of Table 3, the chemical composition of most Jabal Farasan marbles is not commercially suitable for uses other than a dimensional stone. The calcite content that has been calculated from the XRF analysis shows that sample numbers JF4 (white marble) and JF6 (tremolite marble) are the only sample that has more than 97% calcite. Therefore, it is the most suitable variety for use in the paint and plastic industry as filler.

6. DETERMINATION OF PHYSICO-MECHANICAL PROPERTIES

In order to determine the physico-chemical properties of Jabal Farasan marbles, the representative samples underwent several steps of laboratory preparation and measurements for testing such properties. All tests for measuring the physical and mechanical properties were carried out at the Camborne School of Mines, University of Exeter in the United Kingdom. The only exception is the uniaxial compression strength experiments that were done at the laboratories of Environmental and Engineering Geology Department of King Abdulaziz University, Jeddah, KSA.

A. Reflectance/chromaticity determination

A Minolta CR-231 spectrophotometer was used to measure the brightness and the colour of 10 samples of different marble types. The marble samples, in the powder form, were pressed with a palette into the sample holder. The measured colour parameters are L or whiteness (the lightness coordinate from 0 to 100), a (the red/green coordinate where +a indicates red & -a indicates green) and b (the yellow/blue coordinate where +b indicates yellow & -a indicates blue). The parameters were measured following the procedure suggested by the Colorimetry Instruments of Europe (CIE) in 1996 ([13]). The instrument was calibrated against a ceramic tile standard with brightness and chromaticity values of Y = 93.7, x = 0.3133, y = 0.3201 using two different illuminants, namely C and $D_{65.}$ Comparison between the values of the different light sources has been made. The best colour and brightness values of this test were compared with values for other marbles to determine the quality of the marble. Colour measurements were done for the end products. The obtained results of brightness results of the pressed surfaces of marble product are

extremely variable and it was noticed that brightness increases, as more fine grained is the product.

With both illuminant source of light (illuminants C & D_{65}), sample JF6 (the white tremolite marble) displays the highest brightness reading of 92.69 with illuminant C and 93.02 with illuminant D_{65}. Black marble (sample JF10) displays the lowest brightness reading of 57.71 with illuminant C and 57.37 with illuminant D_{65}. However, there is a slight difference in the reading between the samples that use illuminant C and the samples that use illuminant D_{65}. That is because of the fact that illuminant C is based on the noon sunlight and an average of daylight that is given by a gas-filled tungsten filament lamp at a temperature of 2856 K while illuminant D_{65} is based on the daylight with a colour temperature of 6500 K. Brightness and colour of the product with both sources of light are given in Table 4. The variation in the colour measurement results is related to the different structure of each form of marble and the presence of minor impurities, preparation steps and imperfections of surface.

A comparison between the best colour measurement reading of sample JF6 and that of Carrara marble of Italy ([14]) has been made and given in Table 5. The results in this table shows that the brightness and chromaticity coordinates of JF6 with both illuminant sources are even much better than that of the Carrara marble. Therefore, the brightness of sample JF6 of Jabal Farassan would suggest its suitability for use as commercial mineral filler. In addition, the brightness of samples JF9 and JF13 also demonstrates suitability because of its higher brightness compared with the Carrara marble. Comparison with marbles from different parts of the world is not always applicable because different marble products might command different standards thus requiring different results. Also, the illuminant sources might not be

identical. Furthermore, each measuring system applies different geometry and different filter options.

B. Loss on Ignition

Two grams of each marble sample, the required quantity for the test, were used for the determination of loss on ignition. The powders were ignited in the laboratory furnace for half an hour at 1050 ^{o}C and cooled down in a desiccator to reach the room temperature, and then the loss in weight was calculated and recorded as a percentage of the original sample weight. The loss on ignition (L.O.I.) has been determined for extenders and paint as an end product. Marble samples and fluxes are used for this determination. Theoretically, the L.O.I. of pure calcium carbonate is equal to 44 wt% of carbon dioxide. The L.O.I. represents mainly carbon dioxide, water or other volatile components, according to the purity of the calcium carbonate. Hence, it is a very useful applicable way that is used in confirming the CaO content and calculating its $CaCO_3$ content. The following equation was applied for L.O.I. calculation: L.O.I. = 100 (mo – ml) / mo %, where mo is the mass in grams of the test portion while ml is the mass in grams of the test portion after ignition.

The results of loss on ignition are shown in Table 6. Loss on ignition values of samples JF12 and JF13 show big differences in comparison with the rest of samples, and this is attributed to the fact that they are not pure calcium carbonate, in addition of having significant amounts of SiO_2 and MgO. Samples with high loss on ignition values such as 42.32 wt% (sample JF18) and 41.62 wt% (sample JF4) give indication of high calcium carbonate purity. The L.O.I. ranges from 10.61 to 42.32 wt%, which means the proportion of the impurities, is variable with the marble type. Sample JF18 is the purest marble while sample JF12 is the most contaminant marble. As stated

before increase of silica and other silicate constituents in the marble reduces the L.O.I. value.

C. Strength tests

Principle Schmidt hammer rebound

Ten representative samples of marbles with a smooth flat surface and edge length of more than 6 cm were prepared to meet the sample requirement of this test. The aim of this test is to define the compressive strength of the surface joints. So, the hardness extent of the test material will be known. All samples were strongly fixed to a flat rigid base before testing. This was done to make sure that the samples would not move during the test. The Schmidt hammer was calibrated and applied perpendicular to the samples to give correct readings on the scale according to the procedure recommended by [14]. Ten readings were taken for each marble sample. As a rule of thumb for this test, the five lower readings of each sample were discarded, whereas the upper five readings were put in descending order and averaged. At the final stage, the values of the averaged results of all samples were compared to the field estimates of the uniaxial compressive strength, to ascertain the actual sample strength. All the values have been converted into kg/cm^2 and MN/m^2 to show meaningful strength values. That was done by using graphs that display the relation between the Schmidt hammer values with particular rock density and uniaxial compressive strength values.

The average of the samples readings that were taken by applying Schmidt hammer range from 35 to 56 or 61 to 188 MP (after transforming the results into strength values). The averaging results of the top five readings taken by the Schmidt hammer test is shown in Table 7 and the results in strength units are shown in Table 8. The given data show that the average of sample readings taken by applying Schmidt hammer range from 35 to 56 (61 to 188 MPa).

Field estimates of the strength of samples having an average reading of from 30 to 40 is that of hand held specimens broken by a single blow of geological hammer. Samples in this category of estimation are numbered JF 4 (72 MPa), JF5 (61 MPa), JF6 (77 MPa), JF9 (68 MPa) and JF10 (77 MPa). Therefore, any marble having a strength value between 61 and 77 MPa is considered a strong material. Field estimates of the strength of samples that have readings ranging from 40 to 50, is that many blows of a geological hammer is required to break the intact rock specimens. Samples that fit under this field of estimate are sample number JF13 (132 MPa), JF17 (81 MPa) and JF20 (87 MPa). That means any marble that has a strength value that fits between 81 and 132 MPa is considered a very strong material. Field estimates of strength of the samples that have average reading ranges from 50 to 60 show that the rock material only chipped under repeated hammer blows, and rings when hit. Samples in this category are numbered JF12 (145 MPa) and JF18 (188 MPa). Therefore, any marble having a strength value between 145 and 188 MPa is considered extremely strong material. The strength results of the marbles demonstrate that the Jabal Farasan marbles are not susceptible to mechanical and chemical weathering. Therefore, it is considered a suitable product for the building industry. The most suitable marble varieties in this respect are samples JF12 and JF18 since they are the strongest samples.

Uniaxial compression strength test

The intact rock strength for the marble was accomplished by using the uniaxial unconfined compression and the point load strength index tests. The uniaxial compressive strength (UCS) was obtained by compressing a trimmed cylindrical specimen in the longitudinal direction and taking the maximum measured force

divided by the cross-sectional area. The point load index serves as a surrogate for the UCS and is a simpler test in that irregular pieces of rock core were used. In the UCS test, cylindrical rock specimens are tested in compression without lateral confinement. The test procedure is similar to the unconfined compression test for soils and concrete. The test specimen should be a rock cylinder of length-to-width (L/W) or (H/D) ratio in the range of 2 to 2.5 with flat, smooth, and parallel ends cut perpendicular to the cylinder axis. The drill core specimen diameter has a NX size , D = 54 mm).

The uniaxial compression test is the most direct means of determining rock strength. The results are influenced by the moisture content of the specimens. The rate of loading and the condition of the two ends of the rock will also affect the final results. Ends should be planar and parallel per ASTM D 4543 ([15]). The rate of loading should be constant as per the ASTM test procedure.

The strength of marble under uniaxial unconfined compression is given in Tables 9 and 10. The UCS test always has more credibility than the Schmidt hammer rebound test and for this reason the present author was keen on carrying out the UCS test for two representative varieties, namely the white and black marbles. For sample JF4 (white marble), the resultant UCS value amounts 26.47 MPa which is close to the correspondent value obtained by the Schmidt hammer rebound test which amounts 38 MPa. On the other hand, strength results of black marble (sample JF10) by the Schmidt hammer (39 MPa) is nearly doubled by the more convenient USC test (~ 77 MPa).

Strength point load index

The strength point load index test was carried out on rock specimens in the form of cylinder (diametric and axial) or irregular lumps were broken by application

of concentrated load through a pair of spherically truncated, conical platens. The distance between specimen-platen contact points was recorded. The load was steadily increased, and the failure load was recorded. There is little sample preparation. However, specimens should conform to the size and shape requirements as specified by the ASTM specifications ([15 and 16]). In general, for the diametric test, core specimens with a length-to-diameter ratio of 1.0 are adequate while for the axial test core specimens with length-to-diameter ratio of 0.3 to 1.0 are suitable. Specimens for the block and the irregular lump test should have a length of 50±35 mm and a depth/width ratio between 0.3 and 1.0 (preferably close to 1.0). The test specimens are typically tested at their natural water content. Size corrections were applied to obtain the point load strength index, Is 50, of a rock specimen. The strength of marble using point-load strength index is given in Tables 11 and 12. The resultant values for both white and black marbles do not differ from the values by the Schmidt hammer rebound test.

D. Water absorption and bulk specific gravity

The test is based on the American specifications (ASTM, [15]) for measuring water absorption and bulk specific gravity of dimensional stones. All the marbles have been cut into cubes with regular form and smooth surfaces. This operation proved successful with only half of the marbles. Six specimens out of ten samples were successfully extracted. The dimension of the regular form ranges between 5 and 7 cm and the volume to the surface area is less than 12. The same extracted marbles were prepared for both the examination of water absorption and the determination of bulk specific gravity. The six perfect cubes of marbles were placed in electrical oven at 60 ^{o}C for 48 hours to dry. Their individual weight was measured for each of the last three hours to confirm their stability. Then the specimens were cooled at room

temperature for 30 minutes and weighed again to the nearest 0.01 g. After cooling, the specimens were immersed in distilled water at 22 ^{o}C for 48 hours. Weight measurements were taken of the specimens while they were soaked in water and after taking them out.

The results of water absorption and bulk specific gravity are outlined in Tables 13 and 14. Water absorption calculation was based on the weight percentage absorption for each specimen as the follows: weight in percentage of the water absorption = [(B-A) / A] x 100, and A = weight of the dried specimen and B = weight of the specimen after immersion. On the other hand, the bulk specific gravity calculation was based on the following equation: bulk specific gravity = A / (B-C), where A = weight of the dried specimen, B = weight of the soaked and surface- dried specimen in air, and C = weight of the soaked specimen in water.

According to data in Table 13, water absorption results show wide variations (0.03 to 1.05). The highest results might refer to the affect of the solution on the mineral matrix. However, in Table 14, the bulk specific gravity results show slight variations (2.55 to 2.68 g/cm^3). That might relate to the presence of small closed porosities. The true specific gravity for pure calcite is considered to be 2.71 at 20 ^{o}C [17]. Comparisons have been made between the bulk specific gravity and water absorption of the marble of Jabal Farasan and that of different marble deposits from Spain and India. These comparisons are given in Tables 15 and 16. The bulk specific gravity results of the marble of Jabal Farasan is lower than the bulk specific gravity results of most Indian marble deposits and lower than most of the bulk specific gravity results of the Spanish marble deposits. The water absorption results of Jabal Farasan are higher than most of the water absorption results of both the Indian and Spanish marble deposits. The comparisons made indicate that the bulk specific gravity

and the water absorption of the Jabal Farasan marble consider the Saudi example from Jabal Farasan as a poorer quality by comparison. Nevertheless, the Farasan marble is considered as valuable commercial dimensional stone product for the building industry.

E. Binary relationships

A binary plot comparison between the colour measurements (brightness using illuminant D_{65} and C) and the loss on ignition values of the Jabal Farasan marble products was constructed and shown in Figures 4 and 5. Both graphs demonstrate that the relation between the different results of brightness and the loss on ignition is generally proportional. This means that when loss on ignition values decrease brightness measurements will do so. And as loss on ignition for samples increase high brightness measurements will also increase. Also, a comparison between purity (CaO %) and brightness (illuminant D_{65} and C) has been made and given in Figures 6 and 7. The relation between purity and brightness with both illuminant sources is exactly the same. Both relations are proportional and mean that low purity samples have low brightness and high purity samples have high brightness. A third comparison has been made between strength values and loss on ignition and between strength values and purity values. The resulted plots are given in Figures 7 and 8.

There are little differences between these graphs (Figures 8 and 9), as both indicate a proportional relation with gradual and sharp increase. In the first graph, the loss on ignition values and the strength values are gradually increased until they reach a certain point (L.O.I. value of 41.17 wt% shown by sample JF17 and 87 MPa strength value of sample JF20, Table 8) where the values are sharply increased.

7. CONCLUSIONS

1) The marble deposits of Jabal Farasan occur in beds intercalated by schist, volcanic and volcano-sedimentary rocks in fold hills. Jabal Farasan itself is considered as a structural nappe that made up of four thrust sheets of marble interbedded with foliated metachert and mafic green schists [7].

2) The mineralogy and the petrography of the samples have been examined. Calcite is the major mineral in the marbles and quartz appears as the second common and minor mineral almost in all varieties of Jabal Farasan marbles. Other minerals present are amphiboles (tremolite), pyroxene (diopside), talc, graphite and very rare dolomite. In the field, the recognized sample varieties are termed white, grey, dark grey to black and stripped (black & white) marbles. Based on XRD analyses and petrographic investigation, the present author was able to classify the Jabal Farasan marble into four major petrographic types as follows: pure white marble (slightly graphitic), graphitic marble, diopside marble and tremolite marble. Textural evidence suggest that the appearance of diopside depends on the availability of Mg in the limestone precursor prior to regional metamorphism, i.e. dolomitic limestone. Tremolite in most cases is confined to micro-shear planes characterized by relative increase in silica activity.

3) Bulk samples (in the form of equal cubes) have been used to determine the strength, bulk specific gravity and water absorption of the marble samples. The samples have undergone crushing and grinding to powder in some analysis (e.g. chemical analysis) to determine the end product characteristics. Also, the physical properties, loss on ignition and colour measurements of the Jabal Farasan marble deposits were determined to establish its suitability for end-product use. The loss on ignition values vary from low to high (10.61 wt% to 42.32 wt%). The loss on ignition

(L.O.I.) value recommended internationally goes around 40 wt% ([16]). Sample JF6 has the only colour measurement for marble end products acceptable to the market specifications. Jabal Farasan marble end products exhibit lower values of brightness.

4) The chemical analysis of end products shows that CaO content varies from 21.39 to 56 wt%. Other impurities are Fe_2O_3, Al_2O_3, MgO and SiO_2. Only the latter two have content higher than 1%. The results of chemical analysis of sample JF6, when compared to other commercial marble products are similar.

5) Most samples have low brightness parameter due to common presence of both nano- (crypto-) and well crystalline graphite. The white tremolite marble is the only type at Jabal Farasan that fulfils the specifications for use as filler in paper and other industries.

6) The bulk samples have shown satisfactory properties (good strength, water absorption and bulk specific gravity values) corresponding with the requirements of dimensional stones used in the building industry. Jabal Farasan marble deposits could provide the domestic market building industry but it might be difficult to supply for the international market because of acute competition from by the other world deposits.

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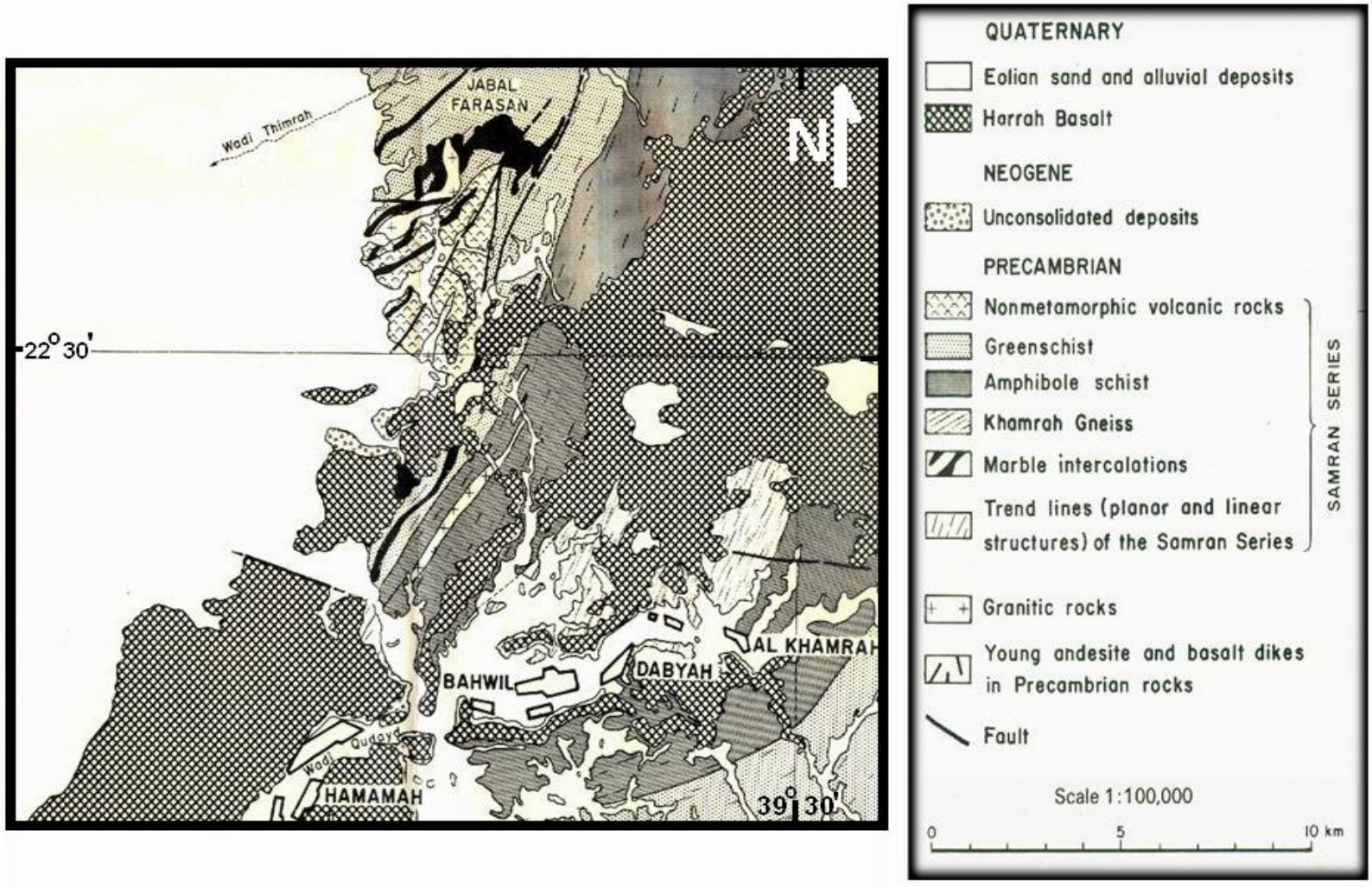

Figure 1: Geological map of Jabal Farasan area (after[8])

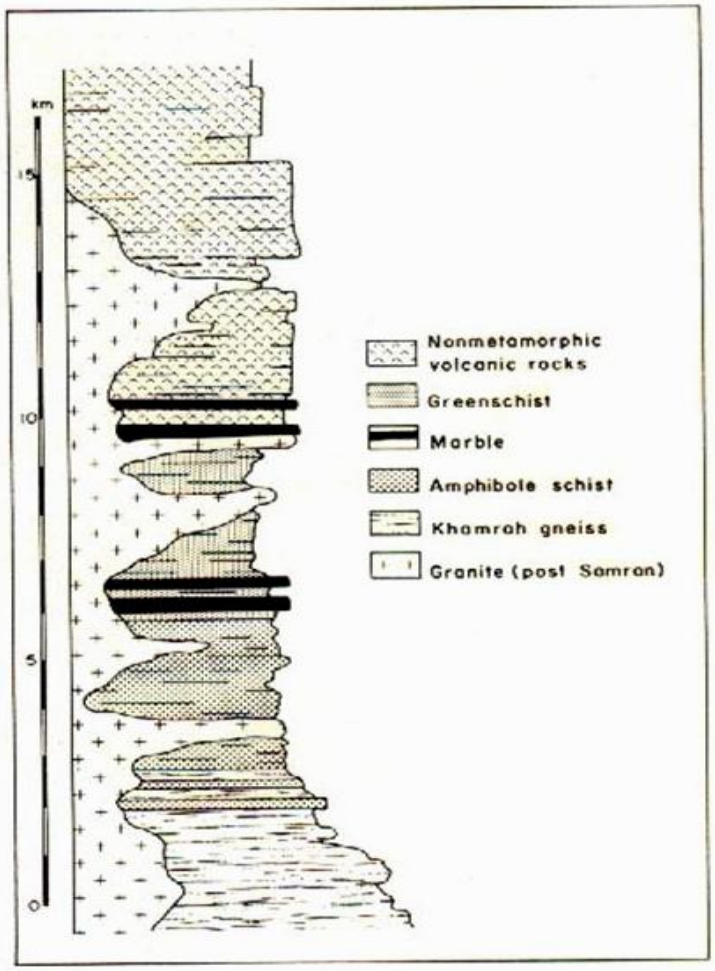

Figure 2: Stratigraphic column of the major units exposed at the area showing the mutual relationships especially those concerning with their relative ages.

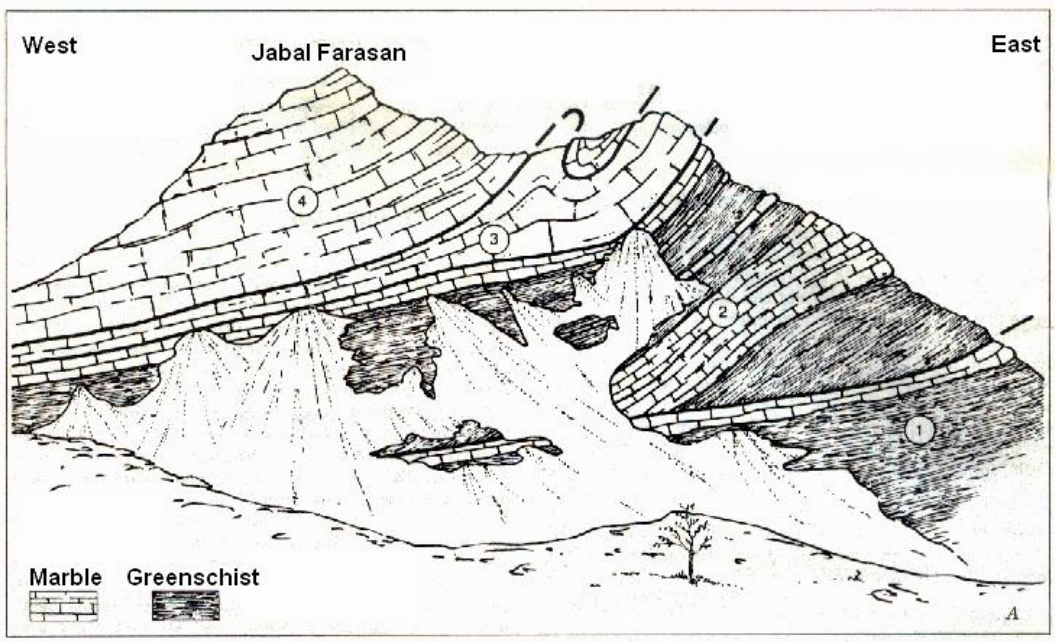

Figure 3: Sketch showing the thrust sheets of Jabal Farasan nappe (from [7]). Encircled numbers indicate thrust sheets and solid lines represent thrust planes.

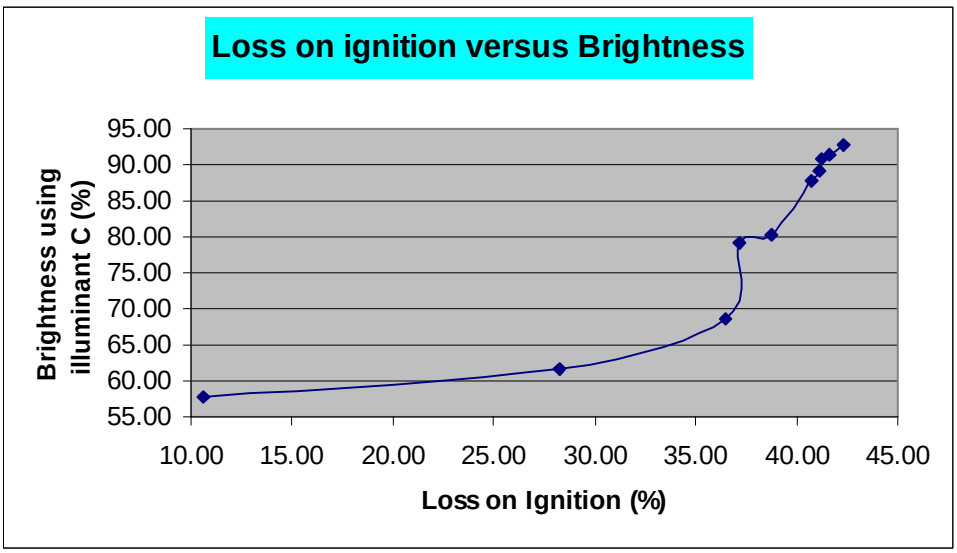

Figure 4: Jabal Farasan marble plot of ***Loss On Ignition*** *vs. brightness using illuminant C*

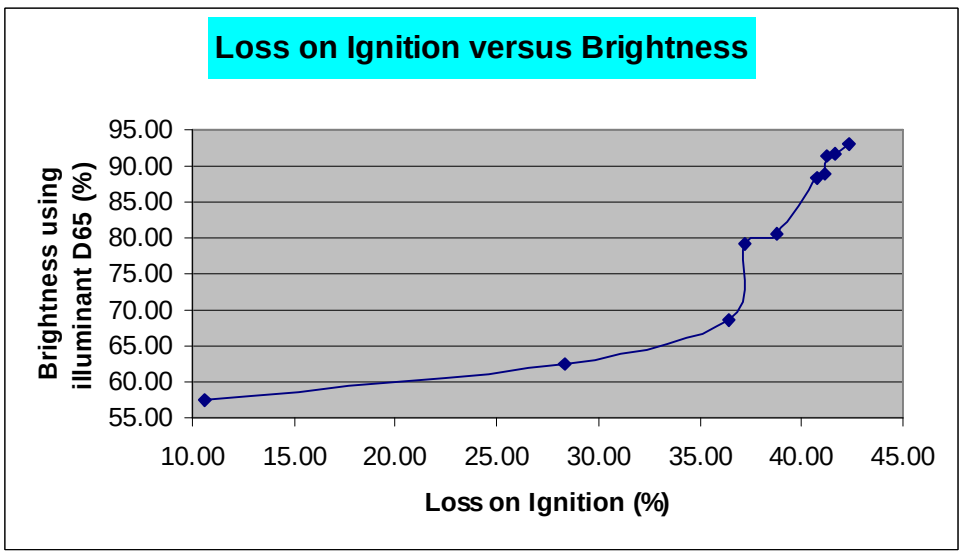

Figure 5: Jabal Farasan marble plot of ***Loss On Ignition*** *vs. brightness using illuminant* D_{65}

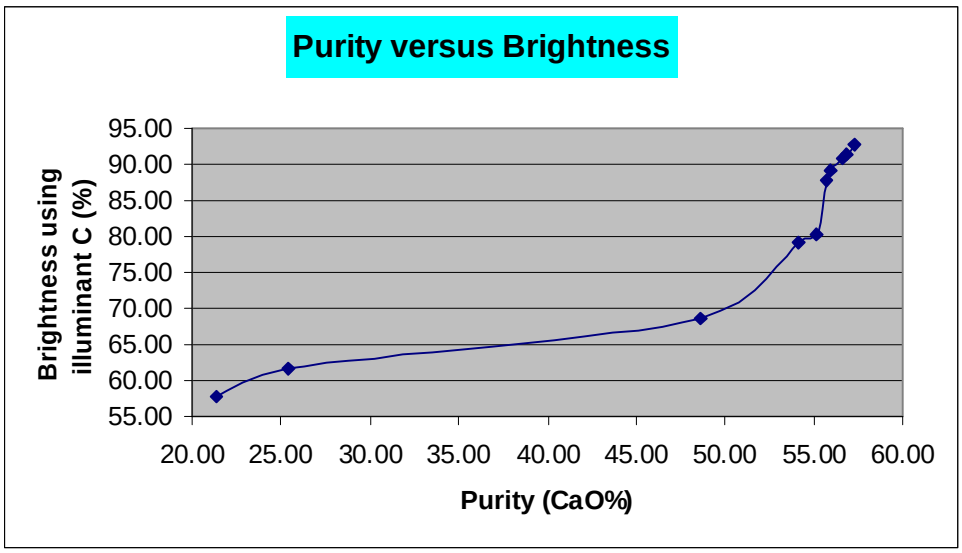

Figure 6: Jabal Farasan marble plot of CaO purity vs. brightness using illuminant C

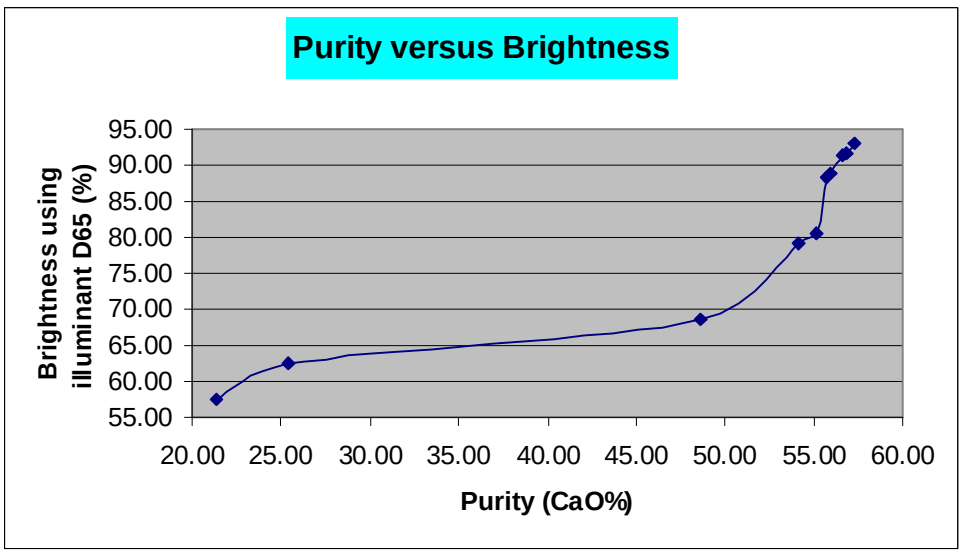

Figure 7: Jabal Farasan marble plot of CaO purity vs. brightness using illuminant D_{65}

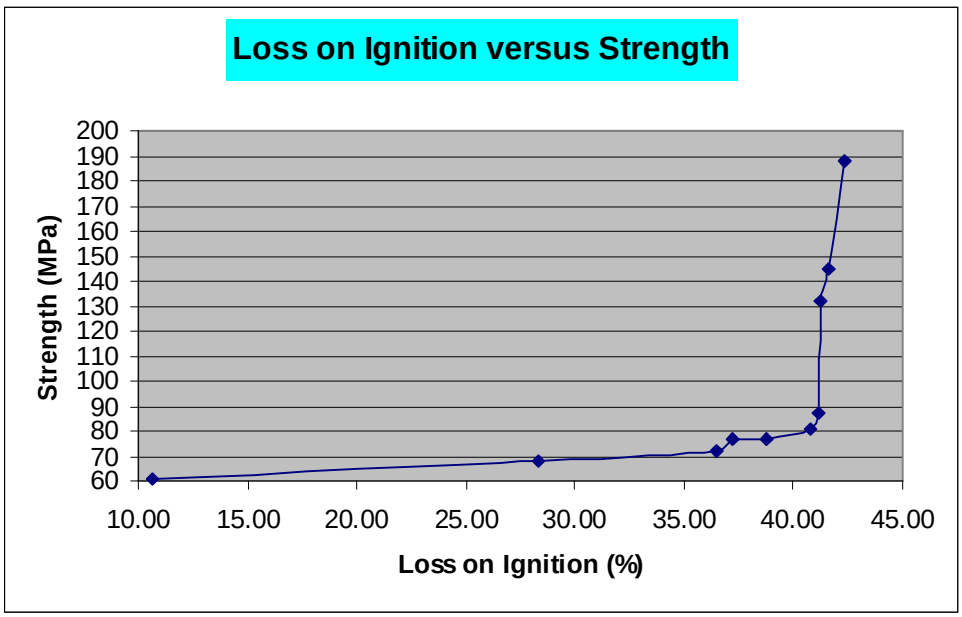

Figure 8: Jabal Farasan marble plot of Loss On Ignition vs. strength

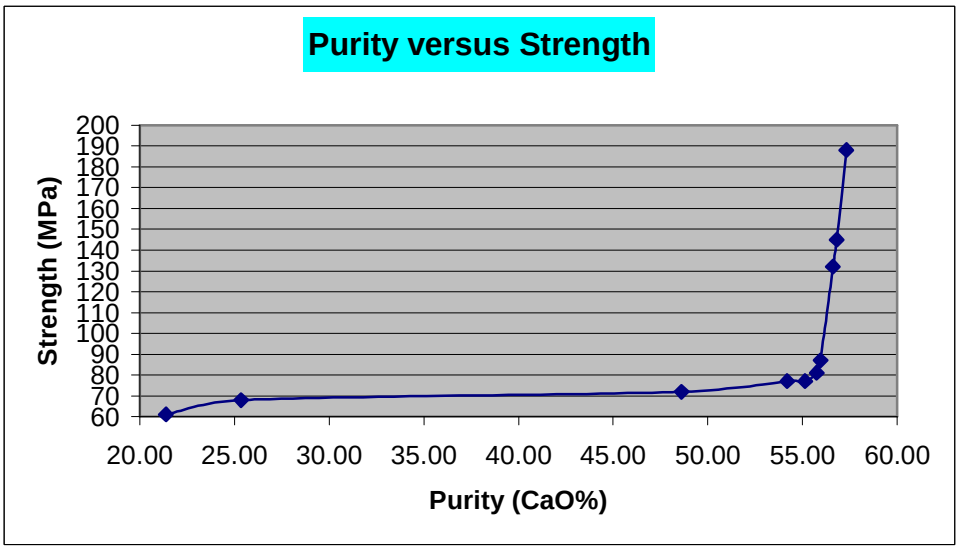

Figure 9: Jabal Farasan marble plot of CaO purity vs. strength

Table 1: **Sample numbering, field nomenclature and exact locations of Jabal Farasan marbles**

Sample Number	Field Nomenclature of Marble Varieties	Geographic Co-ordinates
JF4	Very light grey marble with grey spots	22 32’ 29” N, 39 23’ 49” E
JF5	Light grey marble with grey spots	22 32’ 29” N, 39 23’ 49” E
JF6	White marble (pure)	22 32’ 29” N, 39 23’ 49” E
JF9	White marble with black veinlets	22 30’ 40” N, 39 22’ 59” E
JF10	Deep grey or black marble	22 31’ 03” N, 39 23’ 24” E
JF12	Silicified light grey marble	22 31’ 55” N, 39 22’ 30” E
JF13	Silicified white marble	22 31’ 28” N, 39 23’ 18” E
JF17	Deep grey or black marble	22 31’ 11” N, 39 22’ 48” E
JF18	Deep grey or black marble	22 31’ 30” N, 39 22’ 42” E
JF20	Stripped marble (black & white)	22 31’ 48” N, 39 22’ 36” E

Table 2: Mineralogical characteristics of four marble classes at Jabal Farasan *

Petrographic Name	Sample Number	Major	Minor	Trace
Pure Marble & Slightly Graphitic Marble	JF 4	Calcite	Quartz	---
	JF 9	Calcite	Talc-Chlorite	---
	JF 13	Calcite	Dolomite-Quartz	---
Graphitic Marble	JF 10	Calcite	Graphite-Quartz	Dolomite
	JF 12	Calcite	Quartz-Graphite	---
	JF 17	Calcite	Quartz	Graphite
	JF 18	Calcite	Graphite	---
Diopside Marble	JF 5	Calcite	Diopside	Tremolite
Tremolite Marble	JF 6	Calcite	Tremolite	---
	JF 20	Calcite	Tremolite-Quartz	---

* Data of this table are based on XRD analysis and microscopic investigation

Table 3: XRF analyses of Jabal Farasan marbles

Sample No.	Fe_2O_3	TiO_2	CaO	K_2O	SiO_2	Al_2O_3	MgO	Na_2O	MnO	BaO	S	P_2O_5	Total*
JF4	0.01	0.00	57.32	0.00	0.97	0.04	0.82	0.00	0.00	0.03	0.00	0.03	100.86
JF5	0.00	0.00	55.95	0.00	7.02	0.03	1.26	0.00	0.00	0.02	0.01	0.03	101.50
JF6	0.02	0.00	56.60	0.00	1.32	0.06	1.49	0.00	0.00	0.04	0.00	0.02	100.77
JF9	0.02	0.00	55.14	0.03	7.05	0.08	1.32	0.00	0.00	0.02	0.01	0.20	102.67
JF10	0.01	0.00	48.61	0.00	15.11	0.03	2.87	0.00	0.00	0.03	0.00	0.15	103.28
JF12	0.07	0.05	21.39	0.01	52.04	0.14	12.99	0.00	0.00	0.00	0.00	0.09	97.39
JF13	0.06	0.02	25.36	0.00	23.07	0.27	20.07	0.00	0.00	0.04	0.01	0.87	98.07
JF17	0.02	0.00	54.19	0.00	4.96	0.10	1.15	0.00	0.00	0.04	0.01	0.06	101.71
JF18	0.01	0.00	56.80	0.00	1.11	0.03	1.11	0.00	0.00	0.04	0.01	0.06	101.50
JF20	0.02	0.00	55.74	0.01	4.30	0.08	0.76	0.00	0.00	0.04	0.00	0.01	101.71

* Total including Loss On Ignition values (L.O.I.) given in Table 6

Table 4: Brightness %* and colour parameters of Jabal Farasan marble using two different illuminants (C & D_{65})**

Marble Type	Sample Number	Using illuminant (C)				Using illuminant (D_{65})			
		L	**a**	**b**	**Br %**	**L**	**a**	**b**	**Br %**
Pure Marble & Slightly Graphitic Marble	JF 4	95.58	- 0.26	0.94	**89.06**	95.54	- 0.14	1.01	**88.91**
	JF 9	96.29	- 0.59	0.14	**90.74**	96.60	- 0.74	0.20	**91.48**
	JF 13	96.52	- 0.72	0.46	**91.27**	96.63	- 0.58	0.58	**91.55**
Graphitic Marble	JF 10	80.57	- 0.72	- 0.94	**57.71**	80.38	- 0.96	- 1.10	**57.37**
	JF 12	95.05	- 0.50	1.05	**87.75**	95.30	- 0.61	1.13	**88.34**
	JF 17	86.28	- 0.85	- 1.38	**68.57**	86.37	- 1.26	- 1.29	**68.74**
	JF 18	82.73	- 0.70	- 0.52	**61.66**	83.12	- 0.87	- 0.31	**62.41**
Diopside Marble	JF 5	91.30	- 0.59	- 0.59	**79.16**	91.26	- 0.66	- 0.67	**79.07**
Tremolite Marble	JF 6	97.10	- 0.51	0.46	**92.69**	97.23	- 0.61	0.52	**93.02**
	JF 20	91.80	- 0.69	- 0.64	**80.28**	91.97	- 0.90	- 0.55	**80.65**

* Each value in the table represents an average of four readings

** L= Lightness co-ordinates from 0 to 100, a= red/green co-ordinate (where + ve value indicates red & - ve value indicates green), b= yellow/blue co-ordinates (where + ve value indicates yellow & - ve value indicates blue), and Br % = Brightness percentage.

Table 5: Comparison between the Carrara marble and the white tremolite marble from Jabal Farasan.

Type of Marble	Brightness
Average Carrara White Marble	89.9*
Jabal Farasan White Marble (sample No. JF6) with illuminant C	92.69
Jabal Farasan White Marble (sample No. JF6) with illuminant D_{65}	93.02

* Brightness of average Carrara marble is reported by [13}

Table 6: Loss on ignition data of Jabal Farasan marbles

Sample Number	Loss on Ignition (L.O.I)
JF4	41.62%
JF5	37.19%
JF6	41.23%
JF9	38.79%
JF10	36.46%
JF12	10.61%
JF13	28.29%
JF17	41.17%
JF18	42.32%
JF20	40.74%

Table 7: The average results of the top five readings of the Schmidt hammer rebound test

Sample JF4	Sample JF5	Sample JF6	Sample JF9	Sample JF10	Sample JF12	Sample JF13	Sample JF17	Sample JF18	Sample JF20
38	40	46	44	41	55	52	43	58	45
38	38	39	37	39	52	50	42	57	43
38	34	36	35	39	52	48	41	56	42
37	32	36	34	38	50	48	40	56	40
37	31	36	33	38	49	46	40	55	38
Average									
38	35	39	37	39	52	49	41	56	42

Table 8: The results of Table 7 after transformation into strength units

Sample JF4 MN/cm^2 or Mpa	Sample JF5 MN/cm^2 or MPa	Sample JF6 MN/cm^2 or MPa	Sample JF9 MN/cm^2 or MPa	Sample JF10 MN/cm^2 or MPa	Sample JF12 MN/cm^2 or MPa	Sample JF13 MN/cm^2 or MPa	Sample JF17 MN/cm^2 or MPa	Sample JF18 MN/cm^2 or MPa	Sample JF20 MN/cm^2 or MPa
72	61	77	68	77	145	132	81	188	87
Kg/cm^2	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**	**Kg/cm^2**
734.4	622.2	785.4	693.6	785.4	1479	1346.4	826.2	1917.6	887.4

Table 9: Uniaxial compressive strength of the white marble (JF4)

Specimen No.	Average diameter (mm)	Average Length (mm)	L/D Ratio	Maximum Load at Failure (KN)	Uniaxial Compressive Strength (MPa)
NWZ-1	53.7	114.2	2.13	75.5	33.32
NWZ-2	53.6	115.1	2.15	94.3	41.78
NWZ-3	53.76	112.4	2..09	77.9	34.30

Table 10: Uniaxial compressive strength of the black marble (JF10)

Specimen No.	Average diameter (mm)	Average Length (mm)	L/D Ratio	Maximum Load at Failure (KN)	Uniaxial Compressive Strength (MPa)
NE3-1	53.77	110.43	2.054	139.8	61.54
NE3-2	53.72	120.98	2.25	211.9	93.45
NE3-3	53.63	112.96	2.11	171.9	76.07

Table 11: Point-load strength index of the white marble (JF4)

Specimen No.	Average diameter (mm)	Maximum Load at Failure (KN)	Point Load Strength Index (MPa)	Uniaxial Compressive Strength (MPa)
NWZ-1	53	2.8	0.997	23.92
NWZ-2	53	5.2	1.85	44.43
NWZ-3	53	3.3	1.175	28.2
NWZ-4	53	4.8	1.71	41.01

Table 12: Point-load strength index of the black marble (JF10)

Specimen No.	Average diameter (mm)	Maximum Load at Failure (KN)	Point Load Strength Index (MPa)	Uniaxial Compressive Strength (MPa)
SF1	53	3	1.068	25.63
SF2	53	6	2.14	51.26
SF3	53	4.2	1.5	35.88
SF4	53	5	1.78	42.72

Table 13: Water absorption measurements of Jabal Farasan marble

Sample number	Weight of dried specimen (A) in grams	Weight of specimen after immersion (B) in grams	Water absorption [(B-A) / A] x 100 in %
JF4	478.00	478.36	0.07
JF12	516.22	518.18	0.43
JF13a	461.94	466.19	0.90
JF13b	444.42	449.77	1.20
JF17	541.14	541.32	0.03
JF18	536.63	537.18	0.10

Table 14: Measurements of bulk specific gravity of Jabal Farasan marble

Sample Number	Weight of dried specimen (A) in grams	Weight of soaked and surface-dried specimen in air (B) in grams	Weight of soaked specimen in water (C) in grams	Bulk specific gravity A / (B-C) in g/cm^3
JF4	478.00	478.36	295.22	2.61
JF12	516.22	518.18	326.25	2.68
JF13a	461.94	466.19	282.70	2.68
JF13b	444.42	449.77	266.13	2.42
JF17	541.14	541.32	335.20	2.62
JF18	536.63	537.18	331.30	2.61

Table 15: Comparison between the means of the bulk specific gravity and water absorption of Jabal Farasan marble and that of some known Indian marble deposits*

Type of Marble / Properties	Indian marbles					Jabal Farasan Marble (average)
	Zarci Imperial	***Rosa Valencia***	***Lago Rosa***	***Negro Marquina***	***Amarillo BM***	
Bulk specific gravity (g/cm^3)	2.66	2.79	2.45	2.69	2.75	2.59
Water absorption %	0.30	0.10	0.46	0.17	0.60	0.34

* Data source for comparison as in [18] and [19].

Table 16: Comparison between the means of the bulk specific gravity and water absorption of Jabal Farasan marble and that of some known Spanish marble deposits*

Type of Marble / Properties	Spanish marbles					Jabal Farasan Marble (average)
	Makrana	***Keshariyaji Green***	***Morwadn Rajnagar***	***Agaria Rajnagar***	***Phalodi***	
Bulk specific gravity (g/cm^3)	2.68	2.66	2.84	2.84	2.62	2.59
Water absorption %	0.04	0.07	0.06	0.04	0.64	0.34

* Data source for comparison as in [20].