Lithology, physical and mechanical characterization of Chinese Porphyry

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Abstract. A thorough characterisation of porphyry from China (Province of Fujian) was made, regarding three chromatic variants: red, brown and grey. The properties object of study are: petrographic, chemical and mineralogical analysis, real and apparent density as well as open and total porosity, water absorption at atmospheric pressure, resistance to salt crystallization, rupture energy, compressive strength, flexural strength, abrasion resistance and slip resistance. The achieved results remain in the expected ones for this kind of stone. Nevertheless, small differences were found according to the colour of the sample. Finally, those properties which are covered in the CE marking were compared with the representative values of commercial samples from countries as Italy, Argentina and Mexico.

1. Introduction
The technology development has enabled the production of new type of materials and handling techniques of natural stone. Historically, natural stone has been used for making tools and other equipment, as well as ornamental carving in buildings and monuments, some of them quite relevant as (EXAMPLES). At present, main use of natural stone remains as construction material, because of its resistance and durability [1].

Porphyry is a clear example of this; because of the natural beauty and its good physical-mechanical properties, it has been used from the most ancient civilisations (Assyrian, Babylonian, Egyptian and Roman) to present [2,3]. For instance, the oldest known example of porphyry is a bust dating back to the Egypt dynasty XXVI (664-525 a. C.) [4].

The earliest known porphyry quarries are found in the mountains of the Red Sea, Egypt, known as Mons Porphyrites [5]. The most intensive extraction took place under the Roman Empire, between the first and the end of the fifth century [6], even though other authors suggest that the quarries could have been abandoned in the middle of the fourth century [4,7].

The word “porphyry” comes from the Greek “πορφύρα porphúra” which means purple, considered to be the colour of royalty in the past [8]. It is precisely its unique colour the reason for its high price, being a symbol of prestige and imperial status. Hence, it was known as “Imperial Porphyry” in the past, being its use exclusively reserved for the imperial court [9].

This type of natural stone is not very abundant, being the deposits located in Italy, Argentina, Iran, Ukraine, China, Australia, Mexico, Morocco and Bulgaria the ones where some of the best known commercial varieties of porphyry come from [10]. Of these, Italy is where the porphyry with the highest relevance is mined, known as “Trentino Porphyry”. Its name comes from the fact that it is produced in
the Trentino-Alto Adige region. It has such a historical significance that it has been nominated as Global Heritage Stone Resource (GHSR). This nomination seeks international recognition of those natural stone resources that have been widely used and have a special meaning for human culture [11].

While in the past porphyry was used for sculpting statues and busts, sarcophagi or as an architectural element [12], at present, due to the different production techniques available, this material has numerous uses: cobbles (cubes), tiles, irregular plates or slabs, curbs, ash-lars, steps and copings, and finishes; sawed-off, semi-polished, polished or flamed [13].

In the majority of its uses it is classified as construction material, according to factors such as its size and shape as well as the type of implementation, there is a harmonised standard that dictates the requirements to be complied with its implementation. Just like any other natural stone, the implementation of porphyry as a construction material has to meet the needs and requirements appointed in the rules and regulations of the sector.

To have an in-depth knowledge of the technical properties of porphyry it is especially relevant in the field of heritage restoration and preservation. It is also necessary to carry out the Declaration of Performance outlined in the CE marking, obligatory to commercialise the product within the European Union.

2. Materials and methods

2.1. Materials

The porphyry samples under study were mined in China, specifically in the province of Fujian, and were supplied by a local dealer, which in turn imports them. The study has been carried out regarding three chromatic variants: grey, brown and red.

![Figure 1. Texture and colours variants of porphyry. Scale in cm. (a) Grey (PGR), (b) Brown (PBR), (c) Red (PRD).](image)

In general terms and from a geological point of view, porphyry is a variety of igneous rock composed of coarse-grained crystals (phenocrysts) dispersed in a matrix of fine, feldspathic grain. It is classified as Ignimbrite and its composition is mostly rhyolitic, and can reach dacitic or trachydacitic.

2.2. Lithological characterization

2.2.1. Petrographic analysis. In accordance with the UNE-EN 12407 standard. Thin sheets used have dimensions of 33 mm x 20 mm and a thickness of 0.030 ± 0.005 mm [14].
2.2.2. *X-Ray Fluorescence (XRF) - Chemical analysis*, carried out by Activation Laboratories Ltd. (Canada) with ISO/IEC 17025 and CAN-P-1579 accreditation for mineral analysis. For chemical composition by XRF, the samples were previously pulverized.

2.2.3. *X-Ray Diffraction (XRD) – Mineralogy analysis*, carried out by SIDIX from SEGAI of La Laguna University with Panalytical X’Pert equipment Powder Diffraction (Cu Kα radiation).

2.3. Physical properties

2.3.1. *Real density and apparent density, and total and open porosity*. According to the UNE-EN 1936 standard, apparent density and open porosity are determined by vacuum absorption of water hydrostatic weighing. Six cubic specimens (edges measuring 50 mm) were taken [15]. In order to determine the real density and total porosity, a single specimen was chosen at random from the set of six.

2.3.2. *Water absorption at atmospheric pressure*. This property was measured according to the UNE-EN 13755 standard. Six cubic specimens were used (edges measuring 50 mm) [16].

2.3.3. *Resistance to salt crystallisation*. This test was carried out in accordance with the UNE-EN 12370 standard. Six cubic specimens were used (edges measuring 40 mm) [17].

2.4. Mechanical properties

2.4.1. *Rupture energy*. Specifications in accordance with UNE-EN 14158. Six prismatic specimens were used, with dimensions 200x200x30 mm [18].

2.4.2. *Uniaxial compressive strength*. This test was carried out in accordance with the UNE-EN 1926 standard. A total of 10 cubic geometry specimens (50 mm edge) were tested. Compression surfaces were treated in order to ensure the uniform application of the load to flat parallel surfaces [19].

2.4.3. *Flexural strength*. This test was done according to the UNE-EN 12372 standard. Sets of ten parallelepipedic specimens (180x60x30 mm) were tested for each sample [20].

2.4.4. *Abrasion resistance*. The corresponding standard is UNE-EN 14157, for six specimens (100x100x20 mm) [21]. Note that a coating was applied to the test surface to make visible the footprint and subsequent measurement.

2.4.5. *Slip resistance*. Included in the UNE-EN 14231 standard. This test requires six specimens per sample, measuring 200x200x30 mm [22]. The samples tested present a sawn finish.
3. Results and discussion

3.1. Lithological characterization

3.1.1. Petrographic analysis.

Table 1. Petrographic analysis results for porphyry.

| Petrographic description     | Optical Microscopy |
|------------------------------|--------------------|
|                              | (a) crossed nicols | (b) parallel nicols |
| Grey Porphyry (PGR)          | ![Image](image1.png) | ![Image](image2.png) |
| Porphyritic rock with quartz, plagioclase and alkali feldspar with partial transformation to sericite, heavily chloritized biotite and hornblende. Scarce metals (opaque). Microcrystalline quartz-feldspathic matrix. Quartz-feldspathic porphyry. |
| Brown Porphyry (PBR)         | ![Image](image3.png) | ![Image](image4.png) |
| Brownish rock with serial porphyritic texture. Visible quartz, plagioclase, cloudy alkali feldspar (altered). Occasionally biotite and metals (opaque). Indistinguishable microcryptocrystalline matrix. Chlorite formation and sericitization in feldspars. Quartz-feldspathic cataclasite. |
| Red Porphyry (PRD)           | ![Image](image5.png) | ![Image](image6.png) |
| Reddish rock. Similar to the Brown Porphyry, but with stronger alteration in micas and feldspars. Fibrous-radiated forms of ferric oxide-hydroxide. Biotite transformed to ferric complexes. Unaltered quartz. Quartz-feldspathic cataclasite. |

3.1.2. X-Ray Fluorescence (XRF) - Chemical analysis

Table 2. Chemical composition of porphyry (weight %).

| Sample | SiO₂ | Al₂O₃ | Fe₂O₃(T) | MnO | MgO | CaO | Na₂O | K₂O | TiO₂ | P₂O₅ | LOI | Sum  |
|--------|------|-------|----------|-----|-----|-----|------|-----|------|------|-----|------|
| PGR    | 70,61| 14,50 | 3,13     | 0,07| 0,62| 2,18| 3,21 | 4,60| 0,38 | 0,08 | 0,28| 99,67|
| PBR    | 67,97| 15,91 | 3,41     | 0,07| 0,58| 2,63| 3,71 | 4,74| 0,47 | 0,10 | 0,72| 100,30|
| PRD    | 71,59| 13,67 | 2,77     | 0,08| 0,52| 1,32| 3,14 | 4,70| 0,34 | 0,08 | 1,81| 100,00|
3.1.3. X-Ray Diffraction (XRD) – Mineralogical analysis

Mineral legend: Quartz “○”, Orthoclase “✤”, Albite, calcian, ordered “△”, Phlogopite (Fe-rich) “ الإسلامي”, Potassium tecto-alumotrisilicate “◆”, Sodium tecto-alumotrisilicate “●”, Merlinoite “◆”, Hematite “◇”, Muscovite “★”, Bytownite “☆”, Tamarugite “△”.

Figure 2. TAS Diagram.

Figure 3. Diffractogram. (a) Grey porphyry (PGR), (b) Brown porphyry (PBR), (c) Red porphyry (PRD).
3.2. Physical properties

3.2.1. Real density and apparent density, and total and open porosity.

All the analysed samples have similar real and apparent density, close to 2.7 g/cm³. In contrast, more significant differences are observed in open and total porosity. For the brown porphyry and the red porphyry samples, an open porosity of 0.82 and 0.85 %, respectively, was obtained, almost twice the open porosity obtained for the grey porphyry. The difference among the obtained results for total porosity is even more remarkable, although in this case, it is the brown porphyry the sample that has a much lower total porosity, 0.12 %, compared to the grey and the red porphyries, 1.06 % and 1.52 % respectively.

3.2.2. Water absorption at atmospheric pressure.

Water absorption at atmospheric pressure is a property that depends on porosity and density, mainly apparent density. A priori, it is reasonable to expect that samples with lower apparent density and higher porosity will have higher absorption. However, it can be observed that the obtained results do not follow exactly this premise. In contrast, focusing only on porosity values, it was expected that the samples studied would show low absorptions. The sample which has the highest absorption is the red porphyry, 0.4 % followed by the brown porphyry, 0.3% and the grey porphyry, 0.2 %, with a difference of almost 0.1 % among them.

3.2.3. Resistance to salt crystallisation.

All analysed samples have lost mass after subjecting them to 15 cycles. In the case of the grey porphyry and the brown porphyry it is practically negligible, only 0.03 % on average. The loss is more significant when it comes to the red porphyry, 0.3 %, even though it is still a low value. After a visual analysis of the samples at the end of the test, no fluorescence or surface deterioration were observed.

Table 3. Physical properties results summary.

|                           | PGR  | PBR  | PRD  |
|---------------------------|------|------|------|
| Real density [g/cm³]      | 2.67 | 2.66 | 2.65 |
| Apparent density [g/cm³]  | 2.64±0.00 | 2.65±0.01 | 2.61±0.00 |
| Open porosity [%]         | 0.42±0.00 | 0.82±0.00 | 0.85±0.00 |
| Total porosity [%]        | 1.06 | 0.12 | 1.52 |
| Water absorption at atmospheric pressure [%] | 0.16±0.02 | 0.27±0.01 | 0.39±0.02 |
| Resistance to salt crystallisation [%] | -0.02±0.01 | -0.04±0.02 | -0.32±0.06 |

3.3. Mechanical properties

3.3.1. Rupture energy.

The samples of the grey porphyry (6.4 J) and the red porphyry (6.2 J) have a quite similar rupture energy, being the ones that require more energy to fracture, occurring at an average height of 635 mm. The brown porphyry is the sample requiring the lowest energy to fracture (5.2 J), meaning in terms of sphere drop height an average value of 520 mm.
3.3.2. **Uniaxial compressive strength.**

The three porphyry samples studied have a high compressive strength. The grey porphyry is the sample where a lower strength was obtained: 123 MPa. The brown porphyry has the highest compressive strength: 166 MPa, followed by the red porphyry with a strength of 147 MPa. It should be noted that this test a substantial deviation in the results occurred; while for the grey and red porphyry the deviation is 20 MPa, in the brown porphyry it rises to 40 MPa.

3.3.3. **Flexural strength.**

The result obtained in bending strength tests bear a certain relationship to those achieved in the compressive strength tests, to such an extent that again the samples with the highest and lowest resistance, 28 MPa and 18 MPa, were the brown porphyry (PBR) and the grey porphyry (PGR) samples, respectively. The strength of the red porphyry (PRD), 27 MPa, falls very close to the maximum. In fact, taking into account the standard deviation, we could conclude that the brown porphyry (PBR) and the red porphyry (PRD) have practically the same flexural strength.

3.3.4. **Abrasion resistance.**

With respect to abrasion resistance, it should be noted that bigger the footprint, lower the resistance. In this context, the sample showing the highest abrasion resistance is the brown sample (PBR), with an average footprint of 12.2 mm. The red porphyry (PRD) has a very similar behaviour, with an average footprint of 12.6 mm, while the grey porphyry (PGR) is the sample with lowest resistance, associated to an average footprint of 13.7 mm.

3.3.5. **Slip resistance.**

The grey porphyry (PGR), with 97 USRV, is the sample with the highest slip resistance in dry conditions, followed by the brown porphyry (PBR) and the red porphyry (PRD), with 94 USRV and 88 USRV, respectively. The behaviour of the samples in wet conditions differs from dry conditions. In wet conditions, the red porphyry variant (PRD) presents the highest resistance, 76 USRV, followed by the grey porphyry (PGR), 73 USRV, and the brown porphyry (PBR), 68 USRV. It should be noted that the red porphyry (PRD) is the sample with the smallest difference between both conditions, about 12 USRV, while in the rest, the difference is close to 25 USRV.

**Table 4. Mechanical properties results summary.**

|                          | PGR     | PBR     | PRD     |
|--------------------------|---------|---------|---------|
| Rupture energy [J]       | 6.44 ±0.35 | 5.15 ±0.75 | 6.15 ±0.66 |
| Uniaxial compressive strength [MPa] | 122.86 ±18.49 | 166.11 ±38.87 | 146.70 ±20.34 |
| Flexural strength [MPa]  | 17.62 ±1.51 | 27.99 ±1.88 | 27.21 ±4.52 |
| Abrasion resistance [mm] | 13.73 ±0.40 | 12.22 ±0.20 | 12.58 ±0.27 |
| Slip resistance (Dry conditions) [USRV] | 97.1 ±1.02 | 94.2 ±4.08 | 87.9 ±1.02 |
| Slip resistance (Wet conditions) [USRV] | 72.9 ±2.92 | 68.3 ±2.04 | 75.8 ±1.29 |
4. Conclusions

The lithological characterisation carried out in this study has provided detailed information on the chemical and mineralogical composition of the analysed samples, establishing that the grey and the red porphyry variants are rhyolitic ignimbrites, while the brown porphyry belongs to the trachydacite group. The physical characterisation has revealed that the chromatic variants have very similar properties, finding the most notable differences in the open and total porosity. It was in the mechanical properties where the most remarkable differences between the samples were detected. Excluding the Rupture Energy, where the difference is less significant, in the rest of the tests it can be seen that the behaviour of the samples is more diverse. The largest difference among the chromatic varieties studied was observed in the Compressive Strength.

To conclude, in table 5 it is presented a comparative of the properties obtained in this study with the data found in several bibliographical sources for porphyry extracted in Italy, Argentina and Mexico. It should be noted that the properties of the Chinese porphyry shown in this table correspond to the average values of the grey and the red chromatic variety, for which reason the comparison is made on the basis of the same petrographic classification, rhyolitic ignimbrite in all cases. Furthermore, in the consulted references no noticeable differences were found on the properties according to the chromatic variant of the samples.

| Table 5. Comparison of properties between porphyries. |
|--------------------------------------------------------|
| China | Italy | Mexico | Argentina |
| Apparent density [g/cm³] | 2.63 | 2.56 | 2.56 | 2.57 |
| Water absorption at atmospheric pressure [ %] | 0.28 | 0.50 | 6.53 | 0.36 |
| Uniaxial compressive strength [MPa] | 135 | 205 | 222 | 115 |
| Flexural strength [MPa] | 22.4 | 27.3 | 22.5 | 22.5 |
| Abrasion resistance [mm] | 13.2 | 11.5 | 1.51 | 0.77 |

*^a^ According to article 11 of R.D. 2232 of 16.11.1939 and the norm CNR of 1953. Resistance to abrasion, relative value with reference to the S. Fedelino granite.

*^b^ According to norm ASTM C241. Dorry machine wear resistance (mm/1000 m)

Acknowledgments

Thanks go to the “Área de Laboratorio y Calidad de la Construcción del Gobierno de Canarias” for their collaboration in the execution of the tests, and to the “Mármoles Gestoso S.L” quarry for providing the necessary samples in order to carry out this study. The X-Ray Fluorescence tests were financed through the Nuclear Safety Council PR32960 “Radon emission in the volcanic materials of the Canary Islands. Implications for residential infrastructures and public works” project. This research was supported by the Ministry of Science, Innovation and Universities of Spain, through the pre-doctoral contract of the first author (FPU1605739).

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