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Properties of the volcanic rocks from Canary Islands (Spain) used as breakwater material

Propiedades de las rocas volcánicas de Canarias (España) utilizadas como material de escollera

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ABSTRACT

In the Canary Islands, there is a wide spectrum of volcanic rocks with different properties to be used in public works. The aim of this study is to analyse the physical-mechanical properties of all the volcanic rocks present in the Canary Island archipelago in order to determine their suitability for use in maritime construction works. The great variety of volcanic rocks present on the islands have been grouped into lithotypes based on similar geo-mechanical behaviour. The laboratory test results obtained for these lithotypes establish their suitability or not to be used as breakwater material in accordance with Spanish regulations.

Keywords: volcanic rocks; lithotypes; breakwater; coastal protection; Canary Islands

RESUMEN

En el archipiélago canario existe un amplio espectro de rocas volcánicas con diferentes propiedades para ser utilizadas en obras públicas. El objetivo de este estudio es analizar las propiedades físico-mecánicas de todas las rocas volcánicas presentes en el archipiélago canario con el fin de determinar su idoneidad para ser utilizadas en obras de construcción marítima. La gran variedad de rocas volcánicas presentes en las islas, se han agrupado en litotipos basados en un comportamiento geomecánico similar. Los resultados de los ensayos de laboratorio obtenidos para estos litotipos establecen su idoneidad o no para ser utilizados como material de escollera de acuerdo con la normativa española.

***Palabras clave**: rocas volcánicas; litotipos; escollera; protección de la costa; Islas Canarias*

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1. INTRODUCTION

Maritime works carried out along the insular coasts are numerous and require complex levels of design and construction. Currently, the Canary Islands have 17 ports, 14 harbours and 17 marinas. As a whole, these infrastructures provide entry to most of the goods consumed in the Canary Islands, so their importance and operation is vital to the archipelago. The maritime sector has also been subject to profound changes recently, which have given rise to a new port culture. Factors such as the globalisation of economies has led to an increase in the flow of goods as well as greater demands for quality port services, shorter delivery times and lower costs. There are also demands for greater inter-modality to expand transport alternatives. All these factors have conditioned a new concept of ports and forced them to respond these new market demands by carrying out maritime construction works.

Unfortunately, maritime works in the Canary Islands have been hampered by the difficulty in obtaining natural materials commonly used in such works. Currently, various types of concrete blocks are used, since it is not possible to find natural materials with the necessary weight for sea defence construction. In addition, a lack of geotechnical information on volcanic materials has been the cause of frequent pathologies that seriously affect marine structures, deteriorate their quality and lead, in many cases, to their destruction. In the Canary Islands, the problem is even more serious because of the heterogeneity of volcanic materials and their chaotic spatial distribution. Moreover, despite the fact that the Canary Islands are considered one of the most interesting places in the world from a volcanological point of view (since almost all the volcanic rocks existing on the planet can be found there), it is not an easy task to have them available for use in public works due to the high degree of environmental protection that exists on the island territory. However, in this study, all types of rocks (lithotypes) from the Canary Islands have been analysed, both those commonly used in public works and those traditionally destined for other uses. The aim of this study is to obtain more precise knowledge about the possible use of different lithotypes in maritime works, in accordance with the current Spanish legislation ROM 0.5-05 (1).

Rock armour or armourstone is one of the most common construction materials used on the front line against wave action in coastal protection structures. However, its innate irregularity in geometry poses engineering problems by introducing variability and uncertainty into the final structure (2). Moreover, a common optimisation problem in the design of armour units is the need to choose between hydraulic stability and structural stability (3).

Breakwater structures are a central part of coastal protection and harbour engineering. These structures prevent coastal erosion and ensure safe and functioning ports and harbours (4). There are three loadings that a coastal construction is subjected to: static, hydrodynamic and impact. Static loads are due to unit self-weight and unit-unit wedging. Hydrodynamic loads result from wave action directly on the structure. Impact loads are caused by unit-to-unit collisions instigated by wave-induced rolling and rocking motions (5).

One of the main issues for rock construction projects are their scale (size of the structure and blocks) as well as the availability, quality and handling of materials (6). As we said before, volcanic rocks are not always available for use in construction, because they are sometimes in protected environments where they cannot be extracted.

However, it should be noted that global climate change models predict increases in the sea level, which can lead to higher impact forces on armour units in breakwater structures (7). Therefore, it is extremely worthwhile to check the physical and mechanical characteristics of available rocks.

2. MATERIALS AND METHODS

The Canary Islands are an archipelago belonging to Spain, which is made up of eight islands and five islets, covering an area of approximately 7,500 km^2. They are 1,400 km from the nearest coasts of the European continent (the Iberian Peninsula) and 100 km to the west of the western coast of the African continent (Western Sahara).

Geologically, the most recent hypothesis on the origin of the archipelago of the Canary Islands (8) emerged in the year 2000, establishing the existence, under the Canary Islands, of hot zones associated with a residual thermal plume, active since the beginning of the opening of the Atlantic, 200 Ma ago. From a geochemical point of view, the volcanic rocks of the Canary Islands belong to the alkaline igneous series, in this case, associated with intraplate volcanism. This igneous series is formed by a sequence of rocks whose composition ranges from undifferentiated to represented by basalts to intermediate as represented by trachybasalts and finally, more differentiated or evolved rocks such as trachytes and phonolites.

Silica (SiO_2) is a major component of magmatic rocks present in the earth's crust and can be present as silicate and quartz or only as silicate minerals. It represents more than 90% of the total weight of minerals (to a lesser extent as a percentage by weight). Fe and Ti oxides are also present, as well as calcium phosphate and other minerals. Based exclusively on their SiO_2 content, igneous rocks can be classified as follows (9):

- Acids: >65% SiO_2
- Intermediates: 65 - 52% SiO_2
- Basics: 52 - 45% SiO_2
- Ultrabasics: <45% SiO_2

In order to undertake a geomechanical study of the broad spectrum of volcanic rocks present in the Canary Islands, it has been necessary to simplify them by grouping them into rocks or lithotypes with similar lithological properties and geo-mechanical behaviours. To do this, a simplified classification of volcanic lithotypes of Canary Island volcanic rocks has been used to group them into ten different lithotypes (10) based on the following criteria:

1. Lithological criteria. This is based on the chemical-mineralogical composition of the rocks. In the Canary Island archipelago, the dominant lithology is mostly basaltic in all the islands. Nevertheless, in addition to this material, in Tenerife and Gran Canaria, rocks of intermediate composition (trachybasalts) and salics (trachytes and phonolites) are present in significant proportions. Likewise, the existence of ignimbrites of phonolithic composition with very varied textures is also noteworthy on these two islands.

2. Textural criteria. This is based on the characteristics of volcanic rock-forming minerals, as well as their shapes and sizes. The types of textures present in the different lithological types are defined as follows: aphanitic, porphyritic and trachytic.
3. Void index. This considers the presence or absence of vacuoles in the volcanic rock. In this sense, there are very vacuolar and very massive ones. Undoubtedly, the presence and percentage of vacuoles in a basalt sample substantially conditions the mechanical behaviour of the rock in question and in this sense this third criteria should be considered as a differentiating element of lithotypes.

Therefore, the lithotypes on which this study is focused are the following ten:

Massive aphanitic basalt (MAB); Vacuolar aphanitic basalt (VAB); Massive olivine-pyroxenic basalt (MOPB); Vacuolar olivine-pyroxenic basalt (VOPB); Massive plagioclassic basalt (MPLB); Vacuolar plagioclassic basalt (VPLB); Trachyte (TRC).

For the identification of the rock materials, the corresponding petrographic study of each lithotype was carried out using a thin sheet or section, and for the geo-mechanical characterization, the physical-mechanical tests recommended by the current Spanish regulations (AENOR, Spanish equivalent to ISO Standards) for breakwaters (Figure 1) were performed.

Figure 1. Volcanic breakwater in the Canary Islands

In the Canary Islands at present one hundred rock and soil extraction points are authorised by the Government of the Canary Islands, distributed as follows: 6 in La Palma, 2 in La Gomera, 7 in El Hierro, 15 in Tenerife, 27 in Gran Canaria, 18 in Fuerteventura 18 and 25 in Lanzarote. Of these, 70 corre-spond to quarries of basaltic pyroclasts (lapilli), alluvial depos-its and eolian sands. The remaining 30 are quarries of rock, mostly of a basaltic nature, which could be used as rockfill; these quarries are distributed by island as shown in Table 1.

From the verifications conducted in different quarries, it has been determined that the size of the blocks extracted for use as breakwater ranges from 50 to 200 cm in diameter approximately.

Table 1. Rock quarries for rockfill in the Canary Islands (11)

Island	Exploitation	Lithotype
La Palma	La Caldereta	Basalt
La Gomera	Barranco Hondo	Basalt
La Gomera	Las Toscas	Welded ignimbrite
El Hierro	La Restinga	Basalt
El Hierro	Timijiraque	Basalt
El Hierro	Soliman	Basalt
Tenerife	Guama-Arico	Welded ignimbrite
Tenerife	El Grillo	Unwelded ignimbrite
Tenerife	Archipenque	Basalt
Gran Canaria	Barranco de los Vicentes	Phonolite
Gran Canaria	Mesa de las Cañadas	Phonolite
Gran Canaria	Mesa del Salinero	Phonolite
Gran Canaria	El Cortijo	Phonolite
Gran Canaria	Roque Ceniciento	Basalt
Gran Canaria	Corralete	Phonolite
Fuerteventura	Morro Colorado	Basalt
Fuerteventura	La Lajita	Basalt
Fuerteventura	El Guerepe	Basalt
Fuerteventura	Las Paredejas	Basalt
Fuerteventura	La Antigua	Basalt
Fuerteventura	El Manadero	Basalt
Fuerteventura	Tablero de Las Cristinas	Basalt
Fuerteventura	La Capellanía	Basalt
Fuerteventura	Capellanía II	Basalt
Fuerteventura	Barranco de Barlondo	Basalt
Lanzarote	Los Roferos	Basalt
Lanzarote	Barranco de la Mora	Basalt
Lanzarote	Corral Prieto	Basalt
Lanzarote	Corral de las Camellas	Basalt
Lanzarote	El Volcán	Basalt

3. RESULTS AND DISCUSSION

In the Canary Islands there are practically no quarries that produce breakwaters. The problem is serious on the island of Tenerife, where there is only one legal quarry that only produces aggregates. On this island, the supply of aggregates for concrete and asphalt, as well as rock for rockfill, is obtained from excavations undertaken in public and private works. The materials extracted on site are selected and sent to facilities where they are transformed for their intended use (aggregates or rockfill). On other islands, there are sufficient quarries for the supply of rockfill (Table 1).

The quality breakwater for maritime works is made of basalt; phonolites and trachytes have rarely been used in the outer mantle of breakwaters and dikes. On the eastern coasts of the Canary Islands, the outer layers of breakwaters and jetties can almost always be resolved with natural rockfill (generally basaltic) (12). In contrast, on the north and west coasts, the calculation times are much longer and heavier elements, generally made of concrete, are required (13).

The petrographic study of the lithotypes (14) gave the following results:

Massive and vacuolar aphanitic basalts: Massive (MAB) and vacuolar (VAB) aphanitic basalts are included in this group, since from the petrological point of view, they do not present mineralogical differences and are only distinguished by the content or absence of vacuoles. Lithologically, they are basaltic rocks with aphanitic texture (without visible crystals), generally light grey colour, with a planar fabric which, on occasions, may be marked by the presence of small diaclases with little lateral continuity.

Massive and vacuolar olivine-pryoxenic basalts: Massive (MOPB) and vacuolar (VOPB) olivine-pyroxenic basalts are included in this section, since from a petrological point of view, they do not present mineralogical differences and are only distinguished by the content or absence of vacuoles. The pyroxenic olivine basalts represent one of the most common lithotypes in the Canary Islands. They generally present porphyry texture (large visible crystals), characterised by the existence of olivine and augite phenocrystals encompassed within a microcrystalline matrix of olivine, augite, plagioclase and opaque metallic minerals (mainly magnetite or iron sulphides).

Massive and vacuolar plagioclasic basalts: Massive (MPLB) and vacuolar (VPLB) plagioclassic basalts are in this group, since from the petrological point of view, they do not present mineralogical differences, distinguished only by the content or absence of vacuoles. They are porphyry basalts with a dark grey vitreous matrix with large, elongated plagioclase crystals (white), up to 2 cm long. The presence of microphenocrystals of augite and olivine is also detected under the microscope.

Trachytes (TRC): These are rocks of intermediate chemistry, which are characterized by a typical trachytic texture with visible crystals, mainly sodium-potassium feldspar, pyroxene or amphiboles, encompassed in a matrix of small crystals oriented or randomly arranged of similar nature.

Phonolites (PHON): Phonolites are very massive rocks and with none or few vacuoles. They present typical flow textures with bands of light and dark colour. They can also show a mottled aspect with black and white grains.

Unwelded ignimbrites (UIG): Unwelded ignimbrites are pyroclastic rocks of a trachytic or phonolithic composition, composed of a large proportion of ashes of a light-yellow colour that constitute the matrix of the rock, where fragments of alkaline feldspar, pumice and stone are incorporated.

Welded ignimbrites (WIG): Welded ignimbrites are rocks of pyroclastic origin with a marked flux texture. They have small lithic content of trachytic or phonolithic composition (1-5 cm) and abundant feldspar crystals.

From the petrographic study carried out on these lithotypes, it can be deduced that they do not present any of the excluded minerals specified by the Geotechnical Recommendations for Maritime and Port Works ROM 05.5, such as clay minerals, expansive minerals or soluble minerals.

According to the Guide to good practice for the execution of maritime works (15), it is specified that the classification of breakwaters is done on site in the quarries:

- Quarry run: from 1 kN to 3 kN (100-300 kg)
- Rocks for filter layers of mound breakwaters: from 3 kN to 20 kN (300 kg - 2 Tn)
- Armor layer of mound breakwaters: over 20 kN (2 Tn)

In the quarries, to obtain the dimensions of the breakwaters generated, they measure the diagonal of the cube, obtaining the dimensions shown in Table 2.

Table 2. Diagonal of the cubes as a function of the weight of the breakwater and Length-to-thickness ratio (LT) according to CIRIA 2007 (16). Source: Prepared by the authors

	Volume (m3)	Side a (m)	Diagonal (m) = 1,73205*a	Length Thickness (LT) Ratio
50 Kg, quarry run	0,02	0,27	0,47	1,74
100 Kg, quarry run	0,04	0,34	0,59	1,74
200 Kg, quarry run	0,08	0,43	0,74	1,72
300 Kg, quarry run	0,12	0,49	0,85	1,73
500 Kg, rocks for filter layers of mound breakwaters	0,2	0,58	1	1,72
1 T, rocks for filter layers of mound breakwaters	0,4	0,74	1,28	1,73
2 T, rocks for filter layers of mound breakwaters	0,8	0,93	1,61	1,73
3 T, Armor layer of mound breakwaters	1,2	1,06	1,84	1,74
5 T, Armor layer of mound breakwaters	2	1,26	2,18	1,73

These cubes are not perfect and are fractured by the action of a hydraulic hammer or by explosives, the sizes obtained being very heterogeneous and, therefore, when dimensioning a 100-200 kg protection blanket, according to the table, breakwaters should be chosen whose "diagonal" is between 0.59-0.74 metres. On the other hand, it is very difficult to obtain sizes greater than 5 tonnes to form a homogeneous blanket, so the requirements are obtained by calculation with prefabricated concrete blocks.

For the physical-mechanical rock characterization (17), the current Spanish standard UNE-EN 13383-1:2003 (18) has been chosen. This standard defines breakwaters as granular material used in hydraulic structures and other civil engineering works, also indicating that natural breakwaters are those with a mineral origin that has only undergone mechanical treatment. The UNE-EN 13383-1:2003 establishes different requirements to be met by rocks used in breakwaters, ordering them as follows:

Density of particles: Regulated by Spanish standard UNE EN 13383-2:2003, "Breakwater. Part 2: Test Methods" which indicates that particle density is calculated from the mass to volume ratio of a breakwater component or part thereof.

The average values of mass density of rock that characterize each of the geotechnical lithotypes are given in Table 3 (14):

Table 3. Mass density of rock values of the volcanic lithotypes of the Canary Islands (14)

Mass density of rock (kN/m3)		
Lithotype	**Average**	**Standard deviation**
MOPB	29.2	1.1
VOPB	25.4	1.9
VPLB	25.1	0.6
MPLB	25.1	1.7
VAB	23.4	3.6
MAB	28.4	1.0
TRC	25.2	21.0
PHON	25.5	2.8
UIG	22.0	3.3
WIG	24.7	1.0

The Spanish standard UNE-EN 13383-1:2003 establishes that the value of the particle density of breakwaters must not be less than 23 kN/m^3, therefore, considering the average values of the previous table, the use of VOPB, VAB, UIG and WIG lithotypes for the construction of breakwaters must be rejected.

Armour porosity and the associated packing density are obviously relevant factors affecting breakwater armour hydraulic performance as well as construction cost (19). One of the main reasons why packing density and the associated void porosity are important to coastal engineers, is that they affect hydraulic performance, because of energy dissipation occurring in the voids, which in turn affects wave reflections, stability, run-up and overtopping (2).

Uniaxial Compression Strength (UCS): This test is regulated by the Spanish standard UNE-EN 1926:2007 (20), "Test methods for natural stones. Determination of resistance to uniaxial compression". The average values of UCS for volcanic lithotypes, expressed in MPa, are given in Table 4 (14):

Table 4. Average values of uniaxial compressive strength of volcanic lithotypes in the Canary Islands (14)

Uniaxial compression strength (MPa)		
Lithotype	**Average**	**Standard deviation**
MOPB	114	59.8
VOPB	48	35.7
VPLB	36	14.8
MPLB	61	27.9
VAB	31	16.0
MAB	104	54.8
TRC	95	62.8
PHON	119	76.8
UIG	16	19.5
WIG	48	29.1

The standard UNE-EN 13383-1:2003 indicates that the value obtained in the uniaxial compression test for breakwaters must be classified according to the categories of UCS results: CS80 (≥ 80 MPa), CS60 (≥ 60 MPa) and CS-Declared (declared value less than 60 MPa). Thus, after test results, the lithotypes of Canary Islands are classified as follows (Table 5):

Table 5. Classification of volcanic lithotypes of the Canary Islands according to the categories of resistance to uniaxial compression defined in the declared norm (18)

Lithotype	Category CS (UNE-EN 13383-1:2003)
MOPB	CS80
VOPB	CSDeclared: 48
VPLB	CSDeclared: 36
MPLB	CS60
VAB	CSDeclared: 31
MAB	CS80
TRC	CS80
PHON	CS80
UIG	CSDeclared: 16
WIG	CSDeclared: 48

The Spanish recommendations for the use of rocks in breakwaters establish the following conditions for the results of the uniaxial compression strength:

- The average compressive strength of the series, after removing its minimum value, must be ≥ 80 MPa (SC80)
- At least eight of the ten (8/10) specimens must have a resistance ≥ 60 MPa (SC60)

Wear resistance: The wear resistance of breakwaters is determined in accordance with the Spanish standard UNE EN 1097-1:2011 (21), *"Tests to determine the mechanical and physical properties of aggregates. Part 1: Determination of wear resistance (Micro-Deval)"*. This test defines a reference method for determining the abrasion resistance of coarse aggregates in the presence of water (MDE). It consists of measuring the granulometric evolution of an aggregate fraction between 10 and 14 mms in particle size, which is subjected to

Figure 2. Introduction of the abrasive load (5,000 g of steel balls) in the Micro-Deval cylinder

the abrasion of a load of steel balls (Figure 2), in the presence of water, produced in a rotating cylinder under well-defined conditions. The results obtained using this standard are contained in Table 6.

Table 6. Values of the Micro-Deval coefficient of volcanic lithotypes of the Canary Islands

Lithotype	Coefficient Micro-Deval (MDE)
MOPB	12.0
VOPB	29.4
VPLB	15.7
MPLB	12.5
VAB	13.5
MAB	11.4
TRC	23.1
PHON	8.7
UIG	77.1
WIG	29.6

The Spanish standard UNE-EN 13383-1:2003 establishes a classification for categories of rockfill aggregates based on their Micro-Deval coefficient (Table 7):

Table 7. Classification of volcanic lithotypes of the Canary Islands according to the categories for wear resistance requirements defined in the standard UNE-EN 13383-1:2003 (18)

Lithotype	Category MDE (UNE-EN 13383-1:2003)
MOPB	MDE20
VOPB	MDE30
VPLB	MDE20
MPLB	MDE20
VAB	MDE20
MAB	MDE20
TRC	MDE30
PHON	MDE10
UIG	MDEDeclarado: 76,9
WIG	MDE30

- MDE10 category: Very strongly abrasive environment (seas with frequent storms with interaction of boulder structures, fluvial torrents, dynamic breakwater design concept, etc.)
- MDE20 category: Strongly abrasive environment (seas with occasional storms with sandy or pebble sand beaches)
- MDE30 category: Moderately abrasive environment (occasional wave action or the action of sediment loaded currents)

Water absorption: This test is used as a selection criterion for ice-thaw resistance and salt crystallization. It is determined, in accordance with chapter 8 of the Spanish standard UNE-EN 13383-2:2003 *"Breakwater. Part 2: Test Methods"*, starting from the procedure described for the determination of particle density, weighing the test sample under the condition of surface drying and saturation, and again under the condition of drying in the oven.

The average values of water absorption that characterize each of the geotechnical lithotypes are given in Table 8:

Table 8. Average water absorption values obtained for each of the volcanic lithotypes of the Canary Islands (14)

Water absorption (%)		
Lithotype	**Average**	**Standard deviation**
MOPB	1.33	0.839
VOPB	5.86	5.942
VPLB	2.46	0.281
MPLB	1.60	0.415
VAB	5.66	5.750
MAB	1.23	0.335
TRC	2.00	1.308
PHON	1.10	0.522
UIG	15.98	12.110
WIG	6.52	3,823

In accordance with the UNE-EN 13383-1:2003 standard, given the results obtained in the absorption test, rock for rockfill is considered to be resistant to freeze-thaw and salt crystallization when the absorption value is less than or equal to 0.5%. As can be seen in the table above, volcanic rocks have average water absorption values higher than 0.5% and only some lithotypes (some massive basalts, trachytes and phonolites) reach values lower than that figure. Therefore, in most cases, it will be necessary to carry out salt crystallization and ice-thaw tests.

Sonnenbrand: Sonnenbrand is a type of rock disintegration that may be present in some basalts and which manifests under the influence of atmospheric conditions. The sign of Sonnenbrand begins with the appearance of grey/white star-shaped spots. Under normal conditions, the cracks generated extend radially from the spots and interconnect with each other. This reduces the mechanical strength of the mineral structure, and as a result, the rock disintegrates into small particles. Depending on the source, this process can take place months after extraction or extend over several decades. In exceptional cases, rapid disintegration leads to the formation of large cracks and the breaking up of aggregate or rockfill particles. In the laboratory, the Sonnenbrand signs of basalts can be determined following the procedure described in the Spanish standard UNE-EN 13383-2:2003. This phenomenon was not observed in the analysed samples.

In addition to the classification of the UNE-EN 13383-1:2003 standard (18), the CIRIA Rock Manual for the use of rock in hydraulic engineering (16) classifies rocks into four categories according to their properties and suitability for use as rockfill: excellent, good, marginal and poor. Based on the results obtained in the tests carried out on the different lithotypes of the Canary Islands, these have also been classified according to CIRIA specifications (Table 9).

Therefore, according to the CIRIA Rock Manual, without taking into account the design and site conditions, a tentative interpretation can be made about the tributes as rockfaces of the Canarian lithotypes. A priori, MOPB, MPLV, MAB, TRC and PHON, i.e. massive rocks without vacuoles, can be considered as "good".

Table 9. Classification of the lithotypes of the Canary Islands according to CIRIA (21). (*) Taken from Hernández-Gutiérrez (14).

Lithotype	Sonic velocity (km/s) (*)	Mass density (t/m³)	Water absorption (%)	Compressive strength (MPa)	Micro-Deval (% loss)
MOPB	(5.04) Good	(2.92) Excellent	(1.33) Good	(114) Good	(12.0) Good
VOPB	(4.43) Marginal	(2.54) Good	(5.86) Marginal	(48) Poor	(29.4) Marginal
VPLB	(3.05) Marginal	(2.51) Good	(2.46) Marginal	(36) Poor	(15.7) Good
MPLB	(4.07) Marginal	(2.51) Good	(1.60) Good	(61) Marginal	(12.5) Good
VAB	(3.82) Marginal	(2.34) Marginal	(5.66) Marginal	(31) Poor	(12.0) Good
MAB	(4.75) Good	(2.84) Excellent	(1.23) Good	(104) Good	(29.4) Marginal
TRC	(4.49) Marginal	(2.52) Good	(2.00) Good	(95) Good	(15.7) Good
PHON	(4.86) Good	(2.55) Good	(1.10) Good	(119) Good	(12.5) Good
UIG	(2,59) Poor	(2.20) Poor	(15.98) Poor	(16) Poor	(13.5) Good
WIG	(3.65) Marginal	(2.47) Marginal	(6.52) Poor	(48) Poor	(11.4) Good

4. CONCLUSIONS

In the Canary Islands we can find a wide spectrum of the possible volcanic rocks that can be found on the planet. These have been classified into groups of similar characteristics (lithotypes) and have been studied in accordance with the guidelines of the current Spanish regulations for rockfill (UNE-EN 13383-2:2003) and of the most popular international references for the use of rocks in coastal structures, the CIRIA Rock Manual. The results of the study show that there are a number of volcanic lithotypes that are suitable for use as breakwaters for the most demanding performances.

Regarding mineralogical composition, the lithotypes analysed do not present any of the excluded minerals established by the Spanish Geotechnical Recommendations for Maritime and Port Works.

Concerning the physical-mechanical test results, the following conclusions can be drawn for the use of the volcanic lithotypes as breakwater rocks:

- Particle density test results show that VOPB, VAB, UIG and WIG lithotypes must be rejected, because they have values lower than 23 kN/m³, while MOPB, VPLB, MPLB, MAB, TRC and PHON lithotypes are appropriate.
- Regarding the uniaxial compression strength, the lithotypes that exceed the reference value of 80 Mpa, stablished by Spanish regulations, were the following: MOPB, MAB, TRC and PHON.
- Wear resistance test (Micro-Deval) results indicate that lithotypes can be classified for different sea conditions: PHON is suitable for very strongly abrasive environment; MOPB, VPLB, MPLB, VAB and MAB are appropriate for strongly abrasive environment; VOPB, TRC and WIG can be used in moderately abrasive environment.
- Usually, volcanic lithotypes have water absorption values higher than 0.5%, for this reason, in most cases it will be necessary to carry out salt crystallization and ice-thaw tests.

In the case of the island of Tenerife, one of the coastal areas of the island “San Andres” (22), which has traditionally presented problems due to marine flooding, has basalt defense slopes, as well as the fishing dock and the beach of Las Teresitas. Something similar occurs on the island of Gran Canaria (23), where in the most sensitive coastal areas basalt has also been chosen as a construction material for maritime defense.

As a general conclusion on the suitability of the use of volcanic rocks from Canary Islands (Canarian lithotypes) as rockfill or rock armour, it can be stated that the group of basalt, in their massive forms (MAB, MOPB and MPLB), and the trachytes (TRC) and phonolites (PHON) manifest acceptable physical-mechanical properties, although given the variability within the same lithotype, it will be necessary to carry out the mandatory tests indicated by the current regulations.

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