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Article

Physical-mechanical characterization of the limestone rocks of the Mary Carmen Bank in Seybaplaya, Campeche, Mexico: Implications for the construction and conservation of built heritage

Caracterización físico-mecánica de las rocas calizas del banco Mary Carmen en Seybaplaya, Campeche-México: Implicaciones para la construcción y conservación del patrimonio edificado

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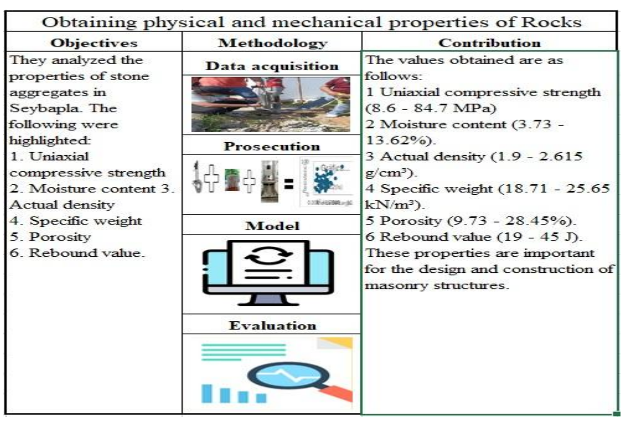
Abstract

The properties of rock aggregates in Seybaplaya, Campeche, Mexico were analyzed, highlighting their uniaxial compressive strength [8.6 - 84.7 MPa], moisture content [3.73 - 13.62 %], real density [1.9 - 2.615 g/cm³], specific weight [18.71 - 25.65 kN/m³], porosity [9.73 - 28.45 %], and rebound value [19 - 45 J], emphasizing the importance of these properties for the design and construction of masonry structures.



Simple uniaxial compressive strength, Moisture content, True density, Porosity and surface area in rocks

Resumen

Se analizaron las propiedades de agregados pétreos en Seybaplaya, Campeche, México, destacando su resistencia a la compresión uniaxial [8.6 - 84.7 MPa], contenido de humedad [3.73 - 13.62 %], densidad real [1.9 - 2.615 g/cm³], peso específico [18.71 - 25.65 kN/m³], porosidad [9.73 - 28.45 %] y valor de rebote [19 - 45 J], lo que resalta la importancia de estas propiedades para el diseño y construcción de estructuras de mampostería.

Resistencia a la compresión uniaxial simple, Contenido de humedad, Densidad real, Porosidad y área superficial en roca

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Introduction

Rocks are formed by hard, compact natural aggregates composed of mineral particles bound together by strong permanent cohesive bonds, making them generally continuous systems. The proportion of minerals, granular structure, texture and origin of the rock are key characteristics used in its geological classification [González, 2002]. All built heritage stands on soil or rock, and every construction project requires the use of stone aggregates, with rocks being the essential raw material for this purpose. It is therefore crucial to take their characteristics into account, as they are fundamental to ensuring structural stability and durability from the foundations up [Naal-Pech, 2023]. In the Yucatan Peninsula, the predominant rock material is limestone, which is inexpensive to extract and has physical and mechanical properties that make it an excellent building material. However, limestone is subject to chemical and physical alterations that can modify both its external appearance and its mechanical behaviour [Espinosa-Morales, 2021].

Rock blocks often show structural weaknesses, such as fractures, fissures, joints, discontinuities, and faults of various sizes, known as joints. It should be noted that virtually all the rocks that make up the kilometres of the Earth's crust have short fissures and cracks [Iriondo, 2006].

The diversity of structures, rock types and their spatial distribution have a considerable impact on the structural damage that can affect built heritage. It is therefore essential to identify these phenomena in a preventive manner, adapt land use according to the level of impact and reduce the vulnerability of buildings. This approach seeks not only to protect built heritage, but also to ensure the sustainability of buildings in complex geological contexts. In terms of size, rock aggregates are classified into two main categories: fine aggregates and coarse aggregates. Fine aggregates are composed of sand, either natural or manufactured, with particle sizes ranging from 60 µm to 5 mm. Coarse aggregates, on the other hand, include particles ranging in size from 5 mm to 125 mm [Neville, 1999]. Among the most relevant physical properties of aggregates are particle shape and texture, porosity, absorption, density, adhesion, and strength, among others.

In addition, the particle size distribution and maximum aggregate size, as in the case of gravel, are crucial factors that influence both the behaviour of concrete in its plastic state and in its hardened state. In tests carried out with concrete specimens made with limestone aggregates from the Yucatan Peninsula, it has been observed that failure occurs predominantly in the aggregates, especially when relatively low water/cement ratios [less than 0.5] are used. In addition to aggregate strength, other characteristics such as size, shape, surface texture and mineralogy also have a significant impact on concrete strength, although to varying degrees [Ezeldin & Aitcin, 1991].

Knowing the distribution of rock banks is essential to facilitate their grouping and subsequent characterisation, assigning mechanical behaviour parameters obtained through tests on representative samples. Among these parameters, the simple uniaxial compressive strength [SUC] of a rock is of particular importance, as it allows it to be classified mechanically. This value is key in the application of the most commonly used failure criteria in geotechnical engineering [Delgado, 2013].

In the state of Campeche, there is an important built heritage of Baroque architecture constructed with limestone masonry. These buildings are exposed to the humid tropical climate of the region, which causes differential alterations in the materials due to weathering. It is therefore essential to determine the properties and characteristics of the stone materials used, as this knowledge is key to their conservation, restoration and proper use in construction applications.

Study area

Seybaplaya, Campeche, is located in the geological region known as the ‘Yucatan Platform’, an extensive sedimentary rock formation, composed predominantly of limestone and clay, which covers much of the Yucatan Peninsula in Mexico.

This platform was formed millions of years ago due to the accumulation of marine sediments and has an approximate depth of 200 metres.

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It is particularly relevant to analyse the properties of the rocks from the bank located in Seybaplaya, known as 'Mary Carmen', as well as its surroundings, due to their extensive exploitation for construction materials. Figure 1 provides a visual reference of the area.

Box 1

Figure 1

Seybaplaya rock bank location in Campeche state, Mexico

The material bank is located in the Payucán region, with specific UTM coordinates of X: 741570.00 and Y: 2174740.00. The type of material available at this deposit is tezontle, with an estimated volume of 500,000 m³ [equivalent to 500 x 1000 m³]. The thickness of the overburden is 0.2 metres. There are no restrictions on the use of explosives at this deposit, which facilitates its exploitation. Furthermore, from an economic point of view, the extraction of the material is considered economically viable.

Methodology

Deposit exploration

The deposit known as Mary Carmen is of great importance due to its geographical location near the deep-water port of API Seybaplaya, as its stone aggregates can be exported to other states in Mexico or to other countries by sea. This rock deposit produces stone aggregates of various sizes for the construction of buildings or for designing asphalt for roads.

Sample size

In research where the main variable is qualitative and is reported as the proportion of the phenomenon studied in the reference population, the sample size is calculated using the following equation, which is used for an infinite population [i.e., when the total number of observation units that comprise it is unknown or when the population exceeds 10,000 units].

$$n = \frac{z_{\alpha}^2 * p * q}{e^2} \quad [1]$$

Where.

n= SAMPLE SIZE
Z_α= statistical parameter depending on the confidence level
e= maximum estimated maximum estimated error
p= probability of occurrence of the event under study [success]
q= [1-p] is the probability that the estimated event does not occur

To determine the number of samples in this research, the analysis was conducted as follows: since the event under study is unknown and considered infinite, proportions of p = 50% and q = 50% were assumed, implying equal probability of occurrence or non-occurrence. A 90% confidence level was used [Zα = 1.645] and a margin of error of e= 12 [https://www.fisterra.com/formacion/metodologia-investigacion/determinacion-tamanomuestral/]

$$n = \frac{1.645^2 * 50 * 50}{12^2} = 46.979$$

Therefore, 50 samples were established for the study.

For sample collection, 5 points were located at sites where the bench had been dynamited, the coordinates of which are presented in Table 1. Figures 2 and 3 show the rock bank named Mary Carmen where the samples were taken.

Box 2

Table 1

Location of simples

Sample Range	Coordinates UTM [X, Y]
Samples 1 to 10	[741595, 2174717]
Samples 11 to 20	[741611, 2174838]
Samples 21 to 30	[741585, 2174851]
Samples 31 to 40	[741591, 2174750]
Samples 41 to 50	[741605, 2174803]

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Box 3

Figure 2
Geographical location of sampling points.

Box 4

Figure 3
Rock bench "Mary Carmen".

2.2 Sample extraction and preparation

The preparation of rock core samples and the evaluation of their dimensions and shape, in accordance with the provisions of ASTM D4543-12 [2012]. This standard specifies that samples must be straight circular cylinders and strictly comply with the established tolerances.

The main requirements include the following:

1. Length-to-diameter ratio: length and diameter between 2.0 and 2.5.
2. Minimum diameter mm.
3. End surfaces: The ends of the cylinders must be polished to a flat surface with a maximum tolerance of 0.001 inches.

These criteria ensure uniformity and precision in the tests carried out on the samples [Figure 4].

Box 5

Figure 4
Samples in the form of a straight circular cylinder

In order to evaluate the rock properties of the "Mary Carmen" bench, the following sequence of tests was designed.

2.3 Resistance to simple uniaxial compression [RCUS]

The uniaxial compression test was carried out in accordance with ASTM D7012-10. The method used to calculate the uniaxial compressive stress is equal to the axial load divided by the cross-sectional area..

$$\sigma = RCUS = \frac{P}{A} \quad [2]$$

Where:
σ = RCUS = simple uniaxial compressive strength
P = Axial load
A = Cross-sectional area

2.3.1 Procedure for simple compression test, on the universal machine model 2000 and Serial No.: 011065

1. Recorded the dimensions to assess the cross-sectional area.
2. Checked that the universal machine is set correctly [at zero].
3. The specimen was placed in the centre of the compression platens of the universal machine [Figure 5].
4. Using the control software to program the machine and run the compression test, the load was applied in a gradual manner.

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5. The test was carried out until failure of the specimen revealed cracks [Figure 6].
6. Finally, the specimen was removed from the machine and a new specimen was placed, repeating the procedure described above. [Nieto & Avendaño, 2015]

Box 6

Figure 5
Position of the specimen in the centre of the compression platens of the universal machine

Box 7

Figure 6
Compressive strength test

2.4 Water content

2.4.1 Current moisture content

This value is a key indicator of the water accumulated in the aggregate, influenced by factors such as bank conditions, ambient humidity and the presence of interconnected pores, among others.

The objective of this test is to determine the moisture content present in a rock in its natural state, as indicated in the standard. [ASTM 2010b D2216-10].

2.4.2 Calculation of moisture content.

Moisture content was calculated using equation 3, which relates the wet weight and dry weight of the samples.

$$\%\, Current\ Humidity = \frac{p_i - p_f}{p_f} \text{x}100 \qquad [3]$$

Where:
Pi= Initial sample weight, g.
Pf= Final weight of the sample, g.
An average of the representative rock samples is determined.

2.5 Procedure for determining the water content in rock

1. Preparation of the sample.
2. Initial weighing [wet weight].
3. Oven drying: Set the oven temperature to 105 ± 5 °C. For 24 hours.
4. Final weighing [dry weight].
5. Calculation of water content.
6. Results.

2.4.4 Actual density test

The actual density test on rock was carried out in accordance with ASTM D 854. This test is used to calculate the actual density of rocks, which represents the ratio of the actual mass of the sample to its actual volume. The value of this parameter was calculated using the equation 4:

$$ɣ = \frac{m}{V} \qquad [4]$$

Where
ɣ = the actual density
m = the mass of the rock
V = the total volume of the sample.

Procedure for determining the true density in rock

- Determine the value of the mass of the sample in grams.
- Determine the volume of the sample in
- Divide the mass by the volume cm

2.6 Specific gravity test

The rock specific gravity test is performed following the guidelines established in ASTM D 854.

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The purpose of this procedure is to determine the real density of the rocks, which is defined as the ratio between the real mass of the sample and its real volume.

Once the density is obtained, the specific weight of the rock is calculated by multiplying it by the acceleration of gravity. This parameter is fundamental to characterise the physical properties of the material.

The calculation of the value of these parameters is done using specific equations, as detailed in the density [4] and specific weight [5] equations.

$$P = \gamma g \quad [5]$$

Where:

1. ɣ = the actual density
2. g = gravity
3. P = specific gravity.
4. Procedure for determining the specific gravity in rock

Once the true density has been determined, the true density is divided by the gravity.

2.7 Porosity

ASTM D4404 establishes the standard procedure for calculating porosity in rocks, which is carried out by the following equation:

$$Poros\ \% = \frac{Vol.\ de\ poros}{Vol.\ total}\ x\ 100 \quad [6]$$

Where:

Pore volume = volume of water absorbed by the rock sample.
Total vol. = total volume of the rock sample..

2.7.1 Procédure de détermination du pourcentage de pores dans la roche

1. Sample preparation
2. Dry weight measurement
3. Saturation of the sample
4. Measurement of the saturated weight
5. Determination of total volume
6. Calculation of pore volume
7. Calculation of porosity

2.8 Surface hardness [sclerometry]

The procedure established by the field index test according to USBR [1998] requires ten readings at different points on each analysed surface. Subsequently, the five lowest values are discarded and the average of the five highest values is calculated, thus obtaining a representative result.

In this case, given that the hammer available is of type N [designed for concrete] and what is required is a hammer of type L [specific for rock], the correlation equation proposed by Poole & Farmer [1980] is used, which allows the results obtained with the hammer of type N to be adjusted to estimate values equivalent to the type L. The correlation equations include specific considerations for the position of the hammer, either horizontal or vertical downwards, and are designed to minimise the standard error [eσ] associated with the estimation of the values [equation 7].

$$R=1{,}838+0{,}813RN; e\sigma=2{,}9 \quad [7]$$

Where:
RN= rebound value of concrete type hammer
R V= rebound value already correlated to the rock type.

2.7.2 Procedure for using the Schmidt hammer in rock

1. Preparation of the test area
2. Verification of the Schmidt hammer
3. Positioning of the hammer
4. Conducting the test
5. Recording of data
6. Calculation of the average
7. Conversion of rebound rate to resistance

3 Results

Tests were carried out on 50 samples of 5.08 cm [2 in] diameter and with a length ratio of 2-2.5 times the diameter. The results of compressive strength in Mpa, moisture content in %, actual density in g/cm3, specific gravity x 103 in N/m3, porosity in %, and rebound value [Table 2] were obtained.] [Naal-Pech et al., 2023].

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Box 8

Table 2

Table 2 Results of 50 samples.

ID	RCUS [MPa]	Water content [%]	Actual Density [g/cm^3]	Specific gravity [kN/m^3]	Porosity [%]	Rebound value [J]
1	31.6	7.79	2.07	20.2969	16.12	30
2	28.6	7.08	2.37	23.2406	16.77	36
3	46.8	7.09	2.38	23.3416	16.87	27
4	15.2	9.24	2.26	22.1972	20.90	31
5	18.3	8.43	2.24	22.0139	18.93	29
6	11.7	6.96	2.32	22.7956	16.16	35
7	22.7	8.01	2.24	21.9463	17.92	33
8	42.1	5.98	2.38	23.3876	14.25	19
9	53.4	5.79	2.42	23.7025	13.98	38
10	14.9	11.25	2.15	21.0619	*24.15*	30
11	68.6	7.49	2.34	22.9992	17.57	32
12	8.6	9.19	1.91	18.7118	17.52	32
13	23.2	6.31	2.30	22.5369	14.49	22
14	40.7	6.72	2.34	22.9663	15.74	38
15	43.5	3.96	2.50	24.4967	*9.88*	20
16	28.7	4.19	2.48	24.3683	10.41	40
17	43.6	7.50	2.29	22.4521	17.17	30
18	55.5	4.28	2.58	25.2793	11.03	42
19	32.3	8.00	2.29	22.4442	18.30	37
20	61.3	5.71	2.43	23.8702	13.89	43
21	78	4.51	2.51	24.5744	11.30	40
22	61.9	6.20	2.40	23.5791	14.90	36
23	42.4	4.23	2.55	25.0202	10.80	44
24	49.1	11.32	2.11	20.6647	23.85	37
25	84.7	5.80	2.52	24.748	14.64	44
26	72.8	5.38	2.46	24.1366	13.23	34
27	38.1	4.31	2.56	25.1228	11.04	29
28	33.2	7.22	2.29	22.4872	16.55	34
29	58	7.24	2.26	22.1556	16.34	31
30	23.9	5.49	2.42	23.6929	13.27	43
31	21.3	7.57	2.27	22.2322	17.16	28
32	40	6.14	2.27	22.2586	13.93	35
33	34.8	5.94	2.39	23.4224	14.18	33
34	43.6	6.02	2.27	22.2384	13.64	32
35	18.5	6.27	2.30	22.5979	14.44	39
36	54.1	7.29	2.24	22.0043	16.35	40
37	45.5	8.03	2.25	22.0671	18.06	27
38	44.1	12.66	2.04	20.0185	25.84	36
39	22.4	6.69	2.27	22.2381	15.16	35
40	35.1	4.39	2.47	24.1842	10.81	27
41	43.4	13.62	2.09	20.4987	28.46	31
42	37.4	5.39	2.46	24.1049	13.25	36
43	31	4.27	2.48	24.3428	10.59	39
44	36.5	3.73	2.61	25.5866	9.73	40
45	63.7	4.08	2.56	25.0749	10.43	43
46	15.7	11.82	2.18	21.3591	25.73	37
47	57.6	4.74	2.58	25.3142	12.22	33
48	40.5	4.97	2.40	23.5603	11.94	35
49	65.1	5.09	2.50	24.5425	12.74	45
50	23.3	3.95	2.62	25.6597	10.32	41

3.1 Physical-mechanical parameter ranges:

Table 3 shows the ranges of values of the different physico-mechanical parameters of the rock samples included in the study.

Box 9

Table 3

Range of values of RCUS, Moisture content, % porosity, True density and Surface hardness, True density [g/cm^3] in rock samples from the Seybaplaya bench.

Concept	Rango	Mean value	Standard deviation
RCUS in [MPa]	8.6 <> 84.7	40.14	17.99
Water content [%]	3.7313<>13.62	6.706	2.34
Actual density [g/cm3]	1.9<>2.615	2.351	0.159
Specific gravity [x103 in N/m3]	18.712<>25.66	23.07	1.56
Porosity [%]	9.7321<>28.46	15.45	4.38
Rebound Value [RV]	19<>45	34.6	6.13

4. Discussion

4.1 Rock sample extraction and preparation process:

For the exploitation of the bench, explosives were used, and large rock fragments were randomly selected to obtain representative samples. During the extraction phase, it was observed that the drilling rate varied according to the hardness of the rocks, which was confirmed by compression tests and the identification of the samples through their respective IDs. In addition, when water was injected into the drill hole, a white liquid was generated, indicating the presence of limestone in the rocks. The observed characteristics are indicative of the heterogeneity of the material.

The studies of the properties of the Yucatan limestone rock, carried out by Lauro A. Alonzo Salomon and Leopoldo Espinosa Graham are shown in Table 4 provided shows the values of standard deviation, mean and coefficient of variation for four properties of the limestone rock: volumetric weight, strength, density and absorption. The meaning of the values and their interpretation is explained below:

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Box 10

Table 4

Values of the coefficient of variation.

Property	Standard Deviation [σ]	Media [μ]	Coefficient of Variation [CV]
Volumetric weight [g/cm³]	0.3769	2.1102	17.86 %
Resistance [Kg/cm²]	161.1550	282.6708	57.01 %
Density [Ss]	0.3525	2.1707	16.24 %
Absorption [%]	7.0257	7.1125	323.66 %

4.2 Sample preparation

The collected samples were measured with a Vernier caliper, and cross-sections were made to adjust them to the required dimensions. However, in some cases, the process was complicated due to the disintegration of the samples, which prevented compliance with the required dimensional ratio of 2 to 2.5 times the diameter. This made it necessary to drill new samples to meet the established requirements.

Once prepared, the samples were subjected to drying and humidification processes in the materials laboratory in order to achieve the optimum moisture content and drying level for subsequent testing.

4.3 Simple uniaxial compressive strength

For this test, it was very important to polish the cross section so that when the load was applied, it complied with the required standard and was distributed evenly throughout the sample. Table 3 shows a very significant dispersion between the samples of this mechanical property, generated by heterogeneity and sampling conditions. It is important to consider these parameters in the design of cementitious base materials in order to obtain the best durability conditions.

4.4 Moisture content

There is a very significant dispersion between the samples with respect to moisture content, which is important for determining the recommended amount of water for designing concrete and/or mortar.

4.5 Actual density

There is significant dispersion among the samples with respect to actual density. These data are important for selecting the location of that sample and selecting the points where there is greater resistance in the bench, thus enabling the design of better resistances.

4.6 Specific weight

There is a very significant dispersion among the samples with respect to specific weight. This data is important for selecting the location of that sample and selecting the points where there is greater resistance in the bench, thus designing better resistances. It can also be confirmed that specific weight is closely related to density.

4.7 Porosity

There is a very significant dispersion among the samples with respect to porosity. It was observed that there are rock fragments with very large pores ranging from 0.5 cm, which affects the compressive strength of the samples and, therefore, their dispersion.

4.8 Rebound value

For this test, rock fragments and a concrete sclerometer were used. Before measurement, the surfaces were polished to remove irregularities.

The following was observed:

- Higher polishing speeds were associated with smoother surfaces.
- Greater difficulty in polishing indicated greater hardness in the rock.

During the polishing process, the rocks gave off a whitish dust, characteristic of limestone, confirming once again its composition.

Conclusions

The findings presented show significant progress in the field of rock mechanics in the state of Campeche. The data obtained and analysed in this document provide a clearer picture for understanding the behaviour of local rocks, which is key to the construction, rehabilitation and/or conservation of the region's built heritage. The main conclusions are highlighted below.

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5.1 Applications in construction and rehabilitation

The information obtained from the aggregates from this rock bank is relevant for the design of mixtures and blocks for the construction of confined masonry walls and low walls, as well as perimeter walls for the reconstruction, rehabilitation and conservation of the built heritage. It is expected that the blocks produced will meet the necessary structural requirements, achieving an average strength of **f´c = 3.92 MPa [40 kg/cm²]**.

5.2 Strength of stone aggregates

The results of the compression tests on these rocks show an average strength of **40.14 MPa [409.31 kg/cm²]**. However, due to the characteristics of the materials available in the region, it is not possible to manufacture high-strength concrete for the built heritage. The maximum concrete strength achieved in the region is **f´c = 29.42 MPa [300 kg/cm²]**.

This information allows appropriate decisions to be made for the design and execution of construction and/or rehabilitation projects for historic structures.

The aggregates from the rock bank studied meet the necessary characteristics for use in the restoration and conservation of the facades of the historic centre of San Francisco de Campeche, as they are very similar.

Declarations

Conflict of interest

The authors and co-authors declare that they have no conflicts of interest. They have no competing financial interests or personal relationships that could influence the content of this article.

Contribution of the authors

Naal-Pech, José Wilber: Contributed significantly to the conceptualisation of the project, as well as to the development of the research method and technique. He supported the design of the field instrument and carried out the data analysis, systematising the results. He was also responsible for writing the article.

Palemón-Arcos, Leonardo: Carried out the background research for this article and provided support in the design of the field instrument. He also contributed to the writing of the article.

El-Hamzaoui, Youness: Contributed to data processing and the generation of tables of contents and their analysis, as well as to the development of the approach, method and writing of the article.

Paat-Estrella, Josefa de los Ángeles: Contributed to the research design, defining the type and approach of the study, as well as the development of the method and the writing of the article.

Availability of data and materials.

The data obtained from this research are available for consultation at any time as needed.

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Abreviaturas

ASTM American Society for Testing and Materials.

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RCUS Compressive Strength Uniaxially Simple Compressive Strength.

R V= Rebound value already correlated for rock type.

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Background

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