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The use of Schmidt's hammer indentation in the characterization of the mechanical properties of rocks

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ABSTRACT

In geotechnics, knowledge of the characteristics of rocks, such as compressive and tensile strengths and elastic properties, is of utmost importance to determine whether a type of rock is suitable for a project. Seeking to facilitate the determination of these parameters, several researchers dedicate their studies to the search for simpler, faster and cheaper methods. These properties are correlated with others that are easier to analyze, such as hardness. A piece of equipment widely used for this is Schmidt's hammer, a type of sclerometer that measures the surface hardness of materials. This instrument correlates its indentation with the properties of the rocks, through simple and direct equations. Thus, the present work aimed to map the literature in which Schmidt's hammer was correlated with uniaxial compressive strength, diametrical tensile strength, modulus of elasticity or Poisson coefficient of rocks. It was verified how the tests are being carried out and how safe their results are.

Keywords: Rocks, Schmitd's Hammer, Mechanical Strength.

INTRODUCTION

The materials used in Engineering are numerous and each one has its applications, versatility and peculiarities. From materials coming straight from nature and applied rustically, to materials manufactured with a high degree of sophistication and rigor. Rocks are very important materials in this field, being used in different ways, and they need to be properly analyzed so that they can be used correctly. Due to this, often, a primary role of the engineer is to know the characteristics of the rocks.

Rocks have several properties, including chemical, physical, mechanical, geological and geotechnical. However, many of these properties require certain methods of analysis that are complex and consequently costly. An example of these are the mechanical compressive and tensile strengths, the modulus of elasticity and the Poisson coefficient, which are obtained through destructive laboratory tests. These tests, in addition to requiring precise and expensive equipment, are complicated, time-consuming, require qualified professionals to perform them and extract specimens of exact shapes.

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In view of this, several professionals in the area have been studying and developing techniques that facilitate these investigations. Some of them consist of correlating properties that are easier to analyze with those that are more difficult to obtain. In this sense, some analyses have already been carried out that relate the hardness properties of the rock with its mechanical and elastic characteristics, highlighting the use of Schmidt's hammer for this purpose.

The growing popularity of the Schmidt hammer (SH) is due to the fact that it is a portable, simple and affordable instrument that has a wide applicability. Thus, the Schmidt hammer setback (N) is considered the most used parameter in rock mechanics practice, to predict the compressive strengths (UCS) and the modulus of elasticity (E) of rocks intact in the field or in the laboratory, as presented by the *International Society For Rock Mechanics* – ISRM (Aydin, 2009).

The correlation between Schmidt's hammer, which measures surface hardness, and the properties of rocks has been investigated since the 1960s, by pioneers Deere and Miller (1966). Yilmaz and Sendir (2002) studied the correlation of N with the UCS and E values for plaster. They found good results through exponential empirical equations, but they emphasized that although this type of correlation is acceptable, specific equations should be used for each type of rock. Subsequently, Aydin and Basu (2005) characterized granitic rocks with different degrees of weathering, using two different types of Schmidt hammers. The authors concluded that both models strongly correlated with uniaxial compressive strength and modulus of elasticity values.

However, despite its countless advantages, N is an indirect answer, and for this reason, it needs correlation graphs to estimate the desired parameters. In other words, the data found in the field and in the laboratory must be analyzed to obtain a reliable answer. In addition, several issues should be analyzed before conducting studies, such as the type of hammer, the normalization of setback values, test procedures, and data reduction and analysis. These parameters directly influence the reliability of the Schmidt hammer test results (AYDIN and BASU, 2005).

Therefore, the present work aims to make a survey of the research already carried out on the subject so far. Thus, it aims to present the studies on the correlation between Schmidt's hammer and the mechanical properties of rocks, more specifically the compressive and tensile strengths, the modulus of elasticity and the Poisson coefficient. The objective is to verify the type of HS and the most appropriate test method, the data analysis model that results in the most reliable correlations, in addition to analyzing the scope of the theme and the importance of new studies.

MATERIALS AND METHODS

To carry out this research, the Mapping Study methodology was chosen, in which the Capes journal portal, Science Direct and Scopus were used as databases. In all, ten combinations of words were used in each of these databases. The expressions "Rock Schmidt" and "Schmidt Hammer" were combined with "UCS", "Elasticity Modulus", "Young Modulus", "Brazilian Tensile Strength", "Indirect Tensile Strength" and "Poisson", as shown in Chart 1 of results. It is worth mentioning that the surveys were carried out in August 2017, since the databases are always updating and presenting new results.

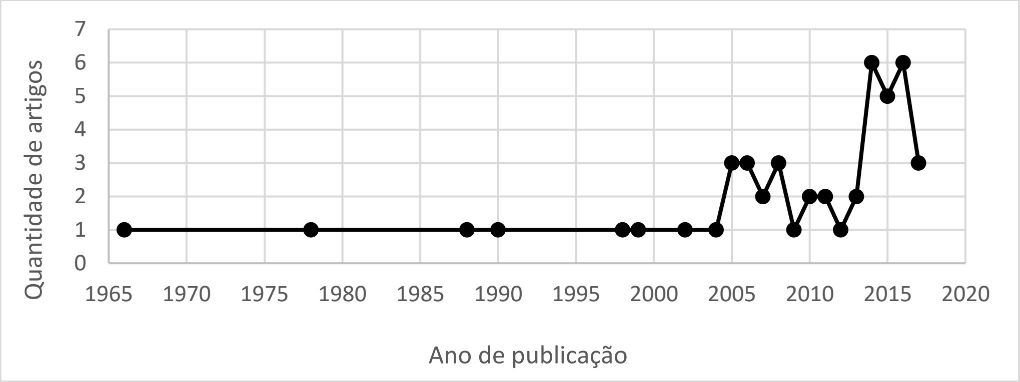
Chart 1 – Mapping results.

Database	Combination		Result	Adherent	Total	No repetition
CAPES	Rock Schmidt	UCS	14	9	40	30
		Elasticity Modulus	2	1		
		Young Modulus	10	5		
		Fish	0	0		
	Schmidt Hammer	UCS	17	11		
		Elasticity Modulus	5	2		
		Young Modulus	12	6		
		Brazilian Tensile Strength	14	2		
		Indirect Tensile Strength	8	3		
		Fish	2	1		
SCIENCEDIRECT	Rock Schmidt	UCS	18	13	41	24
		Elasticity Modulus	10	5		
		Young Modulus	11	5		
		Fish	3	3		
	Schmidt Hammer	UCS	23	5		
		Brazilian Tensile Strength	6	0		
		Indirect Tensile Strength	2	1		
		Elasticity Modulus	7	3		
		Young Modulus	8	4		
		Fish	2	2		
SCOPUS	Rock Schmidt	UCS	49	22	90	64
		Elasticity Modulus	27	10		
		Young Modulus	23	8		
		Fish	7	3		
	Schmidt Hammer	UCS	43	22		
		Brazilian Tensile Strength	12	2		
		Indirect Tensile Strength	7	4		
		Elasticity Modulus	22	8		
		Young Modulus	23	9		
		Fish	5	2		
TOTAL NO REPETITION BETWEEN DATABASES						46

Source – Authors.

Over the years, the number of articles published has increased, as can be seen in graph 1. It can be seen that this amount reached its maximum in 2014 and 2016 with six publications, and even in 2017 three articles related to the subject of this work were published. Therefore, with this evaluation, it is possible to determine that the topic under study is considered current and still has a lot of relevance in research in this area.

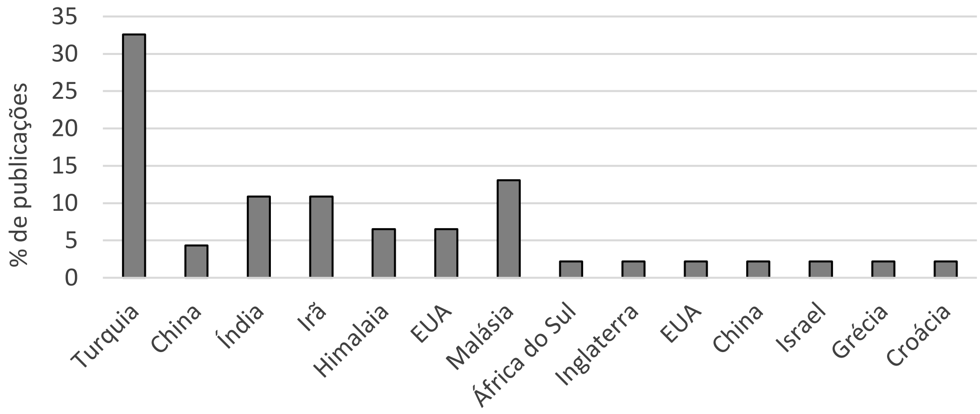
Graph 1 – Frequency of publications.



Source – Authors.

According to graph 2, there are different countries that produce texts related to the subject in question, and in many of them there are large mountain ranges, as is the case of the Himalayas. However, it is possible to see that most of the studies come from Turkey, with 32.6%.

Graph 2 – Percentage of places of publication.



Source – Authors.

REVIEW

By reading the various materials obtained through systemic mapping, it is possible to observe that studies on the correlation between Schmidt's hammer and the properties of rocks began in the 60s. Deere and Miller (1966) carried out an extensive study of different types of rocks from different locations in the United States, in order to develop a classification system in engineering. In this study, surface hardness was measured using Schmidt's hammer and also using another piece of equipment, known as a Shore hardness sclerometer. The authors concluded that rock strength and modulus of elasticity are better correlated with Schmidt hardness than with Shore hardness, which is another type of sclerometer in addition to Schmidt's hammer. They also found that the use of other properties, such as sonic velocity, is not as good as the use of the Schmidt or Shore hardness index in correlation with the modulus.

Some advantages of using Schmidt's hammer in rock characterization are presented by Goudie (2006) such as portability, low cost, capacity for multiple readings in the field, simplicity and easy calibration. The author also highlights some limitations, among which the sensitivities to discontinuity, humidity, texture and mass of rocks stand out. The need to use the equipment carefully and properly calibrated, and to prepare the rock surface with the material supplied with the instrument, removing any residue, is emphasized.

Simpler methods to estimate the value of UCS through N were studied by Karaman and Kesimal (2015b), for this they reduced the number of readings. Three new tests were created and named T1, T2 and T3. The result of the first test is obtained by making six unique impacts and the average of all values. For the second test, eight impacts are recorded and the highest and lowest values are disregarded to obtain the average. And finally, the last one consists of ten unique impacts on the samples, allowing the lowest and highest values to be discarded to make the average.

In order to compare these new methods, Karaman and Kesimal (2015b) also performed four other tests that are already in the literature, including the ISRM (Aydin, 2009) and ASTM (2001) tests. It was concluded that all tests obtained high correlation coefficients, however T1 presented the best result in relation to the percentage error, therefore it presents the best prediction of the UCS. However, the same article warns that all sample preparation procedures were in accordance with ISRM and ASTM standards.

Tandon and Vikram (2015) correlated N with UCS for lithologies of quartz, granite, gneiss, dolomite and metabasic in the Himalayas. And they realized that there is a significant dispersion of the data when all the lithologies were considered together, but when they were considered separately the dispersions were reduced considerably. It is concluded that this difference may have been caused by the great variation in the mineralogical characteristics and the different textures of these lithologies.

Although most studies in this area correlate Schmidt's hammer recoil with the UCS, there are some authors who have published articles correlating this instrument with the BTS. These studies also achieved great success in this correlation (KARAMAN et al. 2015; RAJ and PEDRAM, 2015).

The variation in the reliability of the equations, in high and low, can be seen during the reading of the articles. This is predictable because the UCS parameters are not only linked by the relationships with Schmidt's hammer, but by a multitude of more complex properties to be measured, such as: porosity, water content and the existence of cracks due to bad weather (MOMENI et al., 2015). Although this article was carried out only for UCS, the same interpretation can be considered for the reliability variations of the equations that correlate N with the BTS results of rocks of the same lithology, since the same properties can also interfere in this study.

As there are variations in equations between one study and another and knowing that it is impossible to perform only one equation for all types of rocks, then the suggested equations should be used only when the rocks under study have similar properties. (KARAMAN et al. 2015).

Empirical equations between Schmidt's hardness and Young's modulus (E) and uniaxial compressive strength (UCS) were found by Sachpazis (1990). The author applied the correlation to carbonate rocks from Greece and England and concluded that the equations are practical, simple and precise enough to be applied and are highly recommended to be used in practice. In this work, the applicability of these equations only to carbonate rocks is emphasized, and the need to carry out new work in the area in order to find similar equations for other types of rocks.

A reference work was that of Yilmaz and Sendir (2002), who studied gypsum samples collected from the Sivas Basin in Turkey. Exponential equations relating Schmidt's number and the UCS and Young's tangential modulus (Et) obtained correlation coefficients (R) of 0.98 and 0.95, respectively, and safety of 95%. The authors found that the equations found can be used with acceptable accuracy in preliminary stages of structural design or analysis of building stone strengths.

Also in Turkey, some volcanic rocks from the Bodrum peninsula were studied. Dinçer et al. (2004) also correlated Schmidt's hardness with strength and modulus of elasticity, comparing simple linear, exponential, and logarithmic regressions. For all correlations, UCS-N, E-N and E-UCS, the best relationship found was linear, with correlation coefficients (R) of 0.97, 092 and 0.92, respectively.

This correlation was also analyzed by other authors with the intention of studying the interference of rock conditions in the prediction of properties by means of Schmidt's hammer. Aydin and Basu (2005) used granitic rocks with different degrees of weathering from Hong Kong and two types of Schmidt's hammer (RL and RN), and found that both offer good results for UCS and Et, but RN is better related. Among the various conclusions of the authors, it can be highlighted that: the largest samples are preferred because they dissipate less energy; no reading should be ruled out unless there are visible cracks around the point of impact; repeated impact at the same point leads to wrong prediction of UCS and Et; and the use of additional variables should be avoided in empirical equations for practical use, except when they are extremely important.

Yagiz (2010) conducted a study of nine types of rocks from Turkey, to estimate the modulus, strength and index properties. Linear and nonlinear regressions were performed, and exponential and logarithmic equations were obtained between the variables. The results were compared with those of other authors and it was concluded that even under equal experimental conditions, it is impossible to obtain a single correlation for all types of rock.

A different research was conducted by Dobrilovic et al. (2010), in order to compare some test conditions. In this sense, two types of Schmidt's hammer were used, one digital and one analog, and the samples were submitted to the hardness test in the parallel and perpendicular directions to the rock stratification planes. Mechanical properties of three different samples of Istrian limestone, including the modulus of elasticity, were estimated. The authors concluded that the best correlations, taking into account the dispersion of data due to sample size, were between Schmidt's hammer and the modulus. They also found that the hardness tests in the direction perpendicular to the stratification planes give significantly better correlations for the modulus of elasticity.

In the same work, an analysis was also made regarding the introduction of other variables in the correlation between the properties. To this end, the density of the material was introduced in the application of the hardness values, and it was observed that this incorporation was beneficial, since better correlations were obtained. Overall, the authors found that mechanical properties, such as uniaxial compressive strengths, modulus of elasticity, and tensile strength, correlate well with Schmidt's hammer.

Raj and Pedram (2015) performed tests to obtain Schmidt's hardness, modulus of elasticity and Poisson's coefficient and other properties. Among the various analyses, the authors concluded that the Poisson coefficient has no correlation with any of the results obtained in the tests, and they were not even able to predict correlation equations for this index. It was also noticed that the effect of sample length on Schmidt hardness values is negligible for samples longer than 12 cm in length and that the performance of empirical equations can be improved if more experimental data are available.

For Dinçer et al. (2004) the results obtained using only the Schmidt test in the determination of rock properties are less precise than those with a complete set of data, but the empirical equations obtained by simple regressions can help professionals to make practical decisions.

Chart 2 exposes certain equations found by some of the authors presented here, since some did not present correlations, only theoretical study, and others developed equations by multiple regressions, which is not the focus of this study. It is worth mentioning that some of these studies used more than one method to arrive at an equation, but only the equation of each article that obtained the highest correlation will be represented in the Table.

For each author, the correlation index found is presented, with some using the correlation coefficient R and others using the coefficient of determination R². To understand the difference between these two indexes, we can use the explanation of Triola (1999). According to this author, the correlation coefficient R measures the degree of linear relationship between the x and y values in a sample, and should always be between -1 and +1, and for values close to 0 there are no significant linear correlations between the data. The coefficient of determination R² is the value of the variation of y that is explained by the regression line, and can be calculated by raising the R squared and, therefore, varying from 0 to 1. That is, if R = 0.8, then R² = 0.64 which means that 64% of the change in y can be explained by the regression line, and the other 36% remains unexplained.

Chart 2 – Equations and correlation indices of N with UCS, E and BTS.

References	Types of rochas	Equations	R²
Akram et al. (2017)	Limestone	$UCS = 1{,}1741N + 11{,}94$	0,68
Azimian (2017)	Limestone	$UCS = 2{,}664N - 35{,}22$	0,92
Armaghani et al. (2016a)	Granite	$E = 5{,}6441\ e^{0{,}053\ N}$ UCS = 4,9279N-128,45	0,485 0,491
Armaghani et al. (2016b)	Granite	$UCS = 25{,}952e^{(0{,}030N)}$	0,59
Armaghani et al. (2016c)	Sandstone	$UCS = 3{,}002N^{(0{,}801)}$	0,45
Ataei et al. (2015)	Ferro mine	$UCS = 14{,}428e^{(0{,}0446N)}$	0,95
Aydin A Vasu (2005)	Granite	$Et = 1{,}0405\ e^{0{,}0706\ R_L}$ $Et = 0{,}7225\ e^{0{,}0548\ R_N}$ $UCS = 1{,}4459\ e^{0{,}0706 R_L}$ $UCS = 0{,}9165\ e^{0{,}0669 R_N}$	0,91* 0,92* 0,92* 0,94*
Bejarbaneh et al. (2016)	Sandstone	$E = 0{,}632\ N^{1{,}005}$	0,503
Büyüksağiş e Göktan (2007)	Granites, limestones and travertines	$UCS = 2{,}101e^{(0{,}0613N)}$	0,95
Chand e Subbarao (2007)	Pond ashes	$UCS = 0{,}4992e^{(0{,}0625N)}$	0,98
Deere e Miller (1966)	Different	$Et = 0{,}259N - 4{,}29)10^6$ $UCS = 1{,}246N - 34{,}890$	0,731* 0,880*
Dinçer et al. (2004)	Volcanic	$E = 0{,}47N - 6{,}25$ $UCS = 2{,}75N - 36{,}83$	0,85 0,95
Fakir et al. (2017)	Granitoids	$UCS = 0{,}0142N^{(2{,}3559)}$	0,86
Go on...			
References	Types of rochas	Equations	R²
A Castile in a Car (2015a)	Igneous, metamorphic and sedimentary	$UCS = 0{,}1383N^{1{,}743}$	0,91
Karaman Kesimal (2015b)	Volcanic, metamorphic and sedimentary	$UCS = 0{,}0176N^{2{,}243}$	0,95
Karaman *et al.* (2015)	Volcanic, metamorphic and sedimentary	$UCS = 3{,}66N - 63$ $BTS = 0{,}72N - 16{,}6$	0,84 0,85
Katz et al. (2000)	Different	$E = 0{,}00013\ N^{3{,}09074}$ $UCS = 2{,}208\ e^{0{,}067N}$	0,9936 0,9637

Liang et al. (2016)	Sandstone	$UCS = 10{,}526e^{(0{,}0593N)}$	0,58
Minaeian by Ashngari (2013)	Conglomeratic Rochas	$UCS = 0{,}678N$	0,94
Mishra A. Vasu (2013)	Granite Schist Sandstone All the rocks	$UCS = 5{,}19N - 168{,}1$ $UCS = 2{,}46e^{(0{,}60N)}$ $UCS = 3{,}79e^{(0{,}0558N)}$ $UCS = 2{,}38e^{(0{,}65N)}$	0,75 0,78 0,85 0,87
Raj and Pedram (2015)	Basalt and Rhyolito	$E = 32{,}90\ \ln(N) - 77{,}53$ $UCS = 0{,}25\ N^{1{,}77}$ $BTS = 0{,}15N^{1{,}33}$	0,82 0,88 0,83
Sachpazis (1990)	Carbonated	$N = 0{,}5155Et + 17{,}488$ $N = 0{,}2329UCS + 15{,}7244$	0,7764 0,9178
Selcuk e Yabalak (2015)	Different	$UCS = 0{,}007N^{2{,}443}$	0,92
Tandon and Expression (2013)	Different	$UCS = 12{,}398e^{(0{,}0365N)}$	0,82
Tandon e Vikram (2015)	Quartz Granites Gneiss Metabasics Dolomite Other lithologies	$UCS = 2{,}72251N - 30{,}19$ $UCS = 2{,}2625N - 29{,}38$ $UCS = 2{,}7295N - 41{,}78$ $UCS = 2{,}5475N - 33{,}08$ $UCS = 1{,}2335N - 2{,}846$ $UCS = 1{,}91051N - 10{,}30$	0,91 0,96 0,71 0,93 0,89 0,75
Tong et al. (2015)	Grade III degradation granite	$UCS = 8{,}79e^{(0{,}0386N)}$	-
Tumac (2015)	Marbles, black limestone and limestone	$UCS = 11{,}65N^{(0{,}4951)}$	0,75
Yagiz (2011)	Travertine, dolomite limestone and xisto.	$E = 1{,}233\ N - 17{,}8$ $UCS = 0{,}0028N^{(2{,}584)}$	0,85* 0,92*
Yilmaz e Yüksek (2008)	Chalk	$E = 1{,}2902\ N - 19{,}952$ $UCS = 1{,}2483\ N - 24{,}723$	0,9071 0,9555
Yilmaz e Sendir (2002)	Chalk	$Et = e^{1{,}146+0{,}054\ N}$ $UCS = e^{(0{,}818+0{,}059N)}$	0,95* 0,98*
Where: – Diametrical Tensile Strength; – Modulus of elasticity; – Tangent modulus of elasticity; N – Schmidt's hammer recoil; – L-type Schmidt's hammer; – N-type Schmidt hammer; – Uniaxial Compressive Strength;*= correlation coefficient RBTS$EEtR_LR_N$UCS			

Source – Authors.

Chart 2 represents a summary of the equations performed in each article, through which it is possible to perceive the variety of rocks tested, and the large number of correlation equations of Schmidt's Hammer and the mechanical properties, except for the Poisson coefficient. This difference in equations and correlation indices is due to the type and location of the rock investigated, testing methodology and analysis of the results.

As is the case of the limestone studied by Akram et al. (2017) and Alzimian (2016) who determined different equations and correlations, which can be explained by the fact that the first study was carried out in the Himalayas and the second in Iran. The granitic rocks analyzed by Armaghani et al. (2016a), Armaghani et al. (2016b) and Aydin and Basu (2005) located in Malaysia in the first two articles and in Hong Kong in the last, should not have their correlation indices directly compared, as they are different. It is also noted that even though the first two studies were carried out in the same country, the indices and equations varied from one article to another in correlation with UCS.

Still in the same line of reasoning, igneous/volcanic, metamorphic and sedimentary rocks were investigated by four authors, including: Fener et al. (2005), Karaman and Kesimal (2015a), Karaman and Kesimal (2015b) and Karaman et al. (2015). It should be noted that all the articles analyzed samples from Turkey and even so determined different equations, in which the correlation indices are considered high. It is noteworthy that the two Karaman and Kesimal papers from 2015 were carried out for sample analysis from the same Cambasi Tunnel.

Armaghani et al. (2016c) and Liang et al. (2016), defined different equations for sandstone with reasonable correlation indices. Both studies were carried out in Malaysia, but in different locations in the country. Finally, gypsum samples were analyzed by Yilmaz and Yuksek (2008) and Yilmaz and Sendir (2002), both in Sivas, Turkey, but each article determined different equations and correlation indices, so they cannot be directly compared.

FINAL CONSIDERATIONS

Through the literature review, it is possible to see that Schmidt's hammer has already been widely used in the determination of mechanical properties of rocks. It is noted that the vast majority of the work carried out so far has been developed in Asia, especially Turkey, and that several types of rocks have already been studied. In addition, this type of research has been constant over time and continues to be carried out.

It is possible to see that in most studies Schmidt's hammer is correlated with both modulus of elasticity and uniaxial compressive strength. However, the determination of the Poisson coefficient is not a priority of correlations. Of the few authors who studied this property, one concluded that the coefficient has no correlation with other properties, another performed a comparison only with the Shore hardness, and the other performed multiple regression with the association of several data and obtained good correlations.

Through the analysis of chart 2, it is possible to verify that even though some authors have done studies with the same type of rocks and in similar locations, the equations and determination indices are different from each other. This explains the large number of studies generated for the correlation of Schmidt's hammer and mechanical properties.

The main point presented, which is highly emphasized by most authors, is that the correlations found between Schmidt's hammer and the properties are significant and can be used in practice. However, it is impossible to determine only one correlation for all types of rock, so that the correlations already found can only be applied to the specific type of rock studied.

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