Influence of Specimen Size and Shape on the Uniaxial Compressive Strength Values of Rocks

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Abstract

The most significant factors affecting the results of Uniaxial Compressive Strength (UCS) test are the size, slenderness ratio h/d (ratio of height to diameter), and the shape of the rock specimen. The proposed experimental study shows the variable impact of these parameters on UCS values by implementing several lithological types. Standard strength tests were performed on four lithological types: granodiorite, limestone, sandstone and andesite. Cylindric and cube-shaped test specimens of different sizes were prepared from each rock. Cylindric specimens with diameter 20 mm, 35 mm, 50 mm and 70 mm with height to diameter ratio of 1:1 and 2:1, and cubic and prismatic specimens with an edge dimension of 50 mm were tested and analyzed. Obtained results of strength tests confirmed a high variability of current research opinions on how the size and shape of specimens influence the strength values of rocks. The study revealed the impossibility of conclusive correlations between the UCS and specimens to be generally applicable for all lithological types. Of the observed effects on the strength, the aspect of the specimen slenderness ratio was the most pronounced on all studied rocks.

Introduction

Rock strength is one of the essential characteristics that every engineering geologist or geotechnical engineer needs to find in an engineering geological investigation for designing buildings, lined structures and underground structures. From a wide range of directly determinable strength characteristics, the most important one is the Uniaxial (or Unconfined) Compressive Strength (UCS). It is usually measured in the laboratory on cylindric or cubic specimens. The significance of the UCS parameter was given in its stipulation as a classification measure dividing rocks according to the strength into groups and classes from extremely weak (less than 1 MPa) up to extremely strong, i.e. with strength greater than 250 MPa (EN ISO 14689, STN 72 1001).

The UCS value of rock is influenced primarily by rock genesis, mineral composition and internal structural factors, such as grain size, strength ability of structural binds between rock particles, the strength of crystals and clasts forming rocks, content and composition of cement, presence of various discontinuities, orientation and quantity of cracks etc. However, the UCS can also be affected by factors related to testing methods and conditions, such as loading rate, stiffness of loading machine, the moisture of samples, specimen dimensions (size and slenderness ratio) and specimen shape.

The methodology of determining the UCS parameter in the laboratory is standardized worldwide (Ulusay and Hudson eds., 2007, EN 1926). However, there is an inconsistency in evaluating the same considered parameter by defining different requirements for the methodical manner, prevailing requirements on the slenderness ratio (ratio of height to diameter of cylindric samples or ratio of height to edge of the base of prismatic specimens), namely according to the purpose of the performed strength test. Currently, the standard and test regulations for the UCS test are different for geotechnical purposes and to use rocks as natural building and decorative stone. Despite this fact, experiences from laboratory determination of the UCS show that the dimensions and shape of specimens play an important role.

The main aim of this study was to examine how the size (dimensions), slenderness ratio (ratio of height to diameter of cylindric samples, or ratio of height to edge of the base of prismatic specimens) and shape (cylindrical, cubic and prismatic shape) of specimens affect the UCS value. This issue is widely discussed and quoted by many domestic and foreign authors, who refer to different findings based on the influence of these factors on the uniaxial compressive strength of rocks. One of a stimulus for the study of these aspects was a considerable inconsistency of opinions and often opposed test results presented in the literature (Hoek and Brown, 1997; Thuro et al., 2001; Labaš and Miklúšová, 2004; Yoshinaka et al., 2008; Durmeková and Ondrášik, 2012). Also, other studies were taken into consideration, e.g. specimen size effect on strength behavior of cemented paste backfills subjected to different placement conditions had been studied by Yilmaz et al. (2015). The effects of specimen size and thermal damage on the physical and mechanical behavior of fine-grained marble were analyzed by Rong et al. (2018).

The above-stated circumstances are permanently actual because, in many practice tasks and research projects, there is often a need to determine the rock strength on size non-standard specimens.

Materials And Methods

The impact of the size, shape and h/d ratio of the test specimens on the UCS values was observed on four rock types from different lithological formations (Fig. 1): 1. granodiorite from the Dubná Skala quarry, plutonic igneous rock described more precisely identified as black mica granodiorite to diorite, medium grained with omnidirectional texture; 2. limestone from Vajarská quarry, sedimentary carbonate rock, oosparite limestone with a high content of CaO; 3. sandstone from Spišské Tomášovce quarry, a sedimentary clastic rock classified as graywacke, (i.e. a sandstone with the content of the matrix higher than 15%); 4. andesite from Víglaš quarry, an extrusive igneous rock, classified as pyroxenitic andesite with compact, omnidirectional fine to medium grained texture.

Basic physical properties of rocks examined in the study are specified in the Table 1.

The test specimens were produced from monoliths obtained from particular quarries by altering in the laboratory, i.e. cutting and drilling. Within this process, there was a considerable accent put on keeping the parallel position of the upper and bottom base of the specimen and remaining their perpendicularity towards the load application.

Cylindric shaped specimens were prepared with the ratio, $h/d = 1$ and $h/d = 2$, where h represents the height and d is the diameter of the test specimen. Cylindric specimens of ratio $h/d = 1$ were made with diameters 20 mm, 35 mm, 50 mm and 70 mm, and samples with the ratio $h/d = 2$ were provided with diameters 20 mm, 35 mm and 50 mm. Besides these, the prismatic test specimens in the form of a quadrangular prism with the edge dimension of 50 mm and height 100 mm, and cube specimen with an edge of 50 mm were created. An overview of completed test specimens is listed in Table 2, and their geometry is referred to in Fig. 2. Particular test specimens were sorted into groups with equal dimensions. There in all were created 9 sets for limestone, granodiorite and sandstone and 8 sets for andesite.

Uniaxial Compressive Strength (UCS) test was performed according to the Standard EN 1926 for natural stone and the ISRM suggested methods used in geotechnical practice (Ulusuay and Hudson (eds.), 2007). The UCS test was realized on test specimens dried up to constant mass value by continuous applying the load at a constant stress rate in a hydraulic press until the failure occurred. Uniaxial compressive strength value (σ_c , R) of test specimen in MPa was calculated using the following equation:

$$\sigma_c(R) = F/A \text{ [MPa]}$$

where, F – maximum load necessary for the failure of the specimen (N),

A – loaded area of specimen that is perpendicular to the load (mm²)

The final result strength is referred to the average value of all test trials in a set with an accuracy of 1 MPa.

Experimental Results

The results of realized laboratory tests are presented consecutively according to the factors observed: the specimen size within one h/d ratio, h/d ratio, and the specimen shape.

Effect of specimen size

Thuro et al. (2001) defines the impact of the size of a specimen as an effect of the total specimen size, or more precisely, of the specimen's diameter, at which the ratio of the specimen length to diameter is kept constant. In the presented research, was evaluated this effect, applied on the cylindric specimens with diameters $d = 20$ mm, 35 mm, 50 mm and 70 mm with ratio $h/d = 1$, and samples with diameters $d = 20$ mm, 35 mm and 50 mm with ratio $h/d = 2$.

The values of UCS applied on limestone rock cores from Vajarska Quarry with ratio ($h/d = 1$) slightly increased with a growing diameter and so far, up to diameter 50 mm and then consequently decreased on specimens with a diameter 70 mm (Fig. 4a).

However, it is necessary to point out that the specimen with a diameter of 35 mm had reached strength values of 103 MPa, which is only 1 MPa higher than values acquired for specimens with a diameter of 20 mm. At the same time, the same values were recorded on specimens with a diameter of 70 mm. That means the strength values recorded for specimens of these three diameters were almost equal. The specimens with a diameter of 50 mm indicated an exception as the determined average strength reached the value of 111 MPa. Considering the small scale of the average strength values in particular sets (inclosing from 102 MPa for the specimens with a diameter of 20 mm, to 111 MPa for samples with a diameter of 50 mm), it can be stated that within the range of average values observed on the limestones from Vajarská quarry, no significant effect of the size of a specimen on the UCS has been proven.

The UCS test performed on the limestone specimens with the ratio $h/d = 2$ showed that the average strength value was changing for particular diameters in a range from 95 MPa with a diameter of 35 mm to 104 MPa for specimens with a diameter of 50 mm (Fig. 4b). As the scale of average strength values ranges only up to 8 MPa, it can be considered that the specimen size has not a strong influence on UCS values.

The UCS test results carried out on the sandstones from the Spišské Tomášovce quarry are as following. The results related to specimens with ratio $h/d = 1$ with a growing diameter of specimen up to 35 mm, showed an increasing trend of the strength value. With a diameter higher than 35 mm, the UCS value continually decreases (Fig. 4c). The maximum average UCS figure (161 MPa) was acquired on specimens with a diameter of 35 mm. The minimum average UCS value was obtained on specimens with a diameter of 20 mm, and that is 137 MPa. Based on the scope of average strength values, it may be reviewed that the size of sandstone core with ratio $h/d = 1$ affects to some extent the UCS value.

The sandstone specimens with the ratio $h/d = 2$ revealed comparable results as the specimens with ratio $h/d = 1$ (Fig. 4d). In like manner, the results showed the maximum average UCS value for specimens with a diameter of 35 mm, and the minimum average UCS value for a specimen of 20 mm.

Strength tests carried on granodiorite rock cores suggested the increase of UCS values with a growing diameter and with ratio $h/d = 1$ (for diameters of 20 mm, 35 mm, and 50 mm) (Fig. 4e). The specimens with the diameter 70 mm were an exception, and they produced an average strength value of 129 MPa, which means a higher value than the strength reached by rock cores with a diameter of 20 mm, but at the same time lower than by those of diameter of 30 and 50 mm. Considering the scope of the average strength values in the individual sets (ranging from 129 MPa for specimens with a diameter of 20 mm, to 146 MPa for rock cores with a diameter of 50 mm), the UCS figure for the granodiorite rock cores with the ratio $h/d = 1$ may be slightly affected by the specimen diameter. However, considering the width of the interval of strength values within the particular sets, the size effect of the specimen on the UCS is insignificant.

The tests made on granodiorite specimens with the ratio $h/d = 2$ discovered the range of average UCS values of particular sets, only by 3 MPa. The minimum average strength within the observed diameters was measured on specimens with a diameter of 20 mm, and that was 112 MPa. The maximum average strength value was 115 MPa, referring to the specimens with a diameter of 35 and 50 mm. It can be estimated that considering similar average strength values recorded for individual size sets of granodiorite specimens with ratio $h/d = 2$, no size effect on the UCS was observed (Fig. 4f).

The test results performed on andesite specimens with ratio $h/d = 2$ showed an ascending trend followed by increasing diameter (Fig. 4g). The minimum average UCS value (129 MPa) was recorded on rock cores with a 20 mm diameter. The maximum average weight (215 MPa) was measured on rock cores with a 70 mm diameter. It can be stated that based on the scope of average strength values, the UCS of andesite specimens with the ratio $h/d = 1$ is affected to a large degree by the size of the examined specimen.

The andesite specimens with the ratio $h/d = 2$ performed the same as the sandstone specimens with ($h/d = 1$ and $h/d = 2$) (Fig. 4h). The minimum average UCS value (181MPa) was found out in the set of specimens with a diameter of 20 mm. The maximum average UCS value (196 MPa) was learned on specimens with a diameter of 35 mm. However, the size effect on the UCS value is lower than the one recorded on sandstone.

Effect of height/diameter ratio

The effect of h/d ratio on rock strength is usually determined on specimens with different slenderness ratios (ratio of height to diameter of cylindric rock cores or ratio of height to edge of the base of prismatic rock specimens), or on specimens with the same diameter or base edge. In this study, the effect was investigated on cylindric rock specimens with $h/d = 1$ and $h/d = 2$ with diameters of 20 mm, 35 mm, and 50 mm, as well as cubic specimens with $h/d = 1$ and prismatic rock specimens with $h/d = 2$ with the base edge of 50 mm.

Cylindric rock specimens

The tests carried out on three lithological rock types (limestone, sandstone and granodiorite) showed that cylindric shaped specimens with slenderness ratio $h/d = 1$ unveiled increased UCS values in comparison with the specimens with ratio $h/d = 2$. The tests applied on andesite rock cores revealed mixed results on specimens with a diameter of 20 and 35 compared to specimens with 50 mm. The diameters of 20 and 30 mm showed an adverse effect of h/d ratio compare to limestone, granodiorite and sandstone.

Within all tested lithological types, the lowest effect of the h/d ratio of cylindrically shaped specimens on the UCS was recorded on sandstone (Fig. 5a) and limestone (Fig. 5b). The tests on sandstone displayed the difference of UCS between the samples with $h/d = 1$ and $h/d = 2$ only (0.6 to 3.5%) depending on the specimen's diameter. The UCS value of limestone provided on cylindrical specimens with $h/d = 1$ was (4 to 8%) higher than the UCS determined on rock samples with $h/d = 2$. The highest variance of UCS on limestone was observed on specimens with a diameter of 35 mm, and the lowest difference was recognized on rock samples with a diameter of 20 mm. The tests on andesite specified the effect of h/d ratio prevailingly on samples with a diameter of 20 mm. No huge impact of h/d on UCS value of specimens with diameters 35 and 50 mm was identified (Fig. 5c). The most significant effect of slenderness ratio h/d on the UCS value was recognized on granodiorite rock cores (Fig. 5d). Strength value measured on specimens with a diameter of 50 mm and with ratio $h/d = 1$ was 21.5% higher than the strength obtained on samples with the same diameter but double the height ($h/d = 2$). The lowest effect of the slenderness ratio h/d within the granodiorite rock cores was proven on specimens with a diameter of 20 mm.

Prismatic rock specimens

The effect of h/d ratio of prismatic specimens on UCS value was investigated on three lithological types: sandstone, limestone and granodiorite. According to the records, it can be stated that the tests carried out on prismatic specimens showed identical values as those carried on cylindric specimens. That means the

specimens with the lower h/d ratio (cubic rock samples) acquired higher strength values than the specimen with a higher h/d ratio (Fig. 6).

UCS values applied on prismatic rock specimens with the slenderness ratio $h/d = 1$, were 5 to 13% higher than the UCS values determined on samples with $h/d = 2$ (Table 3). The most significant effect of the h/d ratio on UCS value provided on prismatic specimens was recorded on granodiorite. The lowest impact was seen on sandstone.

Effect of specimen shape

The last observed parameter affecting the UCS value is the shape of the specimen. In our study, the tests were performed on specimens with constant dimensions (h/d ratio, size) yet with different shapes (cylindric and prismatic shape). In the aim to define the effect of the shape, the following comparisons were performed. The average strength values of the cubic specimen with the dimension of the edge ($a = 50$ mm) and cylindric specimens with the diameter ($d = 50$ mm) and ratio ($h/d = 1$) and strength values of a prismatic specimen; block with the dimensions ($a = 50$ mm, $h = 100$ mm) with cylindric rock samples ($d = 50$ mm, $h/d = 2$). The obtained results are seen in Table 3. Except for granodiorite, the strength values gained from cubic and prismatic specimens appeared higher than from the cylindrical ones.

Discussion

One of the first available published sources evaluating the size effect of specimens on UCS value is the research by Abou-sayed and Brechtel (1976). The problem was mainly discussed in geotechnical papers and literature. One of the most complex research study related to this matter was published by Hoek and Brown (1980, 1997). Further investigations were elaborated in papers by Hawkins (1998), Yoshinaka et al. (1988), Letko et al. (1988), Thuro et al. (2001), Labaš and Miklúšová (2004), Kogure et al. (2005), Çobanoğlu and Çelik (2008), Durmeková and Ondrášek (2012), Jamshidi et al. (2014), Jamshidi et al. (2015), Al-Rkaby and Alafandi (2015), Kaklis et al. 2015) and Tuncay et al. (2019).

There is fair evidence of different views published in research papers related to the interpretation of how the size of the cylindrical-shaped specimen affects the results of the UCS test. The broadly declared argument about the size effect of rock core specimen on the UCS values is that “the strength values decreases with the increasing diameter of the specimen” (Abou-sayed

and Brechtel (1976), Hoek and Brown (1980, 1997), Yoshinaka et al. (1988), Hrašna and Hyánková (1988), Labaš and Miklúšová (2004)). This widely brought up statement was, however, not confirmed on studied rock specimens. The andesite specimens with the $h/d = 1$ ratio established a reverse trend. The same results are presented by Durmeková and Ondrášek (2012), as observed on sandstone specimens with lower strength values (very homogenous fine grained sandstones classified as soft or weak rock, with strength up to 50 MPa). The trend of gaining strength values with increasing diameter of core samples is reported in the results of a research program carried out on concrete core samples obtained

from structures that are presented in a European standard EN 12504-1 (in the Annex A). The cores with diameters 25 mm, 50 mm, and 100 mm were tested.

Results obtained on this study on specimens, i.e., sandstone rock cores with $h/d = 1$ and $h/d = 2$, granodiorite rock cores with $h/d = 1$, and andesite rock cores $h/d = 2$ are identical with the outcomes by Hawkins (1998), i.e., the strength value is increasing with a growing diameter of the specimen up to a specific diameter and then subsequently decreases. Still, it is necessary to advise that Hawkins investigated the effect only on specimens with ratio $h/d = 2$. Other results concerning the size effect on UCS, introduced in the study, agree with the conclusion stated in Thuro et al. (2001), i.e., the effect of specimen size on UCS value is insignificant.

One of the first authors, clarifying the effect of the h/d ratio of rock core samples on the UCS values was John (1972). In Slovak literature, the problem in a more detailed manner appeared in the study of Letko et al. (1988). Based on the results provided by several authors, they created a diagram showing the relationship between UCS values and the h/d ratio of rock core samples. Other research devoted to this problem was presented in papers by Thuro et al. (2001), Tuncay and Hasancebi (2009), Durmeková and Ondrášek (2012), Ximeng et al. (2015), Al-Rkaby and Alafandi (2015).

The tests demonstrated the effect of slenderness ratio h/d as clearly more noticeable as the size effect of the specimen. The findings of testing three different lithological rock cores have suggested the specimens with lower h/d ratio gaining higher UCS values, which confirm the results of some authors (John, 1972; Letko et al., 1988; Tuncay and Hasancebi, 2009; Al-Rkaby and Alafandi, 2015). The tests provided on sandstone and limestone with different slenderness h/d ratio, however, showed only minor changes in the UCS values. Similar results are declared in Thuro et al. (2001) and Ximeng et al. (2015). The effect of h/d ratio on the strength values was proved only by testing granodiorite rock cores. The tests on andesite rock cores demonstrated ambiguous outcomes. The acquired findings indicate that the uniaxial compressive strength is influenced by the slenderness h/d ratio of the specimen only to some extent, and its degree is related to the lithological type.

Besides the above-referred effects, the strength is, to some extent, influenced by the shape of the examined rock specimen. The strength values determined on cubic specimens differ from strength values provided on samples of cylindrical shape. The diverse values are a result of a different distribution of applied load stress, and the distinct nature of the failure for cubic rock cores with sharp edges compare to the smooth rounded edges of cylindric specimens. The research devoted to the above issue was explained in papers by Letko et al. (1988) and Durmeková and Ondrášek (2012).

The shape requirements of rock specimens used for uniaxial compressive strength tests were specified in the European Standard. For the utilization of rocks as a building material, the European Standard guidelines EN 1926 refer to execute the UCS test on cubic and cylindric rock cores with ratio $h/d = 1$. That is why, besides the size and slenderness factor, the shape factor was also the subject of our observations. The shape effect of tested rock cores on strength value is not of concern by that many authors as previously observed factors. An exerted and verified argument resulting from concrete testing is that the

strength value specified on cubic specimen was about 20% higher than on cylindric specimens (Harvan, 2010). According to this argument, we raised the assumption that natural rock specimens would behave similarly. As known, concrete is a composite material, so the test samples are much bigger (cubes with a base edge 150 mm, or cylinders with a diameter 150 mm). With the above statement, the rocs would act ambiguously. Within three lithological types, limestone, andesite and sandstone, the strength values measured on cubic rock cores were higher than those on cylindric rock cores. Contrary to the granodiorite, which detected higher values on cylindric rock cores.

The outcomes discovered on rock cores of sandstone and limestones with the slenderness ratio $h/d = 1$ are in accord with the statement that the strength value determined on the cubic specimens is higher than the one on cylindric specimens. The tests on granodiorite specimens disapproved of the proposed thesis. The comparison of block specimens with cylindric specimens with $h/d = 2$ is not commonly used; however, there is a similar tendency as on specimens with $h/d = 1$ recognized.

The uniaxial compressive strength tests were performed on different lithological rock types, all with high strength values (50–100 MPa) and very high strength values (100–250 MPa). The tests confirmed the assumption that when applying uniaxial load, several patterns of behaviour could be recorded due to various dimensions of the tested rock specimen. Interpretation of factors affecting the UCS values, size, the slenderness ratio h/d , and the shape of test specimens uncover one significant fact. It became evident that even visually and macroscopically homogenous sets of rock specimens showed during the tests very high heterogeneity, which led to a wide range of strength values acquired within particular groups.

Conclusions

This research pointed out that widely used arguments about the effect of specimen dimension and shape on final rock strength stated by several authors do not apply for all lithological types. The increasing occurrence of relevant experimental studies involving a wide range of lithological types as rock cores indicates an evident inconsistency of outlooks. Variable outcomes are often seen also within one lithological type. The cause for the controversial results is in the primary mineralogical and structural heterogeneity of rocks. The other reason could be the secondary defect of homogeneity caused by the presence of various superficies of discontinuities in the rock. In the aim to acquire representative and reliable strength values, it is necessary to perform testing of the likely most extensive set of specimens. In the case the rock cores with standard sizes are not available, it is not advised to use the conversion formula determined for different rock types. In heterogeneous specimen sets, which rocks mostly are, the effects of specimen dimensions are difficult to observe, and they usually vanish within the variance of measured values.

Declarations

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Tables

Due to technical limitations, tables 1, 2, 3 are only available as a download in the Supplemental Files section.

Figures

Figure 1

Map of lithological formations of Slovakia with the processed sites (map source: Hrašna and Liščák, 2004).

Figure 2

Specimen geometry (dimensions are in mm).

Figure 3

Hydraulic press (left) and detailed view on examined specimen (right).

Figure 4

Size effect of cylindric specimens on UCS values.

Figure 5

The effect of slenderness ratio h/d of cylindric specimens on UCS values.

Figure 6

Effect of h/d ratio of prismatic specimens on UCS value.

Supplementary Files

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