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CONTENTS

A simple and practical tool for indirect determination of the unconfined compressive strength of most common construction materials

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ABSTRACT

Determination of the unconfined compressive strength (UCS) of construction materials in the laboratory is tedious and time-consuming. There have been many attempts to indirectly predict UCS using simpler tools and techniques. One of them is the nail gun. The scope of this investigation is to design a nailer which can be applied all construction materials whose UCS range from 1-100 MPa. In the research, rocks, bricks, and concretes prepared in different cement/sand ratios with different strength ranges were used as materials. The unconfined compressive strength of the materials used in the experiments was first determined by conventional compression tests. The nail penetration depths were determined by conducting experiments on the same materials using a nailer with two different energy levels. An empirical relationship was developed by using nail penetration depths, driving energies, and nail diameters as the independent variables and the UCS determined by the conventional method as the dependent variable. According to the empirical relationship determined by multiple regression analysis, the UCS of building materials can be estimated with significance level of 99% by the nail penetration method. The research also revealed that the UCS of rocks might have a coefficient of variation as high as 30%.

1. Introduction

Building materials, especially rock, concrete, brick, briquette, and the binder of brick/briquette (mortar) are very diverse. The compressive and shear strengths of each of these materials are determined by laboratory methods. Although measurement of compressive strength (CS) in the laboratory may seem simple, given the conditions such as taking quality core samples with parallel loading planes, running the test on several "identical" samples of the same rock (or concrete) (e.g. ASTM, 2002), it requires considerable labor and is somewhat costly. Laboratory methods are more commonly referred to as "direct test methods". Due to both the high cost of test setups and the relatively time-consuming sample preparation and testing process, numerous studies have been carried out to date on the development of equipment and methods to determine the CS in a shorter time and at a lower cost as an alternative to the methods of direct measurement of the CS. The most prominent ones of such indirect methods are the Schmidt hardness test, needle penetration test, nail penetration test, etc.

Schmidt hardness test can be done according to ISRM (1978) and ASTM (2001) standards. The

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Schmidt hardness test is recommended for rocks with a CS of 20-150 MPa (ISRM, 1978); it does not give reliable results for rocks less than 10 MPa (Li et al., 2000). The main advantages of this test technique are its ease of application, low cost of the setup and zero test cost, and easy portability and repeatability. It is not considered a completely reliable test for rock/concrete strength; rather, it is a type of test that is usually done for preliminary assessment of the CS of the material tested.

The point load test (PLT; ISRM, 1985; ASTM, 1995) is recommended for rocks with CS greater than 15 MPa (Broch and Franklin, 1972). It can be applied to cylindrical, prismatic, and irregularly shaped samples. The CS is obtained by multiplying the point load strength [$I_{s(50)}$] found by this test by a certain coefficient. This conversion coefficient is very speculative and may range from 6 to 105, according to Yılmaz and Sendir (2002). It may only give a rough estimate of the CS of the rocks tested.

Block Punch Index Test (BPI; Van der Schrier, 1988; Ulusay et al., 2001) is performed on specially prepared thin, disc-shaped samples. It is applied on rocks with CS ranging from 0.5-70 MPa. As in many other experiments, it was stated that the effect of sample size and anisotropy on the test results was great. This test method also requires special sample preparation. Mishra and Basu (2012) used BPI method to estimate the CS and tensile strength of some rocks and showed that the BPI method is as useful as the PLT method for measuring the CS and also concluded that estimating Brazilian tensile strength with the block punch index is more precise than point load strength.

Applied on extremely weak- to very weak rocks, the needle penetration was developed to address the shortcomings encountered in test methods such as Schmidt hardness, block punch index test, and point load test. It is also validated for use on shotcrete by considering the penetration depth (Bae et al., 2004). It can measure the CS as low as 0.3 MPa. The upper limit of measurement is 40 MPa (Maruto Corporation, 2006; Ngan-Tillard et al., 2011). When the CS is in the range of 30-40 MPa, it results in standard deviations of up to 30% compared to the values obtained from the direct measurement test. It has been reported to contain large uncertainties in estimating the CS, and it has been proposed as an index test rather than a test that accurately determines the CS. The Equotip hardness tester was originally developed for metals. It was then applied to rocks by a limited number of researchers (e.g. Verwaal and Mulder, 1993; Aoki and Matsukura, 2008). The applicability range for CS is 0.1-100 MPa. It is not yet clear to what degree of reliability this test method gives the CS.

Liberatore et al. (2003) aimed to indirectly determine the strength of mortar in masonry structures with a special penetrometer they developed. The penetrometer assembly was driven into the mortars of different historical structures by repeated hammering operations. Penetration depths varied between 40-50 mm. It has been stated that the number of impacts required to apply 1 mm into the mortar varies between 0.54-1.23. On the other hand, Felicetti and Gattesco (1998) developed a dynamic penetrometer to measure the strength of mortar in masonry structures. It was stated that the impact energy of the penetrometer is 2.2 J. They also sought a relationship between the penetration depth of the penetrometer and the compressive strength of the mortar.

One of the recent methods to indirectly measure the CS of rocks is the nail penetration test (Kayabalı and Selçuk, 2010; Selçuk et al., 2012; Selçuk and Kayabalı, 2015). With this alternative technique, the CS can be measured in the range of 5-100 MPa. Kayabalı and Selçuk (2010) stated that the CS determined indirectly by the nail penetration test gives highly reliable results. They reported that the ability of the nail penetration test to determine CS is superior to the Schmidt hardness hammer and point loading test. Selçuk et al. (2012) also applied the nail penetration test to concrete samples. The results obtained from the nail penetration tests performed on concrete samples with different aggregates are in great agreement ($R^2 > 0.95$) with the results obtained from compression tests. They stated that the nail penetration test well represents the combined effect of aggregate and cement matrix on strength. Selçuk and Kayabalı (2015), on the other hand, applied the nail penetration test with nail guns of different energy levels and different nail diameters to determine the CS. They used 5 different commercial nailers with different impact energies and developed an empirical relationship that can predict CS as a function of nail penetration depth, nail gun energy, and nail diameter.

Palassi and Emami (2014) developed a mechanical nail driver with a mass of 4.54 kg and a drop height of 0.46 m. They carried out a series of experiments on travertines and marbles by keeping the 122J energy constant in a total of 6 driving operations. In their experiment with 3.5 mm diameter nails, they defined an exponential relationship with a coefficient of determination of 0.98 between the CS of intact rock and the nail penetration depth.

Yılmaz (2009) employed a test method called the “core strangle test” for indirectly determining the CS of rock core samples. The principle of this test is based on the “choke” type of loading of a core along a circle perpendicular to its long axis. Some researchers have correlated the results of the indentation test with the CS of rocks. Szwedzicki (1998) proposed a standard notch test as a measure of rock hardness and its use as an estimator for CS.

Another method used to measure strength by penetration is the Windsor probe, which was developed in the 1960s to measure the CS of concrete in situ. This relatively less destructive test is a kind of hardness strength test used to determine the CS of concrete in a short time. This technique is also based on the relationship between the depth of penetration and the compressive strength, measured by driving a special probe into the concrete. It has been reported that the calibration chart provided with the apparatus does not always give reliable results (Malhotra and Carino, 1991; Pucinotti, 2005; 2009).

A simple, robust, and economical nail penetration apparatus capable of applying two different energy levels and using different nail diameters was designed and manufactured as an end product of a research project conducted by the authors. The scope of this investigation is to predict the compressive strength of different construction materials indirectly by correlating the nail penetration depths produced through this nailer and the compressive strengths obtained from test materials (mostly rocks) and to propose an empirical relationship that yields the CS as a function of the nail penetration, nail diameter, and the driving energy.

2. Materials and Methods

The major equipment used in the study is a nail gun that has two different energy levels and can shoot with nails of three different diameters (Figure 1). Sound (or dummy) bullets were used as an energy source. For the impact energy of this tool, nail speeds (V) were determined by shooting sound bullets firing a nail in front of a high-resolution video camera. Since the mass of a nail (m) is known, the energy of the sound bullet was calculated from $W = 0.5\ m\ V^2$. The impact energy of standard sound bullets used in this investigation was found to be 150J. Considering this energy level for low-strength materials would be high, special sound bullets with a 2/3 reduction in

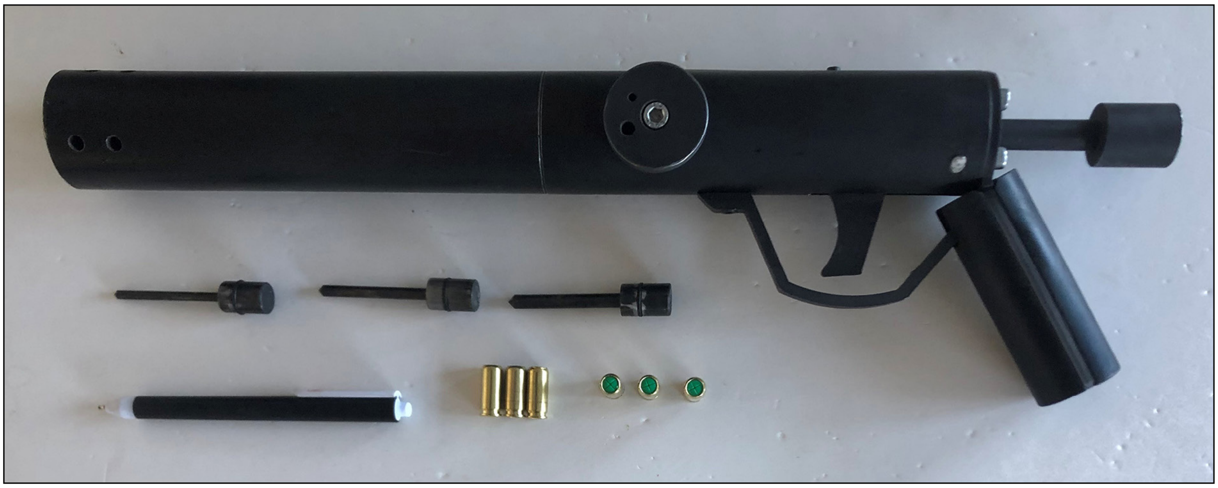

Figure 1- Nail gun, nails of three different diameters, and sound bullets used in the investigation.

gunpowder were manufactured upon special order. Their driving energies were determined as 50J. The point angle of the nails is 45^o, the nails were subjected to heat-treatment against bending during applications.

In the study, 2 types of block brick materials, 8 cast-concrete materials prepared in different cement/sand ratios, 4 concrete materials compacted with vibrating tampers, and 34 types of intact rocks were used. Most of the rocks are of sedimentary and magmatic origin, and a few are of metamorphic origin. Concrete samples were prepared in the laboratory. Brick samples were procured from commercial suppliers.

Five core samples of 54 mm (NX) diameter were taken from the bricks (Figure 2). A press with a capacity of 1000 kN was used to determine the compressive strengths of brick and rock cores.

To perform the unconfined compression tests, the guidelines of the ASTM standard of D2938 (American Testing Society for Materials, 2002) were strictly followed. The test specimens had proper cylindrical shapes with the length to diameter (L/D) ratio of 2.0 to 2.5. The sides of test specimens were kept smooth and free of abrupt irregularities. The ends of test specimens were cut parallel to each other and at right angles to the longitudinal axis. The ability of the spherical seat to rotate freely in its socket before each test was ensured. Two steel platens were used to transmit the axial load to the ends of the specimen. Constant load ratios of 10 kPa/s, 100 kPa/s and 500 kPa/s were applied to test specimen, depending on the expected UCS of the test material, and the loading continued until the specimen fails. For concrete samples a press of 50 kN capacity was employed to run the compression tests.

Figure 2- A view from brick cores.

Some brick specimens were shattered during the shooting of the nail gun owing to the limited size of the tested specimen. To prevent this, plaster was cast around brick specimens (Figure 3) and shots were carried out thereafter with a nail gun after the plaster had dried. While it was observed that the confining plaster was cracked ensuing the nail penetration test on some brick specimens, the confinement by the plaster and the container was sufficient to prevent shattering of brick specimens to obtain proper nail penetration.

The second type of material used in the investigation is concrete blocks prepared by mixing Portland cement and sand in different ratios (C/S). For the preparation of concrete blocks, cement/sand ratios (by volume) were selected as 1/2, 1/3, . . . , and 1/9. These ratios are only arbitrary; the purpose is to obtain a wider range for the compressive strength for concrete samples. The cement paste was poured into plastic containers (Figure 4). Cylindrical samplers with an inner diameter of 57 mm and a height of 120 mm were placed in the “wet” concrete paste in the plastic box (Figure 4). The main reason for placing samplers in the prismatic concrete block is that the concrete block to be used for nail shooting and the cores to be extracted as cylindrical samplers must have identical properties. Concrete mixtures at different Portland cement/sand ratios were left to dry in the open air for 28 days. After the drying process was completed,

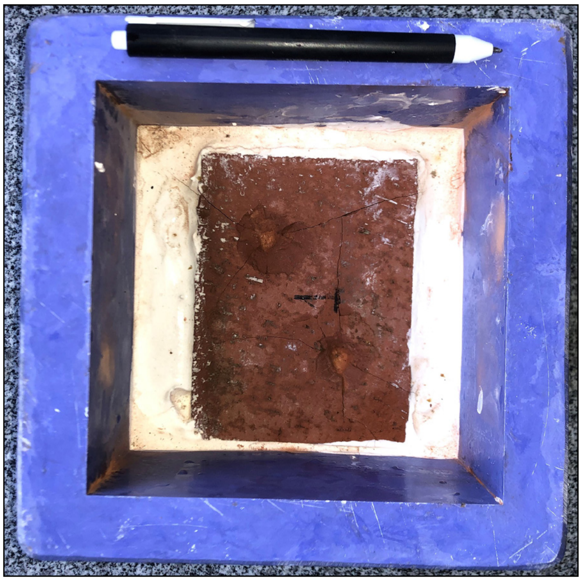

Figure 3- Encapsulated brick.

Figure 4- Casted concrete and impregnated cylindrical core samplers.

the cylindrical samplers placed in the concrete earlier were removed carefully. Five concrete core samples were prepared for each C/S ratio (Figure 5).

To increase the variety of concrete materials, prismatic samples with cement/sand (C/S) ratios of 1/2, 1/3, 1/4, and 1/5 were also prepared with a vibrating rammer. The method described in the previous paragraph was used in their preparation, except for the compaction part with a vibratory rammer.

One of the prominent advantages of the proposed tool is the variability of nail diameter. Early trials showed that a diameter of 5 mm is suitable for a wide range of UCSs. However, the application of 5 mm nails brought up two issues. One is that this nail strength was not sufficient for strong rocks (UCS > 60 MPa). The application of 5 mm nails onto such rocks resulted either in breaking or bending of nails. To prevent this, 6 mm-diameter nails were preferred. Secondly, penetration depth of maximum of 60 mm on some concrete samples were exceeded even when applying the bullets of lower energy and thereby necessitated the use of 6 mm-diameter nails. The reason for also including 4 mm-diameter nails is to increase the coverage of the proposed equation with respect to the nail diameter to predict the compressive strength of tested materials. It should be noted that the distribution of nail diameters is not equal overall in the population of nail penetration test data.

Nails with a diameter of 5.0 and 6.0 mm were used in concretes with very low strength (for samples of C/S ratios of 1/9 and 1/8). The nails with a diameter

Figure 5- Core samples of concrete prepared from different cement/sand ratios.

of 4.0 mm were not used on these concretes, since the entire length of the nail (60 mm) penetrated the concrete. In concretes with a C/S ratio of 1/2 and 1/3, low-energy bullets were not sufficient to drive 6.0 mm diameter nails into the concrete. Concretes having similar C/S ratios were shot with only 4.0 mm and 5.0 mm diameter nails. In concretes with C/S ratios of 1/4, 1/5, 1/6, and 1/7 successful nail shots were performed with all three types of nail diameters (Figure 6). Bullets with an energy of 150J and nails with a diameter of 6 mm were used in concrete samples compacted with a vibratory rammer.

Five core samples were also prepared for each rock block (Figure 7). Concerning the nail penetration tests on rock blocks, the nail piercing was observable for weak- to very weak rocks. Penetration depths were measured such that the only non-penetrating part was measured via a caliper. This length was subtracted from the nail length to find the true penetration. In cases where the rock block was moderately strong to strong, it was not possible to obtain a proper penetration of nail into the rock. In such cases the nail shot onto the rock surface created a chisel-induced ditch on the surface. To determine the penetration depth, the deepest part of the ditch created by the nail on the rock was measured with a digital caliper (Figure 8). In order to make a reliable reading in cases where the surrounding of the chisel-induced ditch has an irregular rock surface, a ring of 10 mm height was placed around the ditch and the depth of the cavity was determined (Figure 8). Since the strength of the bricks used in the study was very high, it was not possible to nail these block bricks, and the depth of the chisel-induced ditch formed by the shots made on these materials was determined similar to that in strong rocks.

3. Experimental Results

The penetration depths of nails driven into test materials were measured by shooting with a nail gun at the rock, concrete, and brick samples used in the research. Five nail shots were made on each test material. For rock materials, nail penetration tests were carried out on block samples, not on cores. In some rock samples where the block size is small, the number of shots (due to the fragmentation of the rock) remained around 3. Appropriate nail diameter and driving energy were selected depending on the strength level of the material. Nail penetration test results are given in Table 1. Five penetration depths for each sample were not entered in the table to save space. Instead, only the minimum, maximum, and average values are given.

The other major test employed for this investigation is the uniaxial compression test or simply the compression test. Five compression tests were performed for each of the rock, concrete and brick samples. The test results are given in Table 2 as minimum, maximum, and average compressive strengths.

Figure 6- Nails shot at the concrete surface. Back row: 6 mm-diameter nails, middle row: 5 mm-diameter nails, front row: 4 mm-diameter nails.

Figure 7- Core samples extracted from different rock types.

Figure 8- Measurement of nail penetration depth when a nail did not exhibit a piercing into rock.

Early trials towards establishing a correlation between nail penetration depths and compressive strengths were not satisfactory. To get an insight into the possible reason for this poor correlation, a statistical analysis was carried out for both the penetration depth of sound bullets and the compressive strength of the selected two rocks. Firstly, 30 shots were carried out on the same rock (lithic tuff-2) using the sound bullets of the first brand and nail penetration depths were recorded to gain an insight into the covariance of penetration depths of these sound bullets. The minimum, maximum, and mean (μ) penetration depths determined for these 30 shots are 6.8 mm, 18.1 mm, and 10.6 mm, respectively. The standard deviation (σ) of these shots is 3.3 mm and the coefficient of variation (COV = σ / μ * 100) is 31%. Considering that this COV is unacceptably high and these sound bullets would not be suitable for this research, 30 nail shots were made on another rock (lacustrine limestone-1) using the second brand of sound bullets.

Table 1- The results of nail penetration tests (Φ: nail diameter, h: penetration depth, E: impact energy).

No.	Name	φ (mm)	h (mm)	E (J)
1	Claystone	5	37.8/40.1/39.0	150
2	Lithic tuff-1	5	8.6/11.2/9.6	75
3	Limestone-1	5	18.5/21.0/20.2	150
4	Andesite-1	6	7.4/8.8/8.1	150
5	Limestone-2	5	8.0/8.7/8.2	150
6	Quartz arenite-1	6	6.7/7.7/7.2	150
7	Ignimbrite-1	4	16.6/20.1/17.8	75
8	Quartz arenite-2	5	12.7/14.8/13.5	150
9	Crystalline limestone	5	9.9/11.9/10.8	150
10	Trachyandesite-1	5	13.3/13.4/13.3	150
11	Marble-1	5	8.9/11.2/10.1	150
12	Granite porphyry	5	10.7/12.4/11.5	150
13	Chalk	5	20.1/21.0/20.6	150
14	Meta-limestone	5	10.4/12.1/11.1	150
15	Calcschist	5	10.8/11.4/11.2	150
16	Ignimbrite-2	4	20.1/24.7/23.2	75
17	Limestone-3	5	9.4/12.4/10.6	150
18	Trachyandesite-2	5	11.1/12.9/12.0	150
19	Granodiorite	6	6.8/7.8/7.3	150
20	Lithic tuff-2	5	20.1/26.2/23.2	150
21	Zeolithic tuff-1	5	11.7/14.0/13.0	150
22	Olivine basalt	6	6.6/9.0/8.3	150
23	Andesite-2	5	9.1/10.9/10.1	150
24	Harzburgite	6	5.4/6.7/6.1	150
25	Lacustrine limestone-1	5	18.7/24.7/21.5	150
26	Dacite	5	8.1/12.1/10.4	150
27	Andesite-3	5	11.5/13.5/12.2	150
28	Andesite-4	5	11.7/14.2/12.5	150
29	Micritic limestone	5	12.3/16.5/14	150
30	Zeolithic tuff-2	5	15.5/23.3/18.2	150
31	Crystalline tuff	5	32.9/46.6/38.6	150
31	Crystalline tuff	6	14/23.9/20.5	150
31	Crystalline tuff	5	5.8/23.6/15.3	50
31	Crystalline tuff	4	16.8/29.2/21.5	50
32	Lacustrine limestone-2	5	7.5/13.6/10.4	150
33	Marble-2	5	8.2/10.8/9.6	150
34	Lacustrine limestone-3	5	6.8/9.2/8.0	150
35	Brick-1	5	8.6/9.3/9.0	150
36	Brick-2	5	8.8/11.5/9.8	150
37	Concrete 1/9	6	21.8/30.4/27.3	50
37	Concrete 1/9	5	33.8/50.3/45.3	50
38	Concrete 1/8	6	21.2/40.8/32.6	50
38	Concrete 1/8	5	37.1/52.7/42.7	50
39	Concrete 1/7	6	20.4/27.3/23.7	50
39	Concrete 1/7	5	22.0/36.1/30.8	50
39	Concrete 1/7	4	38.9/49.4/46.5	50
40	Concrete 1/6	6	16.6/21.7/18.7	50
40	Concrete 1/6	5	18.6/33.8/25.0	50
40	Concrete 1/6	4	24.8/37.0/32.6	50
41	Concrete 1/5	6	12.3/16.7/14.9	50
41	Concrete 1/5	5	19.6/28.4/23.1	50
41	Concrete 1/5	4	21.5/30.7/27.0	50
42	Concrete 1/4	6	9.8/13.4/11.8	50
42	Concrete 1/4	5	16.0/23.9/19.6	50
42	Concrete 1/4	4	20.1/27.1/24.5	50
43	Concrete 1/3	5	14.8/23.4/17.3	50
43	Concrete 1/3	4	20.6/34.8/27.1	50
44	Concrete 1/2	5	17.2/26.2/21.6	50
44	Concrete 1/2	4	19.8/26.5/23.0	50
44	Concrete 1/2	6	33.0/38.4/34.8	150
45	Concrete 1/2*	6	19.2/19.9/19.6	150
46	Concrete 1/3*	6	20.8/23.5/21.9	150
46	Concrete 1/4*	6	23.4/24.7/24.1	150
48	Concrete 1/5*	6	25.2/27/26.3	150
48	Concrete 1/5*	4	15/19.5/17.9	50

The minimum, maximum, and average nail penetration depths recorded for these shots are 18.7 mm, 23.8 mm, and 21.5 mm, respectively. The standard deviation and the covariance are 1.5 mm and 7.0% respectively for this second trademark sound bullets which were evaluated as suitable for the research, and thereafter the nail shots were made with these sound bullets on all materials used in the investigation.

Based on the observation that the energy of the sound bullets is not constant and has a certain coefficient of variation, experimental studies have also been carried out to get an idea about the range of the coefficient of variation for a rock sample tested for compressive strength. For this, compression tests were carried out on 30 core samples (Figure 9) taken from the dacite (number 26 in Table 1). The lowest, highest, and mean compressive strengths

Table 2- The results of uniaxial unconfined compression tests.

No.	Name	σ_c (MPa)
1	Claystone	8.9/14.3/11.0
2	Lithic tuff-1	21.6/42.5/29.7
3	Limestone-1	21.9/62.3/42.6
4	Andesite-1	77.1/94.8/84.3
5	Limestone-2	34.7/90.3/57.9
6	Quartz arenite-1	83.6/137.0/103.5
7	Ignimbrite-1	24.6/29.9/27.6
8	Quartz arenite-2	37.9/59.3/50.9
9	Crystalline limestone	34.4/45.1/39.2
10	Trachyandesite-1	30.2/63.8/51.5
11	Marble-1	41.0/46.5/43.8
12	Granite porphyry	41.7/54.5/47.7
13	Chalk	27.5/50.6/40.6
14	Meta-limestone	33.8/59.5/47.9
15	Calcschist	56.1/83.8/65.8
16	Ignimbrite-2	14.9/20.9/18.0
17	Limestone-3	47.8/73.7/54.9
18	Trachyandesite-2	50.6/75.6/65.2
19	Granodiorite	69.3/112.2/86.8
20	Lithic tuff-2	27.2/50.7/39.5
21	Zeolithic tuff-1	51.2/63.3/55.8
22	Olivine basalt	86.5/119.7/99.6
23	Andesite-2	22.4/81.2/47.0
24	Harzburgite	80.1/123.2/102.4
25	Lacustrine limestone-1	15.3/25.5/20.6
26	Dacite	42.2/101.2/64.1
27	Andesite-3	42.7/59/50.5
28	Andesite-4	40.4/56.3/51.1
29	Micritic limestone	32.2/44.5/41.4
30	Zeolithic tuff-2	18.6/27.7/23.4
31	Crystalline tuff	10.0/12.7/11.3
32	Lacustrine limestone-2	62.6/88.8/79.4
33	Marble-2	37.2/52.2/43.8
34	Lacustrine limestone-3	46.3/99.8/70.4
35	Brick-1	67/127/96
36	Brick-2	44.8/73.7/59.9
37	Concrete 1/9	1.1/1.4/1.2
38	Concrete 1/8	1.0/1.4/1.3
39	Concrete 1/7	1.2/2.0/1.7
40	Concrete 1/6	2.7/3.1/2.9
41	Concrete 1/5	3.5/5.3/4.6
42	Concrete 1/4	4.9/7.3/5.7
43	Concrete 1/3	6.8/9.8/8.1
44	Concrete 1/2	5.5/8.7/7.3
45	Concrete 1/2*	19.2/19.9/19.6
46	Concrete 1/3*	20.8/23.5/21.9
46	Concrete 1/4*	23.4/24.7/24.1
48	Concrete 1/5*	25.2/27/26.3

(* These concrete samples were prepared using a vibrating hammer).

found in these tests are 42.2 MPa, 101.2 MPa, and 64.1 MPa, respectively Their standard deviation and the coefficient of variation were found to be 16.1 MPa and 25%, respectively. Another attempt was also made to determine the second coefficient of variation of compressive strength using a different rock (andesite-2). The recorded minimum, maximum and mean compressive strengths for this rock are 22.4 MPa, 81.2 MPa, and 47.0 MPa, respectively. The standard deviation and the coefficient of variation of andesite-2 were determined to be 14.5 MPa and 31%, respectively. These observations indicate that the coefficient of variation of compressive strength for the tested rocks was surprisingly high. This ensues that the compressive strength of any rock (also perhaps for

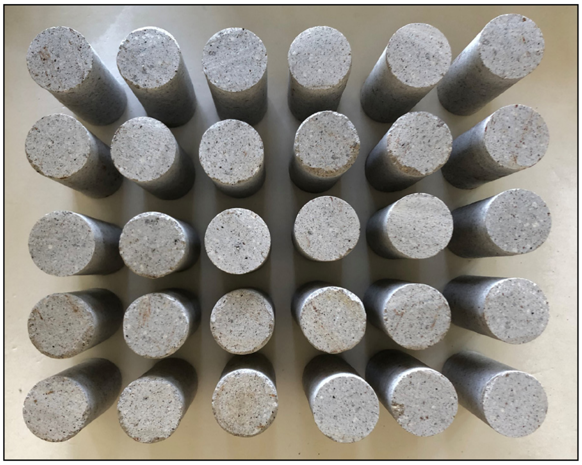

Figure 9- Rock cores from dacite to be used for the coefficient of variation of compressive strength.

any concrete) is not absolute and needs to be seriously taken into consideration when attempting to determine the compressive strength using indirect test techniques. It should be noted that the only averages of UCSs for those two types of rock which were subjected to COV analyses were included in regression analyses.

The experimental data were subjected to multiple regression analyses to seek the most suitable predictive equation to indirectly determine the UCS for various type of materials. A total of 325 nail penetration depths recorded on intact rocks, concrete, and bricks along with the corresponding nail diameters and impact energies were included in the analysis. Concerning the entry for the CS, only the mean compressive strengths were employed in the regression analysis. Apparently, there are not 325 compressive strength values; it includes only 48 sets of means. That is, the compressive strength values were repetitively used in the regression analysis. For instance, two different energy levels and three different nail diameters employed for any rock or concrete sample require the use of the same compressive strength 30 times (2 energy levels x 3 nail diameters x 5 shots = 30). DATAFIT (v. 9.0; Oakdale Engineering, 2008) program was used for multiple regression analysis. In the regression analysis, nail penetration depth, nail diameter, and driving energy are independent variables, while compressive strength is the dependent variable. Different scenarios were considered as: a) All materials, b) only the rock samples, c) only the concrete samples, d) energy level of 150J alone, and e) nail diameter of 5 mm alone. The results are presented in Table 3 along with the statistical indicators such as the Root Mean Squared Errors (RMSE), the Variation Accounted For (VAF), and the Mean Absolute Percentage Error (MAPE). It appears that the inclusion of all materials along with all nail diameters and the two energy levels yields an empirical relationship with the highest coefficient of regression ($R^2 = 0.89$):

$$\sigma_c = \exp^{(0.1453\varphi - 0.087h + 0.0142E + 2.14)} \tag{1}$$

for which the RMSE is reasonably small, the VAF is very close to 100%. However, the metrics of MAPE is critically high (50.3) for which the values greater than 50 are treated as no good. The significance level of equation (1) is 99% according to to the chi square test. This predictive equation is very similar to the one proposed by Selçuk and Kayabalı (2015). While it consists of the same independent variables as those by Selçuk and Kayabalı (2015) the regression coefficient of the predictive Equation by those researchers is higher (R^2 = 0.95) than that presented herein (R^2 = 0.89). The most likely reason for this difference may be attributed to two reasons: One is that they employed gas-nailers in their research in which the COV of penetration depths should be very low owing the constant energy released by the ignition of propane while the COV of nail penetration depths herein is somewhat higher owing to possible variations in the amount of gunpowder in the sound bullets.

The exclusion of concretes and bricks from the regression analysis yield a predictive equation with a lower value of R^2 (=0.81). The authors' preference is to use Equation (1) for all materials since the measured parameter is a common index for the three types of construction materials examined herein.

The next step included the entry of independent variables of 325 sets of nail penetration test to predict the compressive strengths indirectly. The experimentally measured compressive strengths and the computed compressive strengths using Equation (1) are plotted for 325 data sets (Figure 10). Disregarding a limited number of singular points, it is seen that the degree

Table 3- The results regression analyses (φ: nail diameter, h: penetration depth, E: impact energy, RMSE: Root Mean Squared Error, VAF: Variance Accounted For, MAPE: Mean Absolute Percentage Error).

Case	Equation	R^2	RMSE	VAF	MAPE
All materials	σ_c = exp(0.1453φ-0.087h+0.0142E+2.14)	0.89	10.3	91.8	50.3
Rock samples	σ_c = exp(0.227φ-0.07h+0.0095E+2.25)	0.81	11.4	93.5	15.7
Concrete samples	σ_c = exp(0.437φ-0.0746h+0.0177E+4.39)	0.85	1.9	92.4	12.8
E=150 J only	σ_c = 3.69φ-1.1h+0.315E	0.74	12.8	74.5	66.6
φ = 5 mm only	σ_c = 7.74φ-2.77h+0.343E	0.66	16.8	65.8	32.9

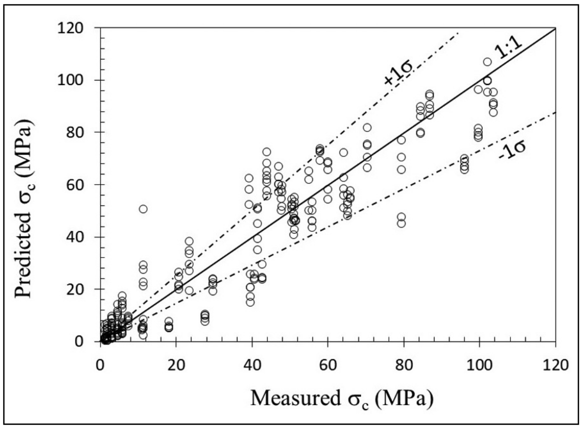

Figure 10- Graph showing the comparison between the predicted and measured compressive 348 strengths using all data.

of agreement between the computed compressive strengths and the measured compressive strengths measured is highly encouraging. The 1:1 line of the two parameters is also given in this graph. In addition, +σ/-σ standard deviation lines are also shown based on the 31% coefficient of variation determined for rock number 23 (andesite-2). A great majority of the predicted compressive strengths of the 48 tested materials were within the +1σ/-1σ standard deviation of the measured compressive strength.

Table 4 was constructed to offer guidelines for the professionals about using the proper nail diameters and different energy levels for different ranges of the UCS.

4. Conclusions and Discussion

The results obtained from this investigation are as follows:

- An empirical relationship to indirectly predict the compressive strength of building materials was established.

Table 4- Guidelines for the use of appropriate nail diameters (in millimeters) for various levels of UCS and the two levels of impact energy.

σ_c range (MPa)	E = 50J	E = 150J
0 - 20	4, 5, 6	-
20 - 60	-	4, 5
60 - 100	-	5, 6
> 100	-	6

- The nail gun employed for this investigation to indirectly predict the compressive strengths of most common construction materials is a non-destructive test and yields a very high correlation coefficient (R^2 = 0.89) between the predicted and measured CSs.

- Wide range of compressive strengths (1-100 MPa and higher) for building materials can be predicted with a great degree of accuracy using the nailer employed.

- The coefficient of variation of compressive strengths of two types of rock sample is surprisingly high. This finding has never been handled in earlier investigations and needs to be addressed further. A possible explanation for such a wide range of compressive strengths of the same rock could be the variations of micro-crack distribution in core samples. A comprehensive study is recommended in that the distribution of micro-cracks in each rock core is correlated to the respective CSs.

- The coefficient of variation of nail penetration depth is significantly smaller than that found for the compressive strength using the direct method.

- While the time required for obtaining a sufficient number of identical rock or concrete samples and running a series of compression tests on the cores of these materials may take up to several hours to one day per sample, obtaining the compressive strength indirectly by a nailer such as the one used in this investigation takes only as short as less than half an hour (for 5 shots).

- The nailer used for this investigation eliminates the need for using several different-energy level nailers for materials of varying levels of compressive strength.

The great variability with the compressive strength of the same rock material brings up the question of “is the compressive strength determined through conventional compression tests unique or an absolute value?”. It also holds for concrete materials. This is an important aspect of direct compression tests to be addressed in further investigations and must be validated by more evidence.

The proposed tool, along with the empirical equation, is capable of predicting compressive strengths greater than 100 MPa by measuring the depth on the rock surface created by the chiseling effect. Nail penetration depths are created this way for strong- to very-strong rocks and thus the compressive strength obtained indirectly may be questionable because the chiseling depth decreases as the compressive strength increases. Considering the pointy character of nails, the pointy part of nailers which ranges from 2-3 millimeters, more tests need to be run to demonstrate if the angle of the point or the length of the pointy part has any effect on the compressive strength.

As a further investigation about abnormally high coefficients of variation of rocks, the authors recommend comprehensive direct compression tests be done on rocks (and also on concretes) involving more variety of test materials. This way, the use of appropriate statistical methods may come up with the optimum selection of the true compressive strengths for building materials.

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