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Technical Note

Evaluation of mechanical rock properties using a Schmidt Hammer

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1. Introduction

The Schmidt Hammer was developed in 1948 for non-destructive testing of concrete hardness [1], and was later used to estimate rock strength [2,3]. It consists of a spring-loaded mass that is released against a plunger when the hammer is pressed onto a hard surface. The plunger impacts the surface and the mass recoils; the rebound value of the mass is measured either by a sliding pointer or electronically. Hammer rebound readings are considered consistent and reproducible [4–6]. Such fast, non-destructive and in situ evaluations of rock mechanical parameters reduce the expenses for sample collection and laboratory testing. Consequently, the mechanical parameters can be determined in dense arrays of field measurements that reflect the real inherent inhomogeneity of rock masses [7].

Schmidt Hammers were used to estimate the strength of concrete and rocks [2,8–11] via empirical correlations between rebound readings and compressive strength determined from standard tests [2,8,11]. This Technical Note extends these correlations, and we present new correlations between rebound readings of seven rock types and their measured laboratory values of Young's modulus, uniaxial compressive strength and density. The studied rocks include soft chalk, limestones, sandstone and stiff igneous rocks, covering a wide range of rock elasticity. These new correlations have already been used for a detailed field study of rock damage [7].

2. Analysis

2.1. Materials and methods

Seven rocks were analyzed: Maresha chalk, Cordoba-Cream limestone, Berea sandstone, Indiana limestone, Carrara marble, Gevanim syenite and Mt Scott granite. The sources and features of these rocks are listed in Table 1.

A digital concrete hammer, model 58-C181/F, made by Controls with an impact energy of 2.207 joules was used. This model complies with the following standards: ASTM C 805, UNI 9189-88, BS 1881, NF P18-417, DIN 1048, ISO/DIN 8045. A well-calibrated hammer of these standards is expected to generate the same readings as presented here.

Hammer readings were determined on samples of the following sizes: NX size (54 mm diameter) cores for Maresha chalk, Cordoba-Cream limestone, Berea sandstone, Gevanim syenite and Mt Scott granite; a 40 mm thick slab of Carrara marble and a 100 mm thick block of Indiana limestone. Each sample was inspected for macroscopic defects to avoid testing near fractures or material inhomogeneities. In both geometries, the tested faces were smooth and the hammer tests were performed according to the Recommended Procedure of the International Society for Rock Mechanics [9]. Core samples were placed in a 40 kg steel V-block while the rectangular samples were clamped to

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Table 1
Mineralogical and lithological properties of the investigated rocks

Rock name	Type/texture	Composition (main/minor)	Grain size	Porosity	Origin [Reference]
Maresha chalk	Sedimentary/fine granular, slightly cemented	Calcite/clay	Fine	52–60%	Bet Guvrin, Israel [13]
Cordoba-Cream limestone	Sedimentary/fine granular, slightly cemented	Calcite (85%), clay (14%), quartz (1%)	Fine	23%	Austin, Texas [14]
Berea sandstone	Sedimentary/granular, cemented	Quartz (80%) feldspar (5%), calcite (6%) clay (8%)	0.25 mm	19%	Amherst, Ohio [15]
Indiana limestone	Sedimentary/granular, cemented	Calcite (98%), minor dolomite	Fine	18%	Bedford, Indiana [15]
Carrara marble	Metamorphic/crystalline	Calcite (99%), minor quartz	0.15 mm	Low	Carrara, Italy [16]
Gevanim syenite	Igneous/crystalline	Feldspar, quartz, and minor mafic	0.25–1 mm	Low	Ramon, Israel [This work]
Mt Scott granite	Igneous/crystalline	Feldspar, quartz, and minor mafic	1–3 mm	Low	Wichita Mts, Oklahoma [17]

the flat side of the V-block. Ten individual impacts were conducted on each sample with a minimal separation of the plunger diameter between impact locations. This separation ensures that the impacts hit undamaged rock. Tests that caused cracking or other visible damage were rejected. The rebound value reported here is the average of the upper 50% of 32–40 individual impacts; averages and standard deviations are listed in Table 2. Samples of Maresha chalk yielded after a few hammer impacts, and thus only the first seven readings are used here.

The mechanical properties of the studied rocks (Young's modulus and strength) were compiled from several sources listed in Table 2. The uniaxial compressive strength and Young's modulus of Gevanim syenite and Mt Scott granite were measured at the Rock Mechanics Institute, University of Oklahoma, USA. The densities of Maresha chalk, Cordoba-Cream limestone, Berea sandstone, Indiana limestone, Gevanim syenite and Mt Scott granite were calculated from oven-dry weight of core samples. The density of the Carrara marble is after Carmichael [12].

2.2. Results: Empirical correlation parameters

The measured mechanical values display a wide range of properties (Table 2). The hammer-rebound (HR) range of 23.9–73.4 corresponds to Young's moduli ranging from 2 to 76 GPa, uniaxial strength varying from 11 to 259 MPa, and density range of 1200–2650 kg m^{-3}. The measured values shown in Figs. 1–3 were used to determine the best empirical correlations between hammer rebound and the mechanical properties. The three properties have three different functional relations to HR (hammer-rebound) as shown in Eqs. (1–3) below. These equations present the correlation parameters and correlation factor R for Young's modulus E (in GPa), uniaxial compressive strength U (in MPa), and density D (in kg m^{-3}). The third term on the right side of each equation is the standard error for the estimation of the relevant variable.

$$\ln(E)\ (\text{in GPa}) = -8.967 + 3.091 * \ln(\text{HR})\ \pm 0.101 \quad (R^2 = 0.994) \tag{1}$$

$$\ln(U)\ (\text{in MPa}) = 0.792 + 0.067 * (\text{HR})\ \pm 0.231 \quad (R^2 = 0.964) \tag{2}$$

$$D\ \left(\text{in kg m}^{-3}\right) = -2874 + 1308 * \ln(\text{HR})\ \pm 164.0 \quad (R^2 = 0.913) \tag{3}$$

Table 2
List of Schmidt Hammer data and mechanical properties of the investigated rocks

	Schmidt Hammer data (this work)					
Rock name	Mean rebound	Standard deviation	Young's modulus, *E* (GPa)	Density, *D* (kg m^{-3})	Uniaxial strength, C_0 (MPa)	Source of *E*
Maresha chalk	23.9	1.4	2.4 ± 1.1	1220	11	[13]
Cordoba-Cream limestone	41.5	2.2	12.5 ± 0.96	2070	32	[14]
Berea sandstone	50.8	1.9	19.3	2100	74	[12]
Indiana limestone	50.6	1.2	25.3 ± 1.2	2360	62	[18]
Carrara marble	58.6	0.8	39.2 ± 5.6	2710	95	[16]
Gevanim syenite	65.0	1.9	53.4 ± 2.4	2468	259	This work
Mt Scott granite	73.4	2.7	75.6	2650	243	This work

3. Applications

3.1. Use of hammer rebound values

Hammer reading values reflect an interrelated combination of rock properties such as elastic modulus, strength, hardness, surface smoothness, density and cementation. In the present work, we found good correlations between HR values and three *specific* rock properties: Young's modulus, uniaxial compressive strength and density (Eqs. 1–3). However, HR values may also display good correlation with a *combination* of several mechanical properties, for example, correlation of HR with the product of log strength and density [2]. Further, HR could be correlated with practical parameters such as tunnel boring performance (Hudson J. A., written communication, 19), or with RQD values. We found that a quantitative evaluation of a specific property with hammer readings requires some precaution as discussed below.

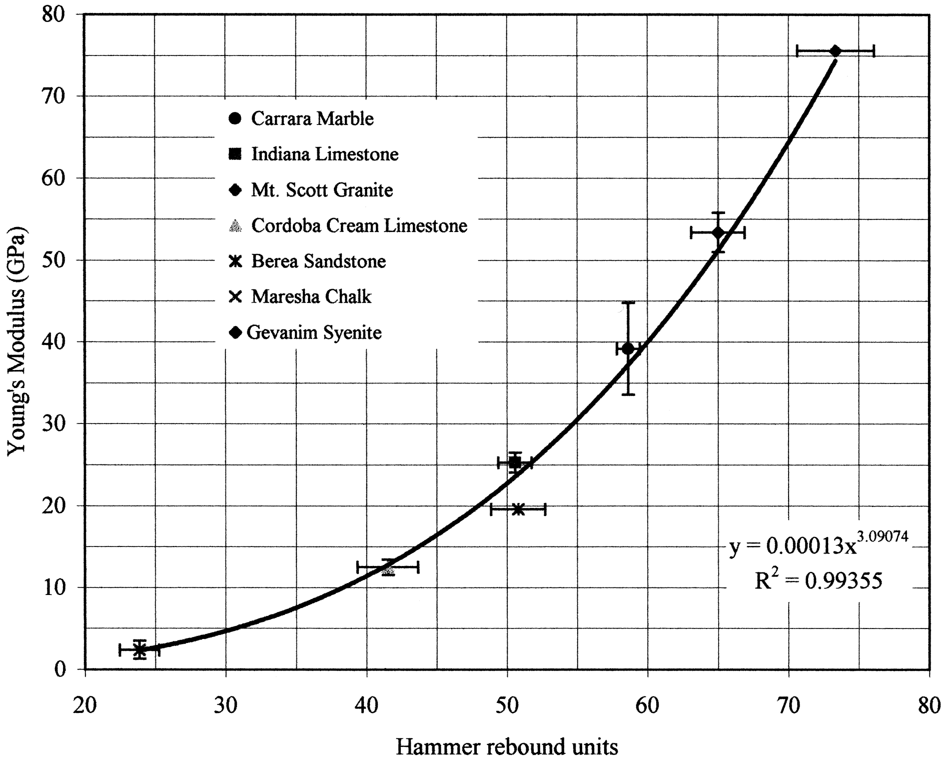

Fig. 1. Empirical relations between hammer rebound values and measured Young's modulus. Heavy line is the best-fit correlation (Eq. 1 in text); horizontal error bars indicate standard deviations of the hammer rebound measurements. Hammer measurements conducted in the present study (see text); Young's modulus sources are listed in Table 2.

3.2. Conditions in field work

We used the Schmidt Hammer for a field survey in an intrusive rock body composed of fine-grained quartz-syenite (granite like), in Ramon, southern Israel [7]. At this site the rock properties and rock structure within a faulted region were mapped in detail. The field measurements were performed on three types of surfaces: naturally weathered rock surfaces, rock surfaces polished manually with the grinding stone provided by the hammer manufacturer and surfaces polished with an electrical grinder. The grinding effectively cleans the inspected surface from the outermost weathered layer and exposes the intact rock. The values and repeatability of the hammer readings increase with intensity of polishing. For six test sites surveyed according to ISRM [9], the standard deviation was 5.57 ± 1.69 for naturally weathered surfaces, 3.80 ± 1.41 for surfaces polished manually, and 1.93 ± 1.34 for surfaces polished with an electrical grinder. Clearly, the high-quality polishing profoundly improved the quality of field measurements.

Another precaution in the field is the proximity to fractures that may reduce HR readings due to displacement or shaking. The measurement of a loose or fractured block provides reliable HR value if the block weighs a few tens of kilograms or more.

3.3. Rock type

We think that the good correlations observed here, and particularly the excellent fit of Young's modulus (Fig. 1 and Eq. 1), indicate that the rocks used are well cemented and elastic. Poorly cemented, friable rocks, that disintegrate or fracture under the hammer impact, could provide less consistent correlation. This dependence on rock type was demonstrated by Cargill and Shakoor [2]. They analyzed hammer rebound data for 13 rock types, and correlated the logarithm of the uniaxial compressive strength with the product of dry density, D, and hammer rebound, HR, i.e.

$$\log(U) = k(D\ \mathrm{HR})$$

where k is a constant. These authors derived two different curves, one for sandstones and one for carbonates, and suggested that the results are sensitive to the rock type.

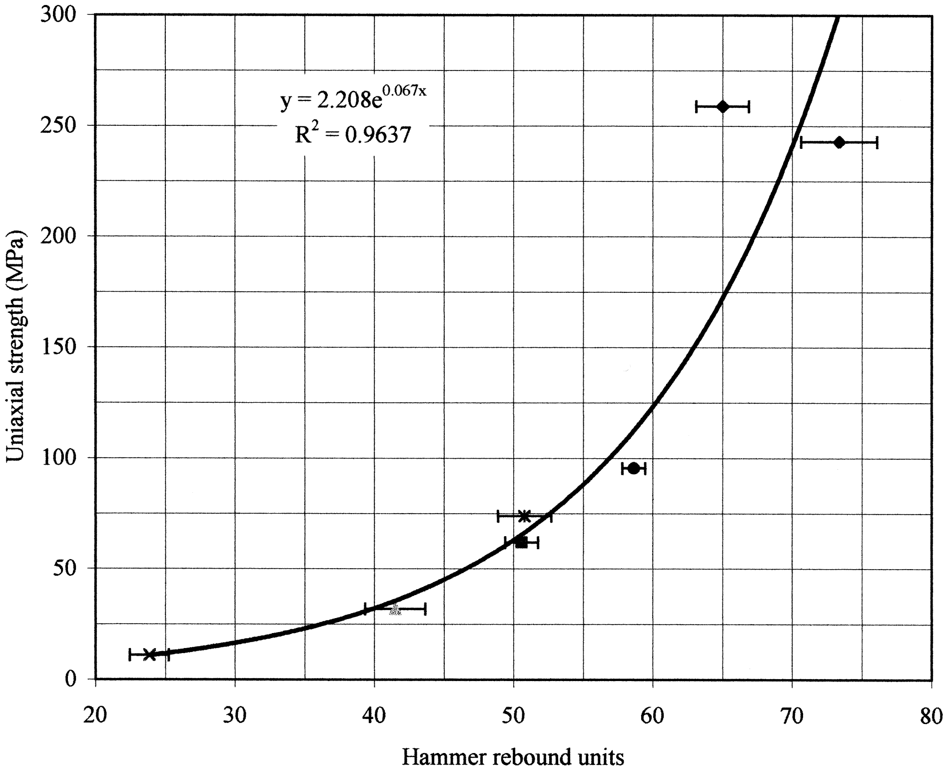

Fig. 2. Empirical relations between hammer rebound values and the measured uniaxial compressive strength. Heavy line is the best-fit correlation (Eq. 2 in text); horizontal error bars indicate standard deviations of the hammer rebound measurements. Hammer measurements conducted in the present study (see text); sources of strength values are listed in Table 2. For legend see Figure 1.

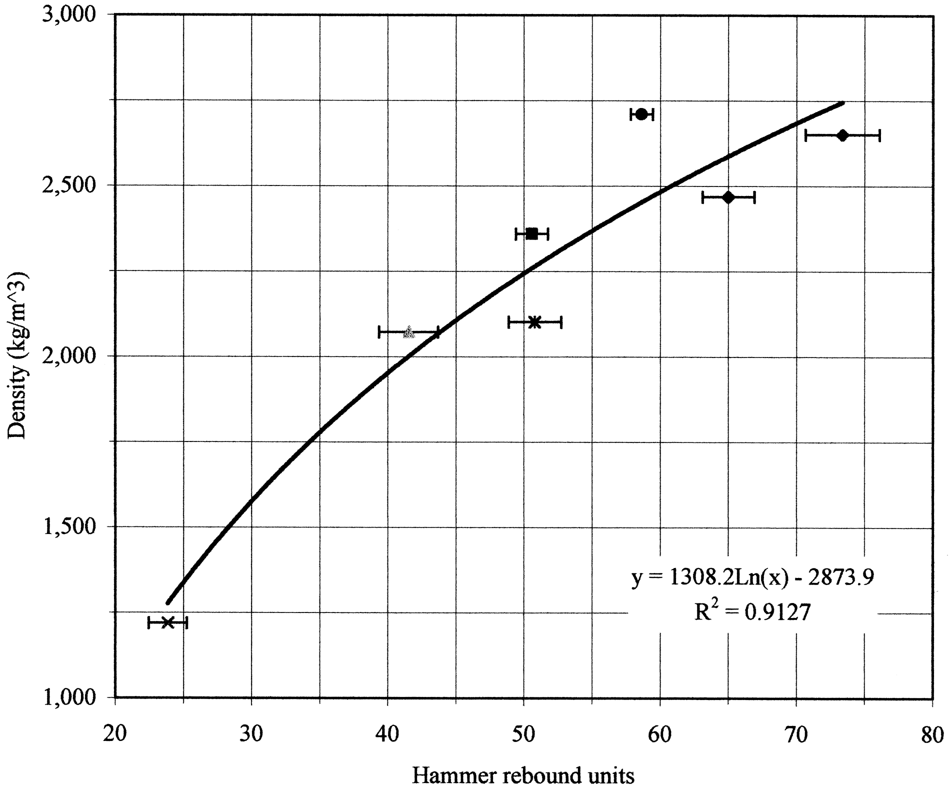

Fig. 3. Empirical relations between hammer rebound values and the measured dry density. Heavy line is the best-fit correlation (Eq. 3 in text); horizontal error bars indicate standard deviations of the hammer rebound measurements. Hammer and density measurements conducted in the present study (see text); density of Carrara marble after [12]. For legend see Figure 1.

4. Conclusions

Empirical correlations between rebound reading of Schmidt Hammer and laboratory measured values of Young's modulus, uniaxial strength and dry density have been presented (Figs. 1–3). The correlation factors of Eqs. (1–3) can be used to estimate the relevant mechanical properties in the field and laboratory subject to the following precautions:

1. The tested rock is well-cemented and apparently elastic;
2. Rocks that tend to disintegrate under hammer impact or samples that crack under the impacts cannot be properly tested;
3. Hammer measurements should be conducted on smooth surfaces; polishing with an electric grinder is strongly recommended for fieldwork; and
4. Loose blocks (or fractured blocks) can be measured if the intact part of the block weighs a few tens of kilograms or more.

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