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TOWARDS A RAPID AND PRACTICAL DETERMINATION OF THE PIN-ROCK INTERACTION PARAMETERS OF THE CERCHAR ABRASIVITY TEST

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Abstract

The CERCHAR test is a widely used index test for evaluating rock abrasiveness and associated tool wear in rock excavation. However, routine testing only assesses the wear on the pin itself. To evaluate the advancement rates in rock cutting during excavation, it is also crucial to consider the material removal of the rock. Recent studies have begun to include this aspect by developing advanced methods, automated testing devices, or using customized equipment for test evaluation. However, these methods are too time-consuming and specialized to be used in routine laboratory testing. This study investigates the correlation between traditional CAI and associated material removal by complementary measurements of the scratch groove on the rock specimen using a stereomicroscope. The presented approach enables the straight forward determination of additional parameters, such as rock volume removal and pin tip loss, based on the inherent pin tip geometry and associated scratch groove geometry. These parameters are then used to calculate the CERCHAR Abrasion Ratio, which serves as a proxy for the excavability of different rock types. Despite some minor limitations, this approach can deliver values that are comparable to those obtained using specialized equipment. Therefore, it has the potential to be a practical method for assessing abrasion and excavation on job sites.

Key words

Rock excavation, CERCHAR Abrasivity Index, CERCHAR Abrasivity Ratio.

1 Introduction

The CERCHAR test was developed over 50 years ago as a quick way to assess abrasivity on job sites (Valantin, 1974; Thuro 2002, Rostami et al., 2005). Since then, numerous studies have presented more comprehensive and sophisticated methods to characterize the processes associated with rock and pin properties during this test. The CERCHAR Abrasivity Ratio (CAR), as well as testing devices equipped with real-time monitoring sensors were recently proposed to address these issues (Hamzaban et al. 2014, Zhang and Konietzky 2020, Zhang et al. 2020, Karrari et al. 2024). Although these studies offer valuable insight into rock excavation, the methods presented require specialized equipment, such as scanning electron microscopes, 3D high-resolution microscopes and/or real-time sensors. The aim of this study is to extend the evaluation of the CERCHAR test to apply these methods outside of academic institutions. This is achieved by addressing rock-pin interaction through the use of intrinsic geometric properties of the stylus and straightforward measurements of the scratch groove on the tested rock specimen. The pin tip wear (CAI) and material removal is linked based on these measurements and the CERCHAR pin geometry. Results are related to other parameters used in the industry such as the Rock Abrasivity Index (RAI) and uniaxial compressive strength (UCS). The method is tested on a wide range of sedimentary rocks (Alpine Flysch Zone, Karawanke Mountains), metamorphic rocks (Austro-Alpine basement) and igneous rocks (Bohemian Massif), to assess its potential applicability and limitations.

2 Methods

In total, 60 specimens of metamorphic, sedimentary and igneous rocks were investigated for their abrasive behavior and excavability. The rocks cover a broad range of fabric characteristics, such as grain size, anisotropy, strength and mineralogical composition. The rocks were tested using a CERCHAR device with a fixed, stationary steel pin while the sample is being moved by a handwheel (West 1989). The pins and testing procedure comply with AFNOR and ASTM standards, and ISRM and DGGT recommendations (AFNOR 2000, Alber et al. 2014, Käsling and Plinninger 2016, ASTM 2022). The pins are 10 mm in diameter and have a Rockwell hardness of HRC 55±1 with a 90° conical tip. Specimens are formatted into blocks of approximately 50 x 50 x 100 mm. The rocks are cut with a diamond saw to ensure uniform test surface conditions (ÖBV 2013). Metamorphic and sedimentary rocks are tested perpendicular to their foliation and bedding, respectively. The pin tip wear of 5 pins for each sample is measured under a transmitted light microscope (80x magnification). From the average of these 5 measurements the CERCHAR Abrasivity Index (CAI) is calculated. The cross diameter of the corresponding scratch grooves produced by the pins on the rock sample are measured under the same microscope in reflected light mode. The uniaxial compressive strength (UCS) tests are conducted load and/or strain controlled with a minimum duration of 5 minutes following the recommendation No. 1 of the Commission on Rock Testing of the German Geotechnical Society (Mutschler 2004) and the standard ON B 3124-9 (Austrian Standards International 1986) using an MTS model 815. Bulk mineral compositions were determined by x-ray powder diffraction analyses (XRD) using a PANalytical X´Pert PRO diffractometer. Based on the mineralogical composition of the samples, the equivalent quartz content (F_{EQu}) is calculated using the quartz normalised factors of recommendation No. 25 of the Commission on Rock Testing of the German Geotechnical Society (Plinninger et al., 2021). The Rock Abrasivity Index (RAI) is calculated as the product of UCS and F_{EQu} (Plinninger 2002).

3 Results

3.1 Parameters of pin-rock interaction

The 90° conus geometry of the pin tip and the associated scratch groove exhibit certain intrinsic relations that are used to extend the evaluation of the standard CERCHAR test. The volumetric wear volume of the pin tip (V_s in Fig. 1) can be obtained from the CAI by either using the conical volume (Eq. 1) where the height and radius are equal (i.e. 0.05 CAI, or pin tip wear height) or the exponential relationship (Eq. 2). The amount of material removed from the rock during the test is indirectly inferred by measuring the scratch width (Sw) produced on the sample (Fig. 1). The pin geometry is directly related to the scratch width, i.e. the deeper the indentation, the wider the scratch. Knowing the CAI and the scratch width (Sw), it is possible to calculate the pin penetration depth into the rock (P_x) and the vertical pin displacement (A_x) using Eq. 3 and 4. Depending on the tested rock type, different scenarios are realized for these geometric parameters. The proportion of P_x varies greatly, being close to zero for hard rocks like granite, or equal to A_x for very soft rocks (Fig. 1a-c).

$$V_s\ [mm^3] = \frac{1}{3}\pi * 0.05CAI^3 \quad (1)$$

$$V_s[mm^3] = 0.00013 * CAI^3 \quad (2)$$

$$P_x\ [mm] = \frac{(Sw - 0.1CAI)}{2} \quad (3)$$

$$A_x\ [mm] = P_x + 0.05CAI \quad (4)$$

From the CAI, P_x and Sw the corresponding idealized removed rock volume over a testing distance of 10 mm can be calculated as a trapezoid (Eq. 5):

$$V_m\ [mm^3] = (Sw + 0.1CAI) * \frac{P_x}{2} * 10 \qquad (5)$$

The ratio between the volume of the removed rock material (V_m) and the abraded pin tip volume (V_s) is the CERCHAR Abrasion Ratio (CAR), providing information on the excavability associated with the abrasivity of a rock (Zhang and Konietzky, 2020). The formula for calculating the CAR is given in Eq. 6.

$$CAR\ [-] = \log_{10}\left(\frac{V_m}{V_s}\right) \qquad (6)$$

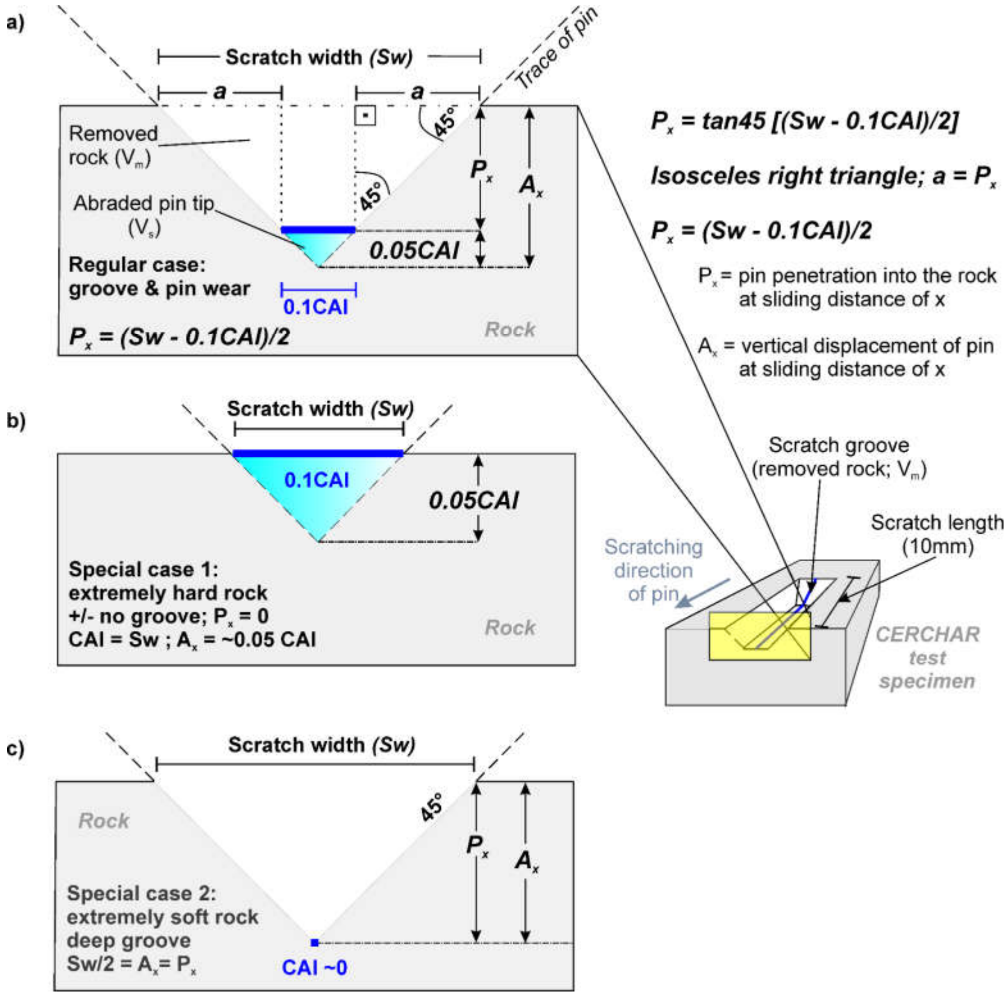

Figure 1. Concept and scenarios of CAI and associated removal of rock material, i.e. excavation. a) regular case: the pin abrasion and rock excavation occur at the same time. b) extremely hard rock: the pin is abraded without significantly penetrating into the rock. c) soft rock: the pin deeply penetrates into the rock with only minor abrasion taking place at the pin tip.

The groove is identified by the color difference to the surrounding diamond saw cut surface and exhibits a prominent edge (Fig. 2). This edge is best developed in fine grained, sedimentary rocks or marbles (Fig. 2a,b). The Sw is measured by applying tangent lines at the edges without incorporating breakout moulds in order to account for an idealized V-shaped groove (Fig. 2c). In hard, coarse grained crystalline rocks the groove is sometimes poorly developed, irregular or almost invisible (Fig. d-g). This may be attributed to the skating effect (Al-Ameen and Waller 1994, Macias et al., 2016) known to occur in these

types of rocks (Fig. 2h). Whenever possible the Sw is measured in the last 25 % of the scratch groove where pin tip wear is already close to the final CAI. Plinninger et al. (2003) showed that about 85 % of the final pin tip wear already occurs within the first two millimeters of the scratch (Fig. 3a). Thus, as the pin loses material at the tip and simultaneously penetrates the rock, the vertical displacement (A_x) also increases and follows a similar pattern (Fig. 3b). The actual removed material corresponds to the area top of the P_x–sliding distance curve recorded during the CERCHAR test (Karrari et al. 2024).
For uniformly shaped scratch grooves one representative cross diameter was measured at each scratch. For irregular shaped grooves (i.e. varying penetration depths), a mean value of multiple cross diameters was determined. Similar to determining the CAI, the mean value of 5 scratch width measurements is calculated for each rock sample.

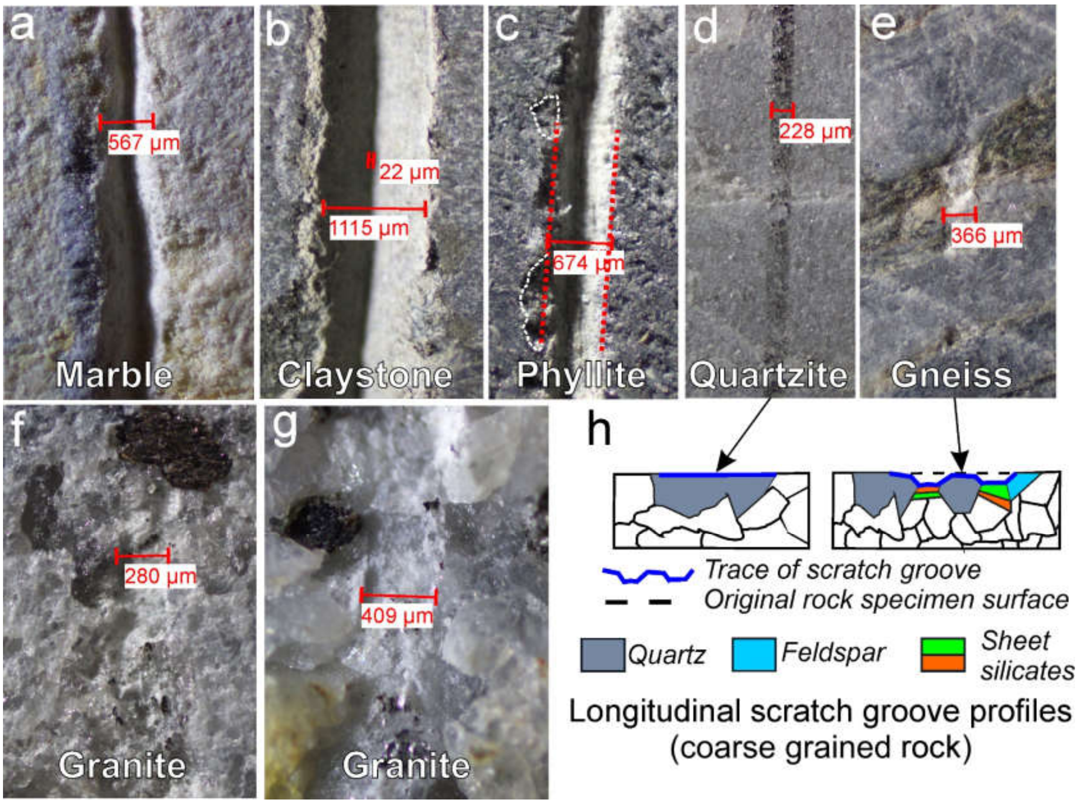

Figure 2. CERCHAR test scratch grooves of different rock types. a) Marble with a distinct v-shaped scratch groove profile. b) Sharply defined scratch groove in a claystone penetrating deeply into the rock. The groove base is close to the actual CAI measured at the pin tip. c) Phyllite with minor breakout moulds (white dashed outlined areas) and applied tangent line at the edge of the scratch groove. d) Extremely hard quartzite with only a surficial trace of the scratch. e) Gneiss exhibiting differential pin indentation due to mineral hardness differences. f) poorly developed scratch groove in a granite. g) granite with quartz grains ripped out of the fabric. h) schematic drawing of a scratch groove with varying P_x on hard, coarse grained rock.

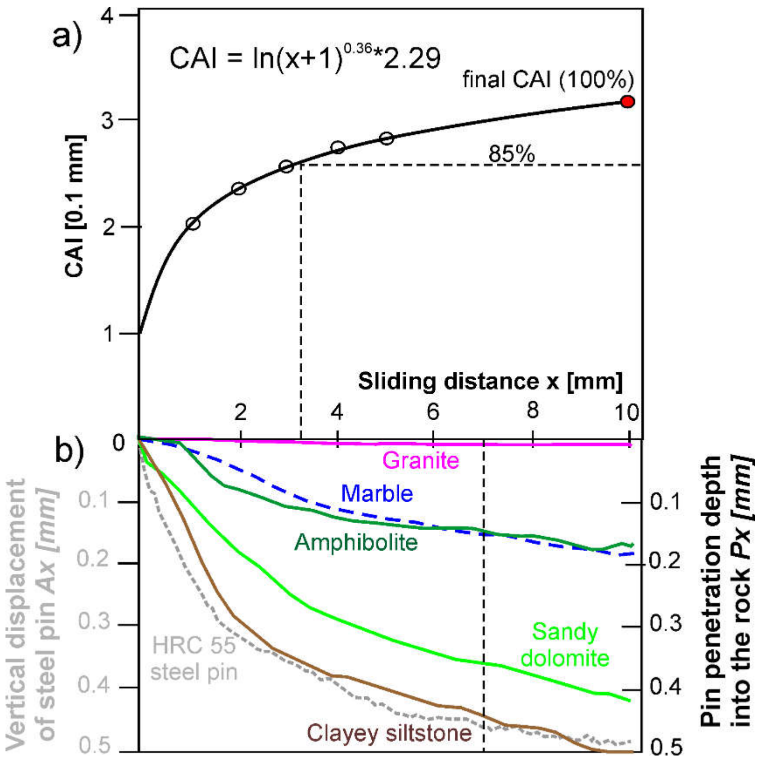

Figure 3. Relation between pin tip wear and penetration depth for different rock types as a function of the sliding distance of the pin. a) CAI vs. sliding distance (modified after Plinninger et al. 2003). b) Vertical displacement and pin penetration depth as a function of the sliding distance (compiled and modified after Hamzaban et al. 2014). Absolute pin penetration depths (P_x) depend on the rock type, but patterns are similar and the pin penetration depth is already close to its final level after 75 % of the sliding distance. The vertical pin displacement (A_x) approaches P_x for very soft, non-abrasive rocks (e.g. clayey siltstone) and is equal to 0.05CAI for very hard rocks (i.e. only pin tip wear with no penetration into the rock; see special cases shown in figure 1b and c).

3.2 Concept evaluation

In general, the penetration depth into the rock decreases with increasing abrasivity. With coarse grained crystalline rocks (granite) there can be a discrepancy between the scratch width and the CAI value, i.e. negative P_x (Fig. 4a). This may be due to the measuring technique for the pins if abrasion is uneven at the tip. Therefore, the measured CAI is higher than the actual contact area of the pin with the rock surface. Especially rocks falling into the classes CAI<3 exhibit a wide range of material removal for rocks falling into one CAI category. Interestingly, the relative range is very similar for the first four abrasivity classes and lies between V_m 2.16 – 2.76 mm³. For the classes CAI>3, the values are between V_m 0.79 – 0.01 mm³. This boundary roughly coincides with the transition from sedimentary to crystalline metamorphic and magmatic rocks (Fig. 4a). Figure 5 shows a compilation of the pin tip wear height and P_x and the associated CAR for the six investigated rock groups.

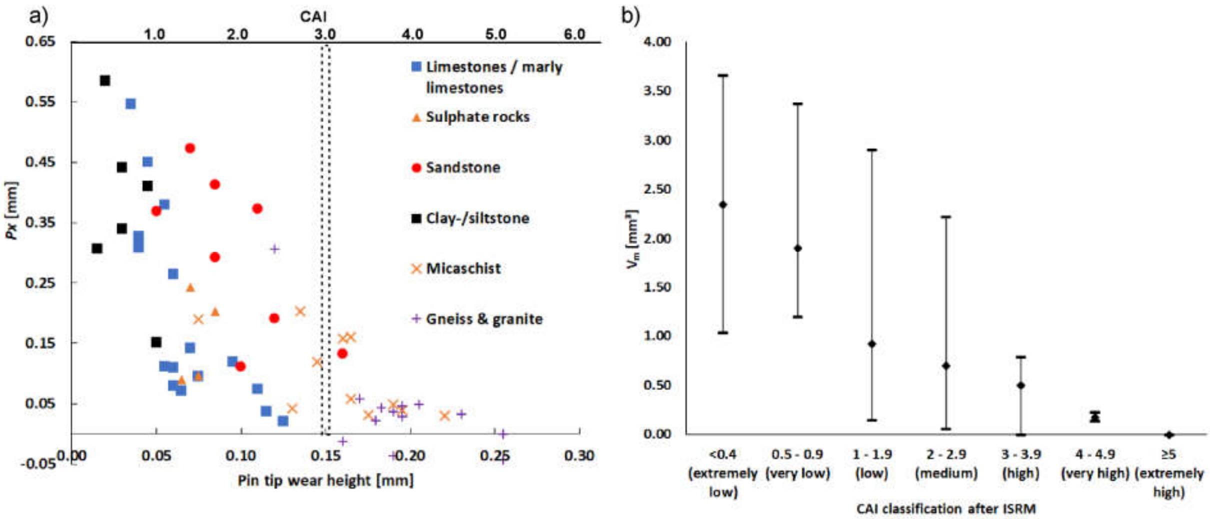

Figure 4. Range of excavability. a) pin tip wear height (or corresponding CAI) versus pin penetration depth P_x. Sedimentary rocks are found at CAI<3. The majority of crystalline rocks exhibits values CAI>3. b) The range of removed rock material (V_m) within the different CAI classes.

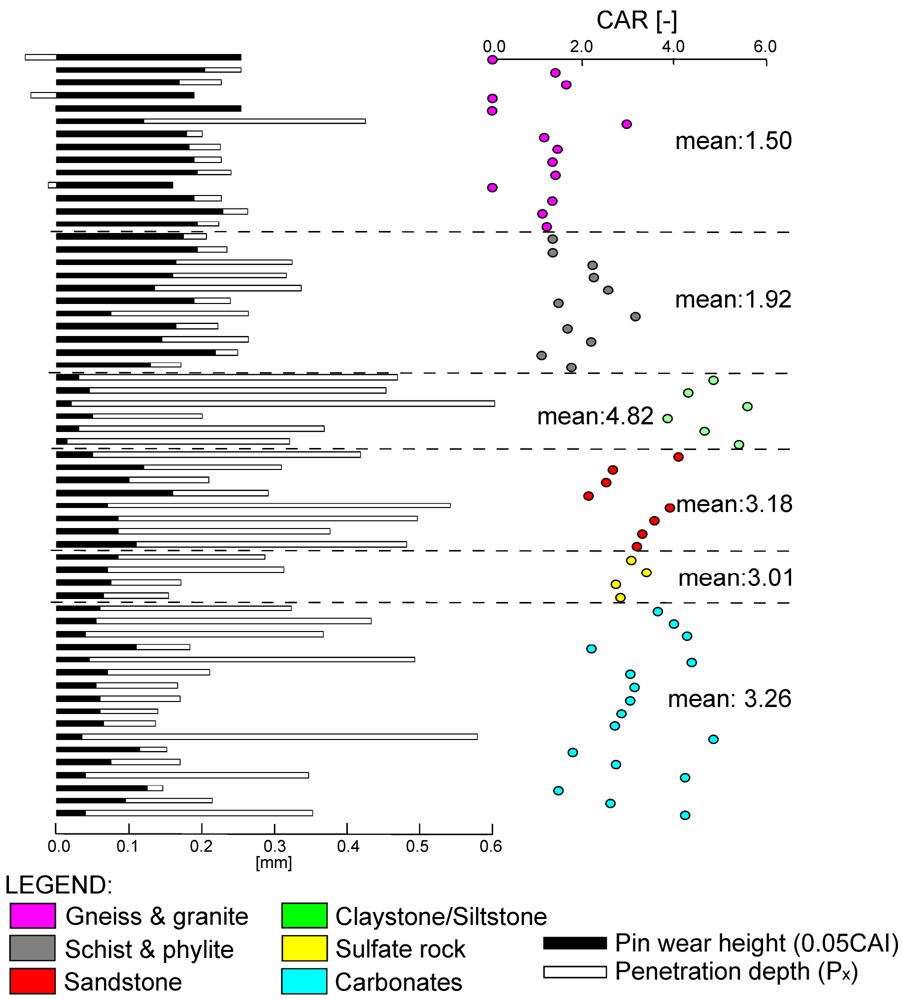

Figure 5. Compilation of the pin wear height, pin penetration depth into the rock and associated CAR for the investigated rock types. Note that negative values for the penetration depth are obtained for some very hard rocks and thus CAR cannot be determined, i.e. becomes zero.

The penetration depth cannot be attributed to a single rock property. P_x is rather controlled by factors such as porosity, grain size and the fabric of the rock type. There seems to be a limitation in penetration depth above a certain threshold of UCS of approximately 60 MPa, where no deep penetrations are realized. This value corresponds to the value reported by Kaspar et al. (2023) above which the CAI can most reliably be predicted from mineralogical analyses using reference values from single crystal scratch tests. Penetration depths higher than 0.25 mm are only observed for sedimentary rocks, while low values (approx. 0.15 mm) are observed for crystalline rocks. However, there are also sedimentary rocks with small P_x. These are dominated by massive, fine grained, relatively pure limestones. In fact, an increase in other components than carbonates (i.e. quartz, feldspars and sheet silicate) seems to have an adverse effect on the penetration depth. The marly limestones, for example, plot in the upper region of the diagram in Fig. 6. Weakly cemented rocks and fine grained rocks such as sandstones and clay-/siltstones exhibit the highest penetration rates and their CAI does not exceed 2. In such cases, mineral grains are probably more easily removed from the rock fabric. The content of hard, abrasive minerals (Mohs hardness >5.5; Plinninger 2008) alone does not serve as a proxy for abrasion or resistance against penetration. The sandstone in Fig. 6, for example, has a quartz content of 84 %, but a very high penetration depth, pointing to a microstructural control rather than mineralogical control. The only crystalline rock with higher penetration depth is a chlorite rich green schist plotting between the two clusters.

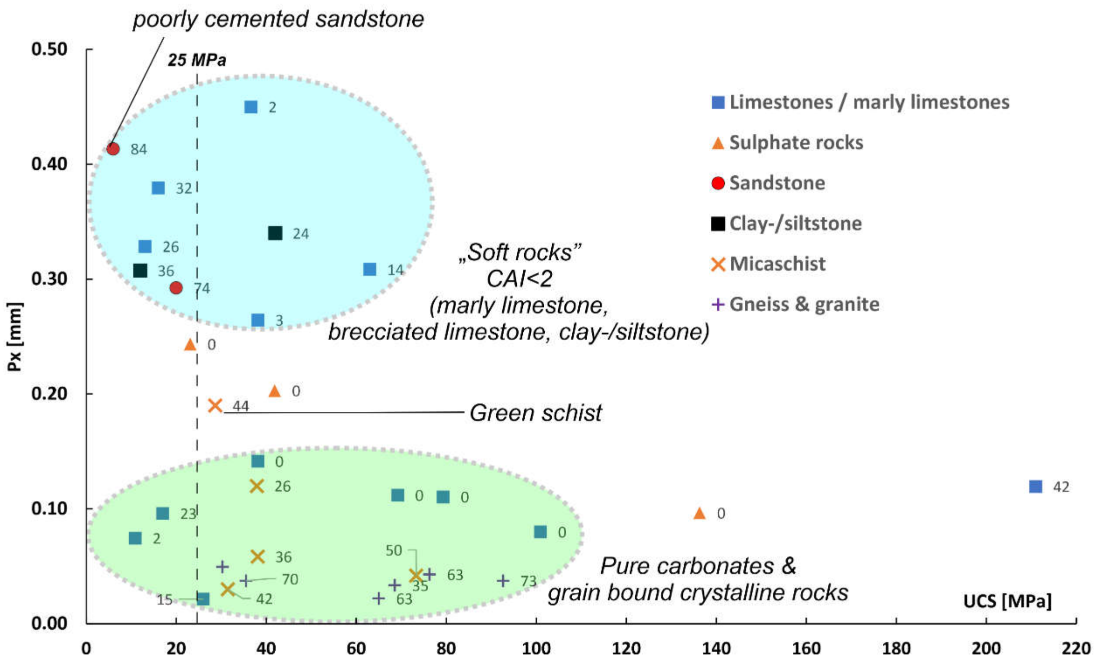

Figure 6. Plot of penetration depth (P_x) and UCS. The cluster in the upper, light blue region comprises weakly cemented sedimentary rocks and impure carbonates (marls) and clay-/siltstones, commonly referred to as soft rocks. The lower, light green cluster comprises well interlocked, pure carbonates and grain bound crystalline rocks. The traditional limit for defining soft rocks by means of UCS = 25 MPa is shown for reference. The numbers next to the symbols indicate the content (percent) of abrasive minerals with a Mohs hardness >5.5.

There is a negative linear correlation between CAI and CAR with the overall regression coefficient being consistent with the one published by Zhang and Konietzky (2020) (Fig. 7). A weak correlation is found for the CAR and RAI (Fig. 8a). It roughly reflects the pattern that rocks with a high CAR have a low RAI and are less abrasive and thus easier to excavate. The fitting for all rock types is slightly lower than for RAI and CAR (Plinninger and Thuro 2004) (Fig. 8b). Crystalline rocks tend to have higher ranges of RAI with low CAR, while the opposite is the case for sedimentary rocks. This supports the general hypothesis that sedimentary rocks can be excavated more efficiently while being less abrasive on the tool. Crystalline rocks on the other hand are less efficiently excavated and cause more damage on the tools. However, there are limestones with low CAR and low RAI. Such rocks might be less efficient to drill/excavate, but are not abrasive on the tool. This points to a mineralogically controlled abrasivity for this kind of rocks.

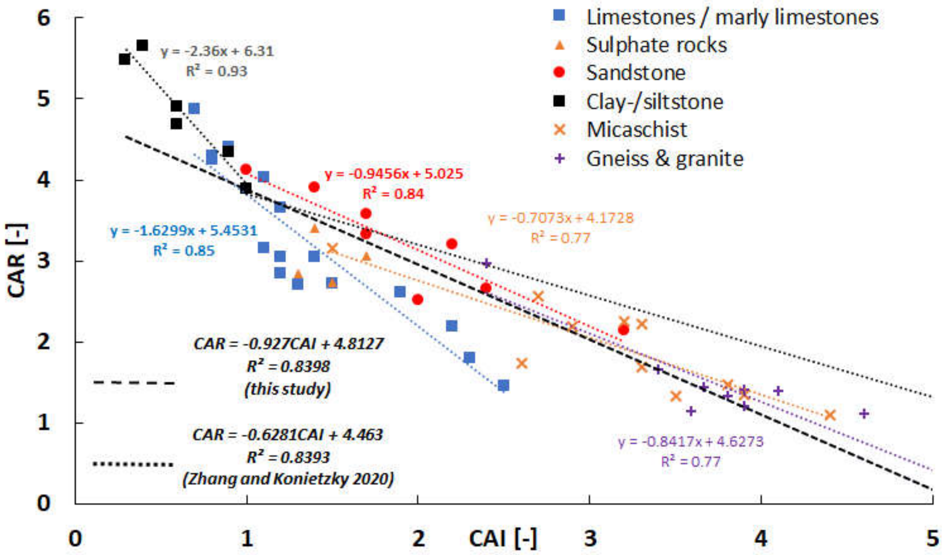

Figure 7. Correlation between CAI and CAR for the different rock types. Overall regression line and formula of Zhang and Konietzky (2020) is shown for comparison.

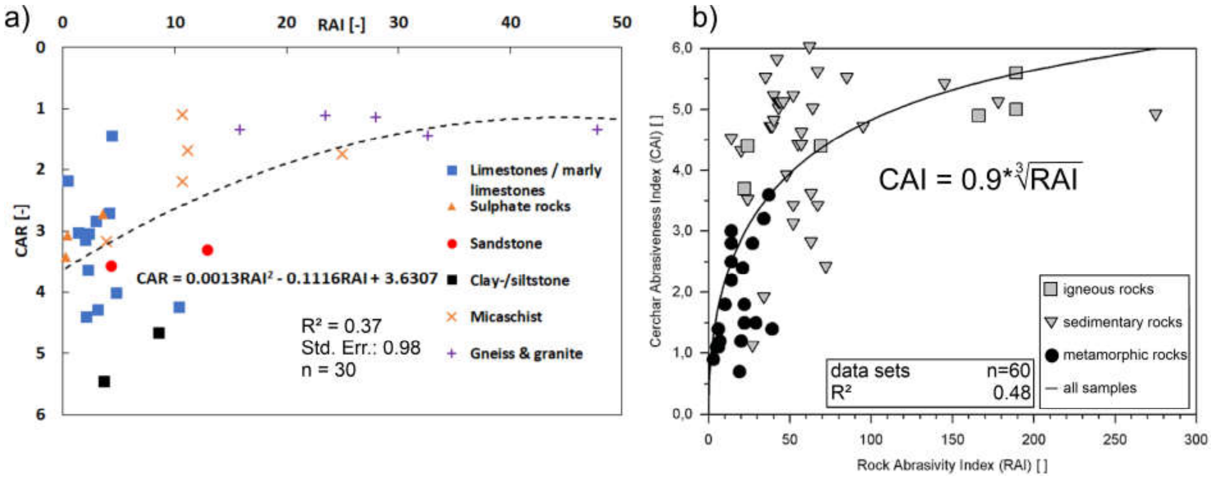

Figure 8. The CAI in relation to other parameters. a) correlation between CAR and RAI obtained for the used dataset. b) correlation between RAI and CAI (after Plinninger and Thuro 2004, Schumacher 2004).

The details of the statistical analysis for Fig.8a is given in Tab.1 and Tab.2. The significance level from the F-test is essentially 0 and the p-values from the t-test are lower than 0.05, fulfilling the conditions for a significant correlation between CAR and RAI.

Table 1. Variance analysis and F-test

Parameters	Degrees of freedom	Sum square	Mean square	F	Sign.-level.
Regression	2	15.23	7.62	7.95	0.002
Residue	27	25.88	0.96	1.5/1	
Total	29	41.11			

Table 2. Regression coefficients and t-test

Parameter	Coefficient	Std. err.	t	p
Intercept	3.6307	0.2732	13.2885	0.0000
RAI	-0.1116	0.0301	-3.7058	0.0010
RAI^2	0.0013	0.0004	2.9338	0.0068

4 Conclusion

The presented approach individualizes the assessment of the CAI and associated material removal irrespective of the tested lithology. So far, the CAI only provided information for the tool wear, but not on the excavation progress. Instead of utilizing a high-resolution 3D model of a scratch groove obtained from specialized instruments, the basic 2D scratch dimensions are measured under the same microscope used for determining the CAI. This is less time consuming and can be performed in a second step at the rock specimen after measuring the pin tip wear. There are limitations such as irregular groove profiles so that only approximations of the actual groove volume are possible. Nevertheless, it provides additional information on the excavability behavior in rock dredging projects. Even though the presented approach uses idealized and simplified geometries the results reflect those obtained from other more laborious methods. The CAR results, for example, are consistent with the findings of Zhang and Konietzky (2020) and show similar patterns and fittings. The absolute values vary, probably as a result of natural variations in rock composition and fabric. Limitations occur for very abrasive rocks with little to almost zero material removal leading to unrealistic negative P_x values. This effect was also observed by Hamzaban (2014) where abnormal curves occurred with very little P_x values. The reason lies in the measurement of the CAI. If the wear flat is not perfectly flat, the contact area of the steel pin with the rock can be smaller than the measured CAI. In combination with very little penetration into the rock, Sw is also close to the CAI, so that the method might not be reliably applicable in such extreme cases. For the evaluation presented here, saw cut rock surface should be used to eliminate the uncertainties due to height changes of rough surfaces. Furthermore, the additional information on the penetration depth (P_x) and the associated removed rock volume (V_m) can be used to refine the traditional understanding of soft rocks. Kaspar et al. (2022) highlighted the heterogeneity of natural stone materials and that both, strength and mineralogical composition influence to varying degrees the abrasivity of different rock types. The presented approach in this study adds information on the excavability to the solely UCS based definition of soft rocks.

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