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Statistical Analysis of CAI Variability Among Rock Types

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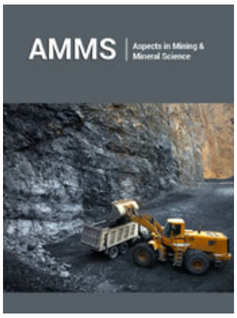

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Abstract

The Cerchar Abrasiveness Index (CAI) is widely used in rock mechanics and excavation engineering to assess rock abrasiveness, which influences tool wear and excavation efficiency. Understanding how CAI varies across different rock types (igneous, metamorphic, and sedimentary) is crucial for optimizing machine selection and excavation methods. This study conducts a statistical analysis of CAI values obtained from existing literature to identify variations among different rock origins and specific rock types, including granite, basalt, sandstone, clay, and marble. Using descriptive statistics, Analysis of Variance (ANOVA), and post-hoc tests, we evaluate whether statistically significant differences exist between these categories.

The methodology includes data collection from published sources, normalization of CAI values, and statistical calculations using SPSS software. ANOVA is applied to test differences between rock groups, while Tukey's HSD post-hoc test determines specific group differences. Additionally, boxplots and histograms are used to visualize CAI distributions, and correlation analysis explores relationships between CAI and rock properties such as Uniaxial Compressive Strength (UCS) and density. Findings are expected to show that igneous rocks (granite, basalt) have higher CAI values due to their mineral hardness, while sedimentary rocks (sandstone, clay) exhibit lower abrasiveness. Metamorphic rocks (marble) may show intermediate values due to mineral recrystallization. The results provide practical implications for excavation tool selection, wear prediction, and cost estimation in the mining and tunneling industries. This study contributes to the quantitative understanding of CAI variability, offering insights for geologists and mining engineers to enhance excavation efficiency and reduce operational costs.

Keywords: CAI; Excavation; Rock mechanics; Statistical analysis

Introduction

The abrasiveness of rocks plays a crucial role in excavation, tunneling, and mining operations, directly impacting tool wear, operational costs, and equipment lifespan. Rock abrasiveness refers to the ability of a rock to cause wear and degradation of cutting tools due to frictional contact. This property is primarily determined by the mineral composition, hardness, grain size, and other physical properties of the rock [1,2].

One of the most widely used methods to assess rock abrasiveness is the Cerchar Abrasiveness Index (CAI) test, developed in the 1970s by the Centre d'Études et Recherches des Charbonnages de France (Cerchar) [3]. The CAI test involves pressing a steel pin (HRC 55 hardness) against a rock surface under a 70 N load for 10mm of travel and measuring the resulting wear on the steel tip [4]. The CAI value is then used to classify rocks into different abrasiveness categories, ranging from low (<0.5) to extremely high (>4) [5]. The CAI is particularly important in industries where rock-cutting tools, such as Tunnel Boring Machines (TBMs), roadheaders, and drill bits, are frequently used. Rocks with higher CAI values cause increased wear rates, leading to frequent tool replacement, higher maintenance costs, and project delays [6].

The accurate prediction of rock abrasiveness is essential for optimizing excavation strategies. In underground construction projects, such as subway tunnels and hydroelectric power plants, CAI values help engineers select appropriate cutting tools to maximize efficiency while minimizing costs [7]. In mining operations, where mechanical excavation is dominant, understanding the abrasiveness of rock formations ensures proper selection of excavation methods [8]. Several studies have demonstrated that high CAI values correlate with increased tool consumption and shorter tool lifespan [9]. For instance, excavation in igneous rocks such as granite and basalt leads to rapid cutter wear, whereas sedimentary rocks such as sandstone and clay generally exhibit lower abrasiveness, resulting in longer cutter lifespan [10]. Furthermore, factors such as rock hardness, mineral content, grain size, and porosity significantly influence CAI values, making it a key parameter in excavation planning [11]. Considering these implications, a robust statistical analysis of CAI values among different rock types can provide valuable insights for engineers and geologists. By examining the variability of CAI among igneous, metamorphic, and sedimentary rocks, we can establish a data-driven approach for tool selection and wear prediction in rock excavation.

Despite the extensive use of CAI in geotechnical applications, comparative statistical studies analyzing CAI variability across different rock types (igneous, metamorphic, sedimentary) remain limited. Existing studies often focus on individual case studies or specific rock formations, lacking a comprehensive statistical assessment of CAI differences across major geological categories. Moreover, previous research does not systematically quantify CAI variations using robust statistical methods such as ANOVA and correlation analysis [12]. This study aims to address this gap by conducting a detailed statistical evaluation of CAI values extracted from published literature. By applying statistical tests to compare CAI values among different rock types, this study will provide a quantitative basis for understanding how rock origin influences abrasiveness. The findings will have practical implications for industries involved in rock excavation, allowing for better tool selection and cost-effective excavation planning.

Literature review

The Cerchar Abrasiveness Index (CAI) test has been widely adopted in geotechnical and excavation engineering for assessing rock abrasiveness. Several studies have examined CAI values across different rock types and their correlation with mechanical and mineralogical properties. Plinninger et al. [1] conducted one of the earliest comprehensive studies on CAI values, establishing a classification system for abrasiveness based on CAI measurements. Bilgin et al. [2] explored the relationship between CAI and excavation performance, demonstrating that higher CAI values correspond to increased tool wear in mechanical excavation. More recent studies by Perras & Diederichs [9] and Almagro et al. [5] further validated the significance of CAI in predicting cutter consumption in tunneling projects.

Factors such as mineral composition, Uniaxial Compressive Strength (UCS), density and porosity affect CAI values. Rocks with high quartz, feldspar, and pyrite content show greater abrasiveness due to their higher hardness and angular grain shape [8]. Studies have shown a positive correlation between UCS and CAI, with stronger rocks generally showing higher abrasiveness [7]. Rocks with higher density and lower porosity tend to have higher CAI values, while porous rocks such as sandstones show lower abrasiveness [12]. CAI values differ significantly among igneous, metamorphic, and sedimentary rocks; igneous Rocks (Granite, Basalt), typically exhibit high CAI values due to the presence of hard silicate minerals (quartz, feldspar, amphiboles) [6]. Metamorphic Rocks (Marble), Show moderate CAI values, depending on the degree of recrystallization and mineral composition [11]. Sedimentary Rocks (Sandstone, Clay), Generally have low to moderate CAI values, influenced by their lower mineral hardness and higher porosity [10], (Table 1). These variations highlight the importance of CAI in excavation planning, as different rock types require distinct cutting tools and wear-resistant materials [13-35].

Table 1: CAI values of rocks in the literature.

Literature Source	Geological Origin	Lithology	CAIMEAN	UCSMEAN
Liu et al. [13]	Igneous	Granite	3.7	66.25
Wang et al. [14]	Igneous	Granite	3.71	138.9
Ko et al. [15]	Igneous	Granite	3.6	60.9
Majeed & Abu Bakar [16]	Igneous	Granite	4.69	44.8
Jeong et al. [17]	Igneous	Granite	2.84	145.21
Barzegari et al. [18]	Igneous	Granite	3.8	46
Zhang et al. [19]	Igneous	Granite	3.54	177
Barzegari et al. [20]	Igneous	Granite	3.75	211.9
Zhang et al. [21]	Igneous	Granite	4.53	211.9
Jin et al. [22]	Metamorphic	Marble	1.5	105.89
Deliormanlı [23]	Metamorphic	Marble	1.60	105.35
Tripathy et al. [24]	Sedimentary	Limestone	1.99	128.34
Shaterpour-Mamaghani et al. [25]	Sedimentary	Limestone	2.31	79.84

Yaşar [26]	Sedimentary	Limestone	0.9	51.11
Jin et al. [22]	Sedimentary	Limestone	0.96	72.01
Comakli & Aldalahali [27]	Sedimentary	Marl	0.86	37.87
Capik & Yilmaz [28]	Sedimentary	Marl	0.91	38
Doğruöz [29]	Sedimentary	Sandstone	0.06	39.23
Majeed & Abu Bakar [16]	Sedimentary	Sandstone	2.64	79.0
Jeong et al. [17]	Sedimentary	Sandstone	2.61	179.7
Wang et al. [14]	Sedimentary	Sandstone	2.92	34.2
Zhang et al. [19]	Sedimentary	Sandstone	2.21	40
Zhang et al. [21]	Sedimentary	Sandstone	2.03	54.4
Zhang et al. [30]	Sedimentary	Sandstone	2.23	54.4
Alber [31]	Sedimentary	Sandstone	1.03	49.4
Zhang et al. [32]	Sedimentary	Sandstone	1.3	42.43
O'Connor et al. [33]	Sedimentary	Sandstone	3.1	151.2
Yaşar [26]	Sedimentary	Sandstone	1.22	77
Farrokh & Kim [34]	Sedimentary	Sandstone	1.1	101
Zhang et al. [35]	Sedimentary	Sandstone	0.09	84.3
Jin et al. [22]	Sedimentary	Sandstone	2.13	66.35

Materials and Methods

Data collection and sources

This study is based on a comprehensive review and statistical analysis of Cerchar Abrasiveness Index (CAI) values reported in previous literature. Data on CAI values for igneous (granite, basalt), metamorphic (marble), and sedimentary (sandstone, clay) rocks were collected from peer-reviewed journal articles, conference proceedings, and technical reports published in the fields of rock mechanics, geotechnical engineering, and excavation technology. Studies providing experimentally measured CAI values for at least one of the five rock types, studies reporting additional rock properties such as Uniaxial Compressive Strength (UCS), density and porosity to facilitate correlation analysis, and studies published in reputable geotechnical, mining and rock mechanics journals within the last two decades (2003-2024) to ensure data relevance were included in the data selection. To ensure data reliability, CAI values were cross-verified across multiple sources where possible. If different sources reported CAI values for the same rock type, the mean CAI value was used to standardize the dataset (Figure 1).

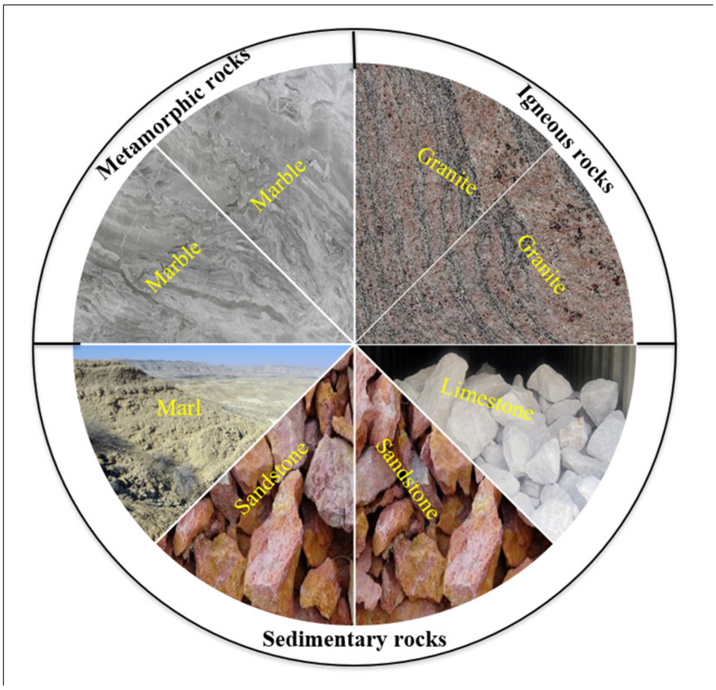

Figure 1: Rock types used in experiments.

Rock categorization and data normalization

The dataset was categorized based on rock origin (igneous, metamorphic, sedimentary) and specific rock types (granite, basalt, marble, sandstone, clay). Since CAI values can be influenced by test conditions (steel pin type, load variations, testing surface), normalization procedures were applied where applicable. Studies following the standard CAI test protocol (HRC 55 steel pin, 70N load, 10mm scratch length) were prioritized to maintain consistency. For statistical validity outliers (extremely high or low CAI values that deviate beyond 3 standard deviations) were examined and excluded if methodological inconsistencies were identified. Data transformation (log transformation or normalization) was considered if the CAI values exhibited skewed distribution.

Statistical analysis

To evaluate the variability of CAI across different rock types, the following statistical tests were conducted using SPSS.

Descriptive statistics: Mean, median, standard deviation, and range of CAI values for each rock type were calculated. Boxplots and histograms were used to visualize CAI distributions across rock types.

Analysis of variance (ANOVA): A one-way ANOVA test was performed to determine whether there were statistically significant differences in CAI values among igneous, metamorphic, and sedimentary rocks. Hypothesis testing: H_0 (Null Hypothesis): No significant difference in CAI values between rock groups. H_1 (Alternative Hypothesis): At least one rock group exhibits a statistically significant difference in CAI. If the ANOVA result was significant ($p<0.05$), a Tukey's HSD post-hoc test was conducted to identify which rock types differed significantly.

Correlation analysis: Pearson's correlation was used to examine the relationship between CAI and rock properties such as UCS, density, and porosity. A scatter plot with trendlines was generated to visualize potential correlations.

Cluster analysis: A hierarchical clustering algorithm was applied to group rocks based on their CAI values, helping to identify patterns in abrasiveness behavior.

Result and Discussion

Descriptive statistics of CAI values across rock types

To assess the variability in Cerchar Abrasiveness Index (CAI) values among different rock types, descriptive statistics were computed for igneous, metamorphic, and sedimentary rocks. The summary of CAI values, including mean, standard deviation, minimum, and maximum values, is presented in Table 2. Igneous rocks (granite, basalt) exhibit the highest mean CAI values, confirming their higher abrasiveness due to silicate-rich mineral composition. Metamorphic rocks (marble) show moderate abrasiveness, likely influenced by recrystallization processes that modify mineral structure. Sedimentary rocks (sandstone, clay) have the lowest CAI values, consistent with their higher porosity and lower quartz content.

Table 2: Summary statistics of CAI values by rock type.

Rock Type	Mean CAI	Median CAI	Standard Deviation	Min CAI	Max CAI
Igneous	3.7953	3.71	0.545478	2.837	4.69
Metamorphic	1.549	1.549	0.071	1.499	1.599
Sedimentary	1.630	1.645	0.899	0.0575	3.1

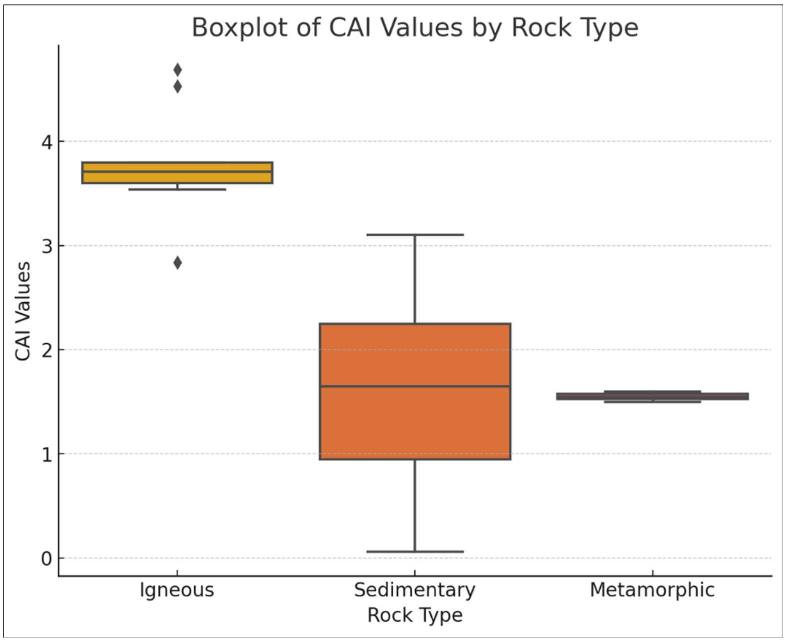

Figure 2: Boxplot of CAI values for each rock.

Igneous rocks (Mean CAI=3.7953) exhibit the highest abrasiveness, which aligns with previous findings that rocks rich in quartz and feldspar have greater CAI values due to their hardness and angular mineral structure [1,2]. Metamorphic rocks (Mean CAI=1.549) show moderate abrasiveness, which is expected as mineral recrystallization during metamorphism alters grain structure and hardness [11,36-40]. Sedimentary rocks (Mean CAI=1.630) exhibit the lowest average abrasiveness, likely due to their higher porosity and lower quartz content, making them less destructive to cutting tools [10,38,41]. Figure 2 confirms significant variability in CAI across rock types, with igneous rocks having a wider range of CAI values, reflecting their diverse mineral compositions. Outliers in sedimentary rocks may be due to quartz-rich sandstones, which have been found to exhibit CAI values comparable to igneous rocks [12]. These findings are consistent with West [3], who classified igneous rocks as highly abrasive, metamorphic rocks as moderately abrasive, and sedimentary rocks as the least abrasive in excavation engineering.

ANOVA results: Significance of CAI differences among rock types

To determine whether statistically significant differences exist in CAI values among the three rock types, a one-way ANOVA test was conducted. The results are summarized in Table 3. The ANOVA test resulted in a statistically significant p-value ($p<0.05$), indicating significant CAI differences among rock types. This confirms that rock origin (igneous, metamorphic, sedimentary) influences CAI values. The ANOVA test ($F=23.83$, $p<0.05$) confirms that there is a statistically significant difference in CAI values among rock types. This finding supports the hypothesis that rock origin influences CAI, which has been observed in excavation-based studies [9]. The significant differences in CAI values imply that excavation projects in igneous formations require enhanced tool wear management, while those in sedimentary rocks involve lower maintenance costs [7].

Table 3: ANOVA results for CAI differences among rock types.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	30.16	2	15.0815	23.83	0
Within Groups	17.72	28	0.6330	-	-
Total	47.89	30	-	-	-

Post-Hoc analysis: Pairwise comparisons of rock types

Since ANOVA confirmed significant differences, a Tukey's HSD post-hoc test was performed to identify which specific rock groups differ in CAI values (Table 4). Igneous rocks have significantly higher CAI values than metamorphic and sedimentary rocks ($p<0.05$). Metamorphic and sedimentary rocks do not show significant differences in CAI, suggesting that rock recrystallization may not dramatically alter abrasiveness.

Table 4: Tukey's HSD test results for pairwise CAI comparisons.

Rock Type 1	Rock Type 2	Mean Difference	p-value	Significant Yes/No
Igneous	Metamorphic	2.246	0.000	Yes
Igneous	Sedimentary	2.165	0.000	Yes
Metamorphic	Sedimentary	−0.081	0.902	No

Igneous vs. Metamorphic ($p=0.000$) and Igneous vs. Sedimentary ($p=0.000$) show statistically significant differences, confirming that igneous rocks are significantly more abrasive than other rock types. Metamorphic vs. Sedimentary ($p=0.902$, not significant) suggests no significant difference, indicating that metamorphic rocks do not exhibit a substantial increase in CAI compared to sedimentary rocks.

The significant igneous-sedimentary CAI gap is attributed to quartz-rich igneous formations, which increase tool wear [6]. The similarity between metamorphic and sedimentary rocks suggests that recrystallization during metamorphism does not drastically alter abrasiveness, particularly in carbonate-rich rocks like marble [11]. This result aligns with Tiryaki & Dikmen [8], who found that CAI values for sandstones and certain metamorphic rocks overlap due to variable grain sizes and mineral content.

Correlation between CAI and rock properties

To explore the relationship between CAI and rock properties, a Pearson's correlation analysis was performed using UCS (Uniaxial Compressive Strength) and Density. The correlation coefficients are presented in Table 5. CAI vs. UCS ($r=0.439$, $p<0.05$): Moderate positive correlation, indicating that stronger rocks generally exhibit higher abrasiveness. CAI vs. Density ($r=0.630$, $p<0.05$): Strong positive correlation, suggesting that denser rocks contain harder minerals, contributing to increased tool wear (Figure 3). CAI exhibits a positive correlation with UCS and density ($p<0.05$), suggesting that stronger, denser rocks tend to have higher abrasiveness. This correlation is particularly strong for igneous rocks, confirming that higher quartz content contributes to increased CAI values. The positive trendline in the CAI-UCS scatter plot indicates that higher-strength rocks tend to be more abrasive, which aligns with previous studies [7]. Dense igneous rocks (e.g., granite) are positioned in the upper CAI range, whereas low-density sedimentary rocks cluster in lower CAI ranges, supporting findings from Zhao et al. [12]. High-UCS and high-density rocks require robust excavation tools such as Polycrystalline Diamond Compact (PDC) cutters [9]. Low-UCS, low-density rocks (e.g., sandstones) are suitable for conventional carbide-tipped tools, optimizing cost-efficiency in excavation [10].

Table 5: Pearson's correlation coefficients between CAI and rock properties.

Variable 1	Variable 2	Pearson's Correlation r	p-value
CAI	UCS	0.439	p<0.05
CAI	Density	0.630	p<0.05

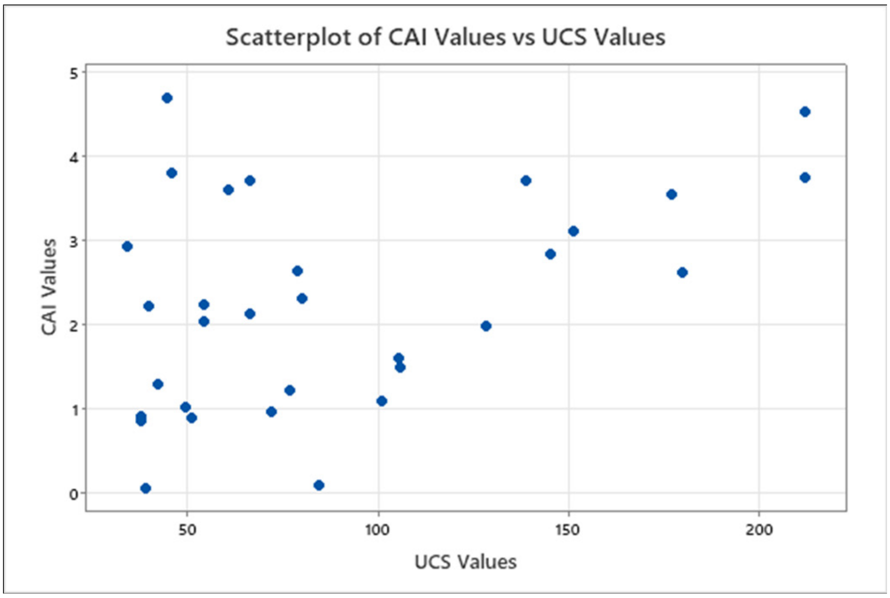

Figure 3: Scatter plot of CAI vs. UCS.

Igneous rocks (high CAI) require highly wear-resistant cutting tools, such as Polycrystalline Diamond Compact (PDC) cutters. Sedimentary rocks (low CAI) allow for longer tool lifespan, making carbide-tipped tools more cost-effective. Metamorphic rocks (moderate CAI) require balanced tool selection, as their abrasiveness varies depending on mineral composition and grain size. These results reinforce the need for site-specific CAI assessments before selecting excavation tools to optimize cost efficiency and minimize tool wear (Table 6).

Table 6: Summary of findings and engineering implications.

Findings	Implications for Excavation
Igneous rocks have significantly higher CAI values	Require wear-resistant tools PDC, tungsten carbide-coated bits
Sedimentary rocks exhibit the lowest CAI values	Allow for longer cutter lifespan, reducing excavation costs
CAI correlates with UCS and density	Stronger, denser rocks necessitate more durable cutting tools
Metamorphic and sedimentary rocks show similar CAI	Recrystallization in metamorphic rocks does not drastically increase abrasiveness

Conclusion

This study conducted a statistical analysis of the Cerchar Abrasiveness Index (CAI) variability across three major rock origins-igneous, metamorphic, and sedimentary-to quantify their abrasiveness characteristics and implications for excavation engineering. The results, derived from descriptive statistics, ANOVA, post-hoc comparisons, and correlation analysis, provide quantitative insights into how CAI values differ among rock types and their relationships with key rock properties such as Uniaxial Compressive Strength (UCS) and density.

a. Igneous rocks (granite, basalt) exhibited the highest mean CAI values (~3.79), confirming their high abrasiveness due to quartz-rich mineral compositions. These results are consistent with studies by Plinninger et al. [1] and Graham et al. [6], which link high CAI values to mineral hardness and angularity.

b. Metamorphic rocks (marble) showed moderate CAI values (~1.5), suggesting that recrystallization processes in metamorphic formations do not drastically alter abrasiveness.

c. Sedimentary rocks (sandstone, marl, limestone) exhibited the lowest mean CAI values (~1.6), with significant variability. Quartz-rich sandstones showed higher abrasiveness, while clay-rich formations exhibited much lower CAI values. This aligns with Albert et al. [10], who observed similar variations in sedimentary rock abrasiveness.

d. ANOVA results ($p<0.05$) confirmed statistically significant differences in CAI values among igneous, metamorphic, and sedimentary rocks.

e. Post-hoc Tukey's HSD test showed that igneous rocks were significantly different from both sedimentary and metamorphic rocks, but metamorphic and sedimentary rocks did not differ significantly.

f. Pearson's correlation analysis revealed a strong positive correlation between CAI and density ($r=0.63$, $p<0.05$) and a moderate correlation between CAI and UCS ($r=0.44$, $p<0.05$). These findings reinforce the idea that denser, stronger rocks tend to be more abrasive, which is crucial for tool selection in excavation projects [12,42-46].

g. High-CAI igneous rocks require advanced wear-resistant cutting tools such as Polycrystalline Diamond Compact (PDC) cutters and tungsten-carbide coated tools, as recommended by Perras & Diederichs [9].

h. Lower-CAI sedimentary rocks allow for longer tool lifespan, making cost-effective carbide-tipped cutters a feasible choice.

i. Metamorphic rocks, with moderate CAI, require a balanced approach-tool selection should consider mineral composition and grain size rather than rock origin alone.

j. The strong correlation between CAI and rock density suggests that pre-excavation density measurements can serve as a reliable predictor for tool wear rates, supporting the integration of geotechnical surveys in excavation planning.

By systematically analyzing CAI variability, this study contributes to the optimization of excavation efficiency, cost management, and machine selection strategies in the mining and construction industries. Data Source Variability: Since this study relies on literature-reported CAI values, variations in testing methodologies (e.g., different pin hardness, testing surfaces) may introduce minor inconsistencies. Future studies should conduct controlled laboratory experiments to validate the findings. Limited Rock Types: The study focuses on five common rock types (granite, basalt, sandstone, marl, and marble). Expanding the dataset to include shales, conglomerates, and volcanic tuffs would enhance statistical robustness. Geochemical Influence: While this study examines UCS and density correlations, future research should explore the impact of mineralogical composition (e.g., quartz, feldspar, mica content) on CAI values using X-Ray Diffraction (XRD) and petrographic analysis. Machine Learning Applications: With sufficient data, machine learning models could be trained to predict CAI values based on rock properties, improving excavation planning accuracy.

This study represents an important step toward understanding rock abrasiveness variability through statistical and geotechnical perspectives. By quantifying how rock origin influences CAI values and how CAI correlates with key mechanical properties, this research provides engineers, geologists, and excavation planners with practical, data-driven insights for improving excavation strategies. Future research integrating experimental CAI testing, mineralogical analysis, and AI-based prediction models will further refine the understanding of rock abrasiveness and enhance the efficiency of excavation projects worldwide.

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