CHAPTER II
LITERATURE REVIEW

This section gives a summary of the literature review to improve an understanding of the impact of bedding planes on CERCHAR abrasivity index (CAI) test and the influencing factors related to CAI.

2.1 Rock abrasiveness

Rock abrasiveness is understood as the ability of a rock or minerals to cause wear, erosion, or damage to cutting or grinding tools upon contact. It is considered a vital characteristic in several industries, such as mining, construction, and geology. The performance of mine excavation machinery is significantly influenced by it. The expenses and delays incurred in replacing worn-out parts directly impact the overall machinery performance (Atkinson, Cassapi, and Singh, 1986). Mucha (2023) emphasizes the widespread and aggressive nature of abrasive wear, particularly in the processes concerning the extraction, transportation, and utilization of hard-rock-type mineral substances.

Commonly used testing methods for assessing the abrasiveness of geological materials are developed in France, including CERCHAR abrasivity test for rocks and LCPC abrasivity test for soils or grain materials (Janc, Jovicic, and Vukelić, 2020). Test procedure follows the International Society for Rock Mechanics (ISRM) in Alber et al. (2014) suggested method. The test procedure is also given by ASTM D7625-22 standard practice as presented in Table 2.1.

Table 2.1 Classification of CAI (ASTM D7625-22).

Mean CAI	Classifications
0.30 – 0.50	Very low abrasiveness
0.50 – 1.00	Low abrasiveness
1.00 – 2.00	Medium abrasiveness
2.00 – 4.00	High abrasiveness
4.00 – 6.00	Extreme abrasiveness
6.00 – 7.00	Quartzite

2.2 Factors affecting CERCHAR abrasivity index

2.2.1 Surface conditions

Several researchers investigate the effects of rough and smooth surfaces on the CERCHAR abrasivity index (CAI). Their results show that rough surfaces tend to yield higher CAI values compared to smooth surfaces due to increased friction and resistance. Al Ameen and Waller (1994) highlight that rough surface, with their asperities and irregularities, cause greater tool wear, resulting in higher abrasivity readings. Käsling and Thuro (2010) confirm that rough surfaces generate higher CAI values because of increased friction, while smooth surfaces produce lower values due to reduced friction. Aydın, Yaralı, and Duru (2016) find similar results, emphasizing the importance of standardizing surface texture to improve test accuracy and repeatability, Yaralı and Duru (2016) perform tests on both rough and saw-cut rock samples, resulting in a total of 27,000 scratches (Figure 2.1). CAI on the rough surface is approximately 18% higher than that on the saw-cut surface (Hamzaban, Rostami, Dahl, Macias, and Jakobsen, 2022) reinforced these findings in a critical review, noting that rough surfaces lead to higher CAI values and greater tool wear, while smooth surfaces result in lower CAI values. Together, these studies underscore the necessity of consistent surface preparation in CAI testing to ensure reliable and comparable results.

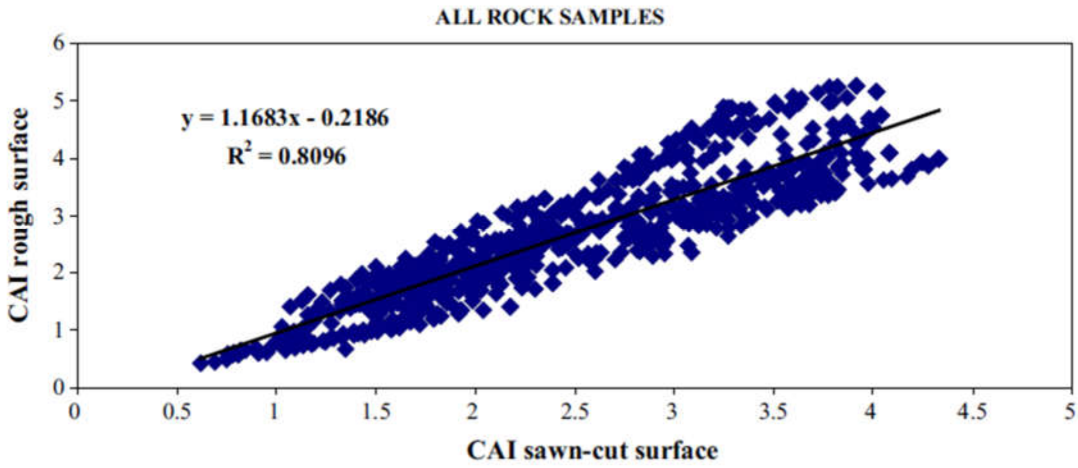

Figure 2.1 Relationship between CAI values of rough surface and saw-cut surface (Yaralı and Duru, 2016).

2.2.2 Stylus hardness

Sanford and Hagan (2009) assess the impact of stylus metallurgy on CAI measurements, finding that using harder materials like tungsten carbide for the stylus results in more reliable and accurate CAI values compared to steel. Specifically, the hardness of the stylus, such as those with a Rockwell Hardness (HRC) of 55, plays a critical role in the accuracy and consistency of CAI measurements. Yaralı and Duru (2016) investigate the effect of mechanical properties of rocks on CAI, revealing that higher rock strength and hardness positively correlate with higher CAI values. Teymen (2020) demonstrates the usability of CAI for estimating mechanical rock properties, showing a strong correlation between CAI and rock strength and hardness. The research underscores that a stylus with HRC 55 hardness provides a reliable standard for measuring CAI, ensuring consistent and reproducible results.

2.2.3 Scratching rate

Aydın (2019) investigates the effects of various testing parameters on CAI and its repeatability, finding that pin speed is a crucial factor affecting CAI results. Hamzaban, Karami, and Rostami (2019) examine the impact of pin speed on CAI test results and discovere that higher pin speeds lead to reduced CAI values. Supporting this, Kotsombat, Thongprapha, and Fuenkajorn (2020) study the effects of scratching rate on CAI of sandstones, finding that lower scratching rates result in lower CAI values. Zhang, Konietzky, Song, and Huang (2020) also highlight the importance of controlling testing conditions, including pin speed, to improve the reliability of CAI measurements.

2.2.4 Grain size

Research spanning from Al Ameen and Waller (1994) to Zhang et al. (2021) consistently emphasizes the significant impact of abrasive minerals, particularly quartz, on the CERCHAR Abrasivity Index (CAI). Al Ameen and Waller (1994) demonstrate that rocks with high quartz content exhibit higher CAI values. Building on this, Er and Tuğrul (2016) confirm a positive correlation between rock density, quartz content, and CAI. Similarly, Torrijo, Garzón-Roca, Company, and Cobos (2019) find that higher quartz content directly increases CAI. Zhang et al. (2021) further reinforced these findings, showing a positive relationship between rock hardness, quartz content, and CAI. Across these studies, the presence of abrasive minerals like quartz consistently correlates with the increased CAI, indicating their crucial role in determining rock abrasivity.

2.2.5 Moisture content

Plinninger, Käsling, Thuro, and Spaun (2003) find that moisture conditions significantly influence CERCHAR abrasiveness index (CAI) values. Supporting this, Aydın (2019) investigates the effects of various testing parameters on CAI and its repeatability, finding that moisture is a crucial factor affecting CAI results. Kotsombat et al. (2020) further find that saturated sandstones exhibit lower CAI values compared to dry sandstones under the same scratching rate. Zhang, Konietzky, Song, et al. (2020) also highlight the importance of controlling moisture conditions during CAI testing, noting that variations in moisture can lead to significant discrepancies in CAI values. Comakli and Aldalahali (2024) explore the effect of water saturation on CAI in clay-rich rocks at different scratch lengths, finding that increasing water saturation reduces CAI values.

2.3.6 Temperature

Plinninger et al. (2003) suggest that testing temperature conditions significantly influence CAI values. Aydın (2019) investigates the effects of various testing parameters on CAI and its repeatability, showing that temperature is a crucial factor affecting CAI results. Rossi, Saar, and Rudolf von Rohr (2020) demonstrate that combining thermal and mechanical drilling reduces CAI values. Similarly, Ji, Wang, Zheng and Wu (2021) show that higher temperatures reduce CAI values of Bukit Timah granite, providing clear evidence that thermal treatment supports more efficient and durable drilling operations. Wang, Guo, and Wu (2023) find that thermal treatment reduces CAI of brittle rock. Zhang, Konietzky, Song, et al. (2020) further analyse the impact of various testing conditions, including temperature, on CAI values.

2.3.7 Mineral compositions

Numerous studies have investigated parameters influencing CAI test outcomes. West (1989) underscores the pivotal role of quartz content (QC) in affecting CAI results. Plinninger et al. (2003) highlight the insufficiency of solely relying on equivalent quartz content (EQC) for interpreting CAI values. Conversely, Lee, Jeong and Jeon (2013) show the significant impact of EQC on CAI values compared to quartz content. However, Lassnig, Latal and Klima (2008) observe no direct correlation between CAI values and grain size. Yaralı, Yaşar, Bacak and Ranjith (2008) test sedimentary rocks, proposing a robust linear relationship between CAI values, quartz content, degree of cementing, equivalent quartz content, and quartz grain size. Er and Tuğrul (2016) investigate the correlation between CAI and physico-mechanical characteristics of granitic rock samples. The study's findings suggest a substantial influence of quartz size and content on CAI. An escalation in quartz content and size within granitic rocks leads to higher CAI values. Kathancharoen and Fuenkajorn (2023) highlight importance of not solely considering EQC but rather focusing on volume metric hardness as a more relevant factor as shown in Figure 2.2.

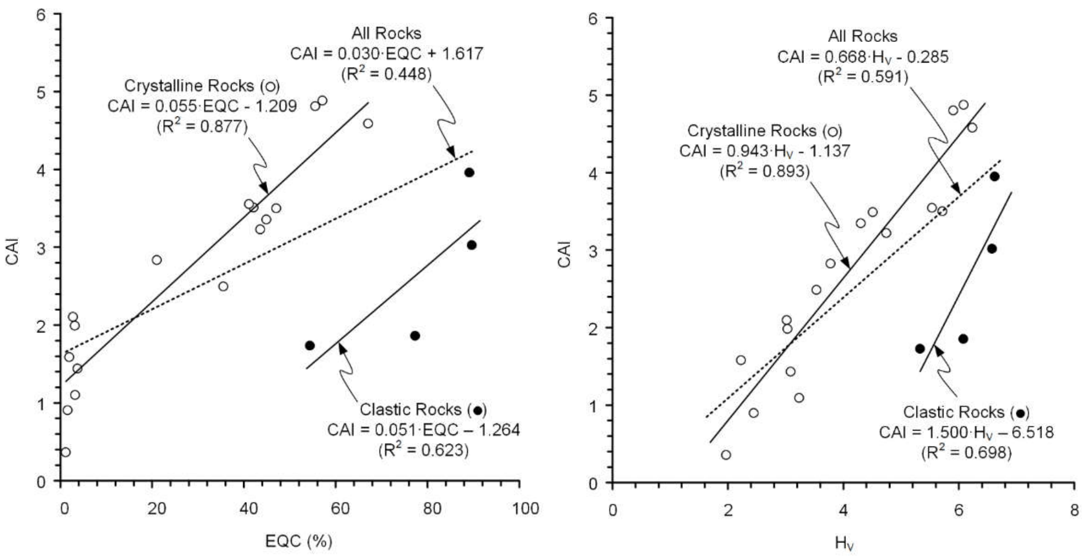

Figure 2.2 CAI testing, where black solid line represents mean CAI derived from single test, and red dashed line represents mean CAI value obtained from all individual tests (Kathancharoen and Fuenkajorn, 2023).

2.3.8 Rock properties

Bedding plane anisotropy characterizes specific rock formations, notably prevalent in sedimentary rocks like sandstone, siltstone, mudstone, and shale (Ramamurthy, 1993). Jin, Li, Jin, Hambleton and Cusatis (2018) perform a study on the relationship between the calculated P-wave velocities for individual specimens and their anisotropy angle (Figure 2.3). The highest velocities are observed when the direction of longitudinal wave propagation aligns parallel to the isotropy or bedding plane, as notably seen in the specimen with θ = 90°. In contrast, the lowest velocity occurs at an anisotropy angle of 0°, where the direction of longitudinal wave propagation is perpendicular to the isotropy plane. In uniaxial compression test, specimens are prepared with five different bedding plane orientations: 0°, 30°, 45°, 60°, and 90° with respect to the applied loading direction. As for the Brazilian test, the samples were shaped into dice-like forms with orientations consistent with the UCS test in Figure 2.4.

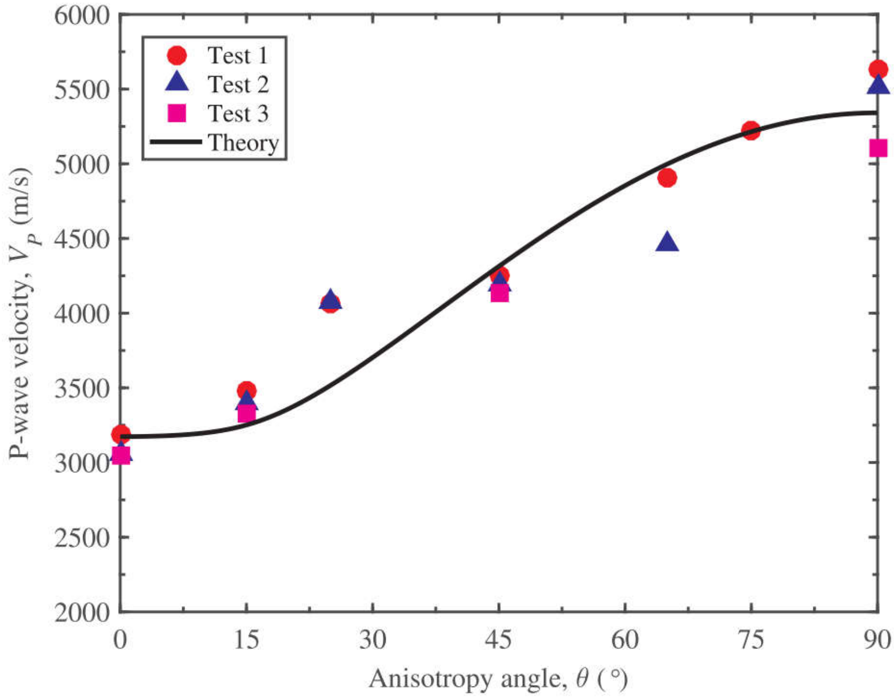

Figure 2.3 P-wave velocity in relation to the anisotropy angle (Jin et al., 2018).

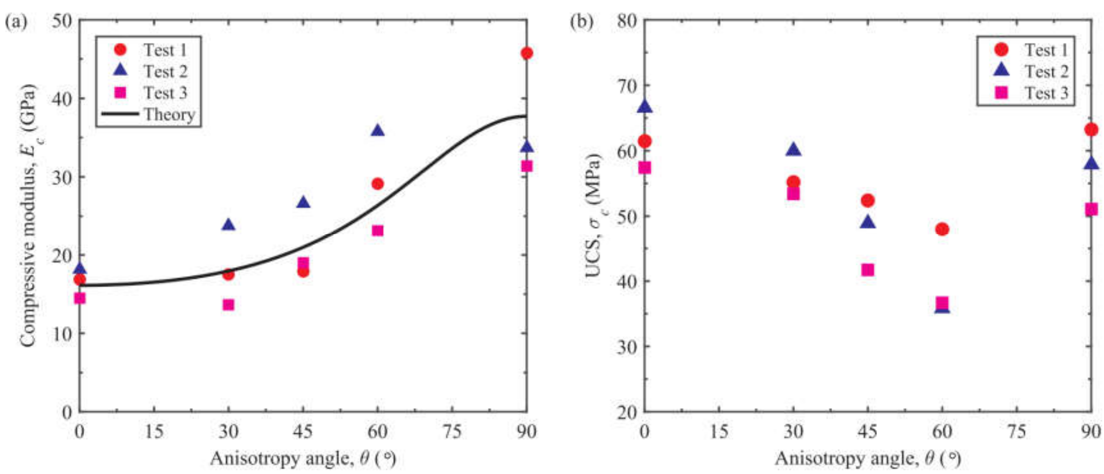

Figure 2.4 Correlation between (a) compressive modulus and (b) Uniaxial compressive strength (UCS) concerning the anisotropy angle (Jin et al., 2018).

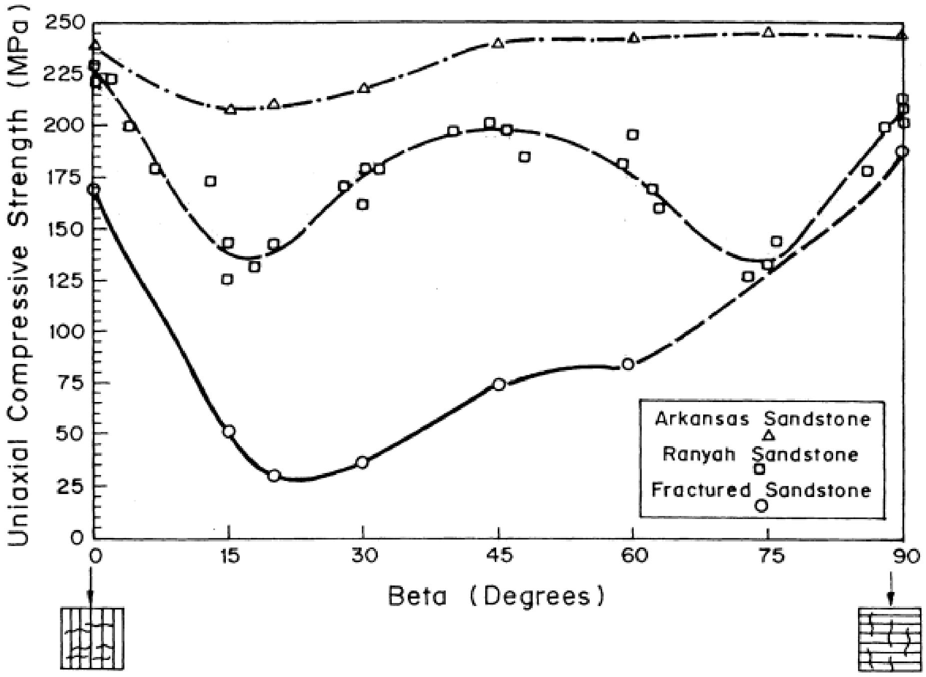

Figure 2.5 Correlation between strength anisotropy curves of Arkansas, Ranyah, and fractured sandstones (Al-Harthi, 1998).

Al-Harthi (1998) establishes a correlation between the strength anisotropy curves of Arkansas, Ranyah, and fractured sandstones (Figure 2.5). Correlation is obtained between the strength anisotropy curves of Arkansas, Ranyah, and fractured sandstones (Chenevert and Gatlin, 1965) and another fractured sandstone (Horino and Ellickson, 1970) Arkansas sandstone exhibits light banding and features as a single set of discontinuities. The highest compressive strength is observed at orientations of both β = 0° and β > 45°. The anisotropy curve for Arkansas sandstone follows the typical U-shaped pattern, with the lowest compressive strength at β = 15° and a relatively flat region between β = 45° and 90°.

Sukjaroen, Thongprapha, Liabkrathok, and Fuenkajorn (2021) study the impact of bedding planes at various angles of gypsum by conducting compressive strength tests. The strengths are found to be highest at β = 0° and lowest at β = 60°.

Additionally, Fuenkajorn and Singkhiaw (2022), who tested sandstone, observed that the compressive strengths are highest at β = 0° and lowest at β = 75°.

Teymen (2020) performs a series of statistical analyses to estimate the fundamental rock mechanics test results performed on specimens of specific sizes using the CAI test, commonly applied in rock abrasion assessments. The study reveals a significant relationship between the basic rock mechanics properties, such as Young's modulus and uniaxial compressive strength, and CAI (Figure 2.6). The multiple regression models are found to be more reliable than simple regression equations, displaying correlation coefficients ranging from 0.72 to 0.96.

Li et al. (2021) find a substantial impact of the bedding angle on the strength of layered rocks. Typically, the maximum failure strength is observed at 0° or 90°, while the minimum failure strength tends to occur within the range of 30°–45° bedding angles.

Zhang, Konietzky, and Frühwirt (2020) find that CAI test may not offer a dependable indication for anisotropic rocks like phyllite, owing to their distinctive characteristics (Figure 2.7).

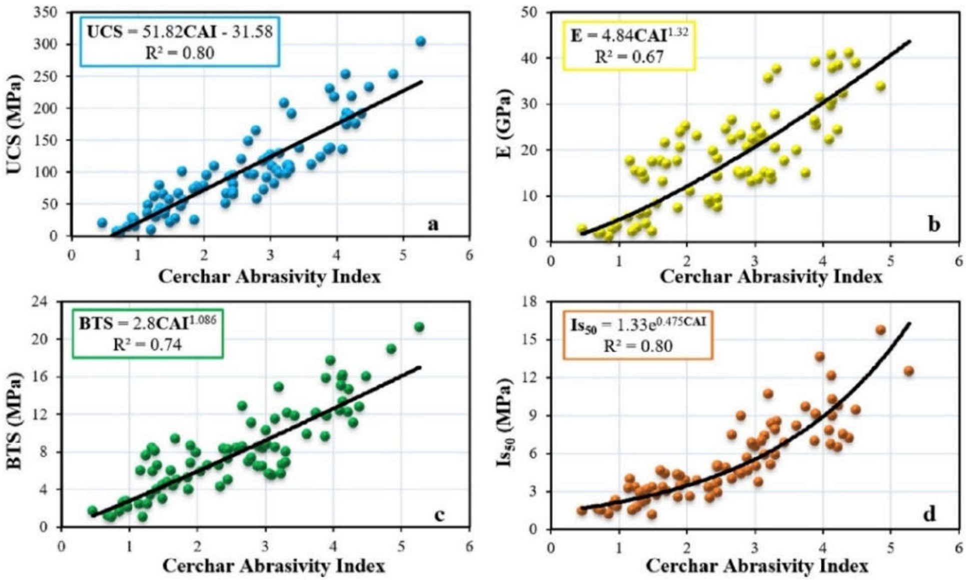

Figure 2.6 Relationship between CAI and basic mechanical tests a) UCS b) E c) BTS d) Is_{50} (Teymen, 2020).

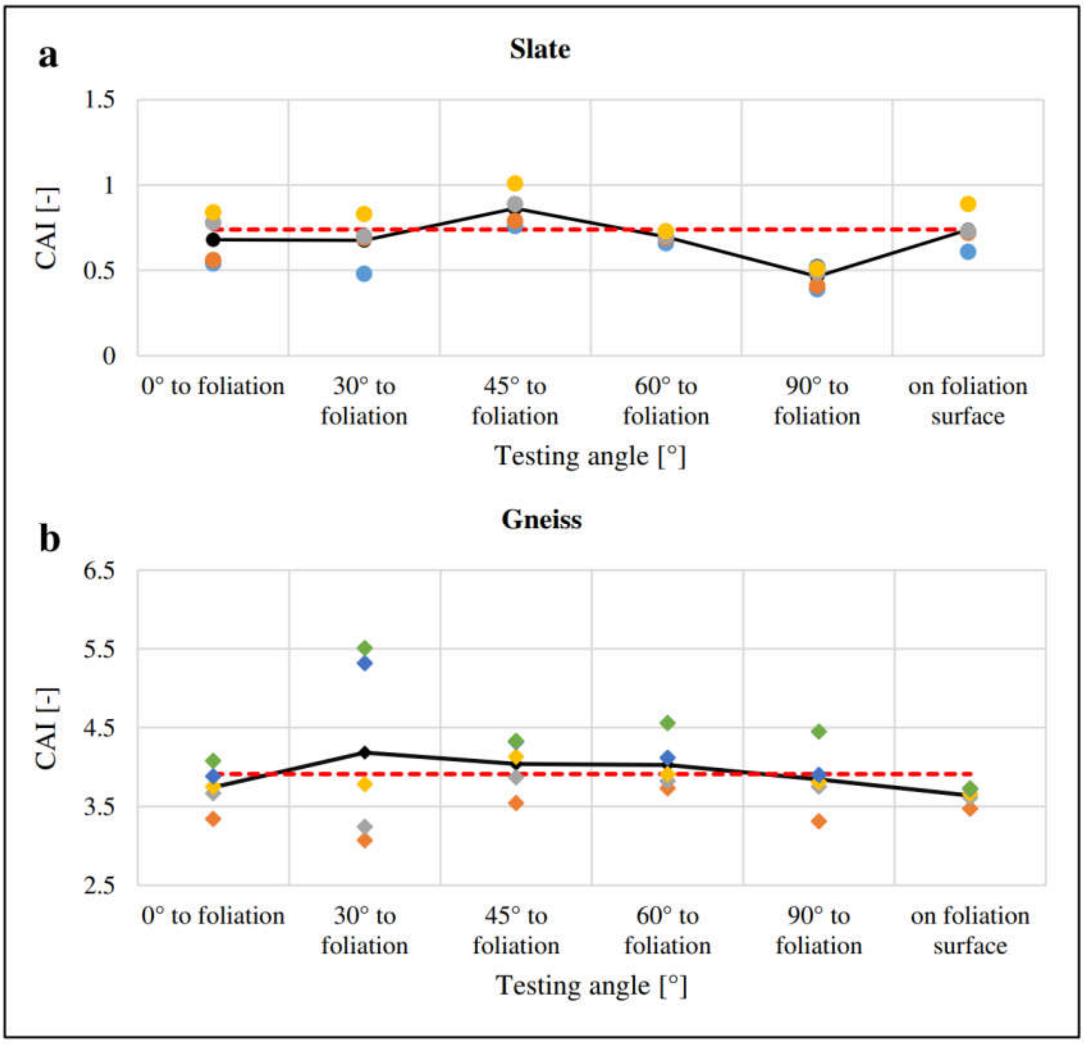

Figure 2.7 CAI versus testing orientations, where black solid line represents mean CAI derived from single test, and red dashed line represents mean CAI value obtained from all individual tests (Zhang, Konietzky, and Frühwirt, 2020).

2.3 CERCHAR specific energy

The concept of specific energy (SE) in the context of the CERCHAR test revolves around the energy derived from the action of a stylus scratching across a rock surface, as introduced by Hamzaban, Memarian, and Rostami (2018). This energy, crucial in assessing rock material properties, is further elaborated upon by Zhang, Konietzky, and Frühwirt (2020). In their work, they introduce additional terms for this parameter, referring to it interchangeably as scratching specific energy (SSE) or CERCHAR specific energy (CSE). The energy in question can be quantified by determining the work done (W) during the movement of the pin stylus. This is accomplished by integrating the scratching force exerted on the stylus over a predetermined scratching distance, conventionally set at 10 mm. The scratching force, measured throughout the scratching process, encapsulates the resistance encountered by the stylus as it traverses the rock surface. Upon obtaining the total work done (W), it is then divided by the excavated or removed volume (V) of the specimen. This volume measurement encompasses the entirety of the material displaced or removed by the scratching action along the entire length of the scratch.