

Assessing Rock Hardness of Isfahan Sandstone using the Cerchar Abrasivity Index (CAI)

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Abstract: This study investigates the geomechanical properties of sandstone from the southern part of Isfahan city using the Cerchar Abrasivity Index (CAI), Unconfined Compressive Strength (UCS), and point load tests. Twelve sandstone samples were analyzed to evaluate their abrasiveness and mechanical strength. The CAI value was determined to be 3.55, indicating a moderately high level of abrasiveness. The UCS test revealed strength of 35 MPa, and the estimated Hardness Rating (HR) was 25.6. These findings offer critical insights into the material properties of Isfahan's sandstone, which are essential for construction and excavation projects in the region. The results provide a useful framework for predicting tool wear and rock behavior during engineering operations.

Keywords: Rock hardness, Isfahan sandstone, Cerchar abrasivity index (CAI), Abrasivity testing, Geotechnical assessment.

I. INTRODUCTION

Geotechnical engineering focuses on the behavior of soil and rock in relation to construction and environmental challenges (Basu et al., 2015). Accurate assessment of rock properties is crucial in this field as it informs the design and safety of civil engineering projects, such as foundations, slopes, and tunnels (Azarafza et al., 2021). In the meantime, sedimentary rocks, being common in various geological settings, present unique challenges and opportunities for geotechnical evaluation (Chandler et al., 2004).

Sedimentary rocks, formed from the accumulation and consolidation of sediments, exhibit unique geotechnical characteristics that significantly impact their behavior in engineering contexts (Husson & Peters, 2018). These rocks, including sandstones, shales, and limestones, can vary widely in terms of strength, porosity, and permeability depending on their mineral composition and sedimentary history. Sedimentary rocks encompass a range of rock types, including shale, limestone, and conglomerate, each with distinct properties. Shale, for example, is characterized by its fine-grained texture and can exhibit different mechanical behaviors compared to coarser rocks like

conglomerates. For example, sandstone, with its granular texture, often displays good compressive strength but can also be highly porous, affecting its stability and water permeability. On the other hand, shale, with its fine-grained, laminated structure, tends to be more prone to splitting and has variable strength properties that can complicate foundation designs and slope stability analyses (Prothero & Schwab, 2013).

The geotechnical assessment of sedimentary rocks requires careful consideration of these inherent properties (Ismail et al., 2012). Testing methods such as uniaxial compressive strength (UCS), point-load, and permeability tests help engineers determine how these rocks will perform under different loading conditions (Jaeger et al., 2007). Regional factors, such as the presence of natural fractures or variations in cementation, further influence rock behavior. Understanding these aspects allows engineers to make informed decisions regarding material selection, foundation design, and overall stability of structures, ensuring both safety and functionality in construction projects (Hudson & Harrison, 1997). Sedimentary rocks, formed through the accumulation and lithification of sediments, are prevalent in the Earth's crust. Their widespread occurrence makes them critical subjects for geotechnical assessment. These rocks often serve as aquifers or building materials and can influence the stability of engineering structures (Jaeger et al., 2007).

Sandstone is a clastic sedimentary rock composed mainly of quartz grains cemented together (Prothero & Schwab, 2013). Its geomechanical properties, such as UCS, shear strength, and porosity, vary depending on mineral composition, grain size, and cementation (Ioanna et al., 2009). Understanding these properties is essential for evaluating its suitability for construction and its behavior under load. The mineral composition of sandstone, commonly including the proportion of quartz, feldspar, and other minerals, significantly impacts its mechanical properties. The cementing agents, which can be silica, calcium carbonate, or iron oxides, also affect hardness and durability (Prothero & Schwab, 2013). Analyzing these compositional factors helps in predicting the rock's performance in engineering applications (Pitts, 1984).

Understanding the geotechnical properties of sandstones is crucial for a variety of reasons, particularly when it comes to civil engineering, construction, and environmental management.

Sandstone, as a common sedimentary rock, forms a significant portion of the Earth's surface and is frequently encountered in construction projects, especially in areas where rock excavation or tunneling is necessary (Castro & Bell, 1995). Its geomechanical behavior, including strength, porosity, and durability, directly influences the stability and safety of structures built on or within it. Ignoring these properties can lead to miscalculations in design, potentially resulting in costly failures or hazards (Ulusay et al., 1994). One key reason for studying sandstone's geotechnical properties is its UCS, which determines how much load the rock can bear before it fails (Bell et al., 2009). In foundation design, particularly for large structures like buildings, bridges, or dams, knowing the strength of the underlying rock is essential for calculating load-bearing capacities. If the rock is weaker or more porous than expected, it could lead to settlement issues or even catastrophic failure (Castro & Bell, 1995). Engineers must account for these factors to ensure that the foundation is stable and capable of supporting the intended load.

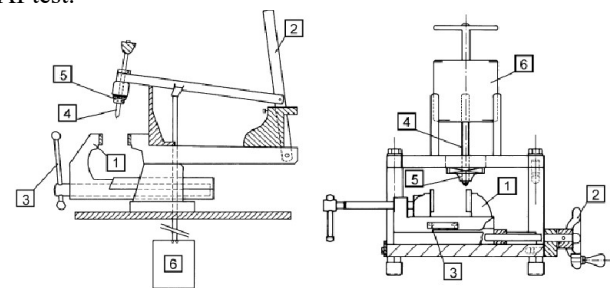
Additionally, sandstone's permeability and porosity play a significant role in groundwater flow and drainage characteristics (Ismail et al., 2012). These properties influence how water moves through rock layers, which is vital in designing drainage systems, preventing water infiltration, and managing underground water resources. High porosity or permeability in sandstone could lead to challenges in construction, such as water seepage into tunnels or excavation sites, increasing the risk of erosion or undermining structural stability. Properly assessing these properties helps mitigate such risks during construction and long-term infrastructure performance (Hurst & Archer, 1986). Moreover, the abrasiveness of sandstone is an important consideration for projects that involve excavation or drilling. Sandstones with high abrasivity can cause significant wear and tear on drilling equipment, leading to increased costs and delays (Petrica et al. 2013). Understanding the abrasivity of the rock, often measured using the Cerchar Abrasivity Index (CAI), helps engineers and contractors choose appropriate tools and machinery, plan for equipment maintenance, and budget for these additional expenses (Plinninger et al., 2003).

Another factor to consider is the variability of sandstone's properties due to its mineral composition and the environment in which it formed (Moradzadeh et al., 2013, 2016). Sandstone may contain different minerals, such as quartz, feldspar, or calcite, which affect its hardness, durability, and overall behavior under stress (Fowell & Abu Bakar, 2007). For example, quartz-rich sandstones tend to be harder and more resistant to weathering, while calcite-cemented sandstones may be more prone to dissolution and weakening over time (Moradzadeh et al., 2016). Understanding these variations is important for predicting the long-term performance of structures and ensuring that materials used in construction are durable enough for their intended purpose (Altindag et al., 2009; Bakar et al., 2016). Lastly, geotechnical assessments of sandstone are vital for environmental and risk management, especially in regions prone to natural disasters like landslides or earthquakes. The behavior of sandstone during seismic activity or under slope loading conditions must be understood to design resilient structures and to predict the potential for slope failures. By thoroughly understanding the geotechnical properties of sandstone,

engineers can design projects that not only perform well under normal conditions but also withstand extreme environmental stresses, safeguarding human lives and reducing economic losses (Özbek & Gül, 2015).

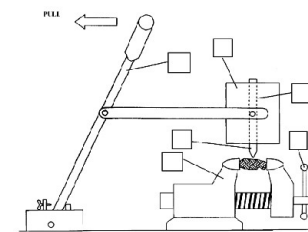
II. CERCHAR ABRASIVITY INDEX

The CAI is a widely used method to assess how abrasive a rock or geological materials (Nikoobakht et al., 2015). This information is crucial in industries like mining, tunneling, and construction, where machines and tools need to cut or drill through rock (Özbek & Gül, 2015). The more abrasive a rock is, the faster it wears down the equipment used, leading to higher costs and more frequent maintenance (Deliormanlı, 2012). Understanding a material's abrasiveness helps engineers plan better for these challenges (Majeed & Abu Bakar, 2016). The CAI is determined through a test that involves scratching the surface of a rock sample with a steel pin. This pin has a pointed tip and is made from hardened steel, which mimics the material used in cutting tools. A constant force is applied as the pin is dragged across the rock's surface. The amount of wear on the tip of the pin after this action gives an indication of how abrasive the rock is the measure value (Ko et al., 2016; Teymen, 2020). To conduct the test, a cylindrical sample of the rock is prepared, usually measuring about 10 cm in length and 5 cm in diameter. The steel pin is pressed onto the surface of the rock with a force of 70 N, and then dragged across the surface for 10 mm. This process is designed to simulate the kind of interaction that would occur between a cutting tool and rock during excavation or drilling (Teymen, 2020). Figure 1 illustrates a schematic view of CAI test.



A- Cerchar apparatus
1+3-Vice 2-Hand lever 4-
Testing pin 5-Pin chuck 6-
Weight

B- West apparatus
1-Sample vice 2-Hand crank
3-Vice sled 4-Testing pin 5-
Pin guide 6-Weight



C- CSM apparatus
1+3-Vice 2-Handle 4-Testing pin
5-Pin chuck 6-Weight

Fig. 1 A schematic view of CAI test
(Plinninger et al., 2002; Rostami et al., 2005; Ghasemi, 2010)

After the test, the wear on the steel pin is measured by examining the flat spot formed at the tip. The diameter of this flat spot, usually measured in mm, is directly related to the abrasiveness of the rock. A larger flat spot means more wear, and therefore, a more abrasive material. The CAI is calculated based on this wear, with values typically ranging from 0 to over 6 (Ghasemi, 2010; Teymen, 2020).

The CAI is categorized into different levels of abrasiveness. Rocks with a CAI between 0 and 0.5 are considered to have low abrasiveness, while those with a CAI over 6 are extremely abrasive (Nikoobakht et al., 2015). As the abrasiveness increases, so does the wear on tools, meaning that projects involving highly abrasive rocks require more durable equipment and incur higher operational costs (Alber et al., 2015). In practice, CAI is a valuable tool for engineers and project managers. By knowing how abrasive a particular rock is, they can make informed decisions about the types of tools to use, the expected wear on equipment, and the overall costs of a project. This helps to optimize operations, reduce downtime from equipment failure, and improve the efficiency of rock excavation projects (Fowell & Abu Bakar, 2007).

III. MATERIALS AND METHODS

Isfahan, located in central Iran, sits within the central Iranian plateau and is characterized by a diverse geological makeup. Figure 2 shows the study location. Isfahan's geomorphology is marked by its surrounding mountains, arid plains, and river valleys. The Zayandeh River, which flows through the city, is a vital geographical feature, providing water to the region and supporting agriculture. However, the river has been drying up in recent years due to overuse and climate change. The terrain around Isfahan is predominantly flat, with a gradual slope leading towards the river, while to the east and south, mountain ranges provide a striking contrast to the otherwise level plains. This combination of geological formations, climate, and topography has played a significant role in shaping the city's development and history (Mohammadi et al., 2020).

The region is composed primarily of sedimentary rocks, including limestone, sandstone, and shale, which date back to the Mesozoic and Cenozoic eras. The area also exhibits volcanic rock formations due to historical volcanic activity. Additionally, Isfahan lies near the Zagros Mountain range to the southwest, which influences the city's structural geology through fault lines and folding, contributing to the region's occasional seismic activity (Aghanabati, 2007). Figure 3 is provided with the geological map adapted for Isfahan city. The climate of Isfahan is semi-arid, with hot summers and cold winters, typical of much of Iran's interior. Temperatures in the summer can reach up to 40°C, while in winter, they often dip below freezing. Precipitation is limited, with the city receiving an average of 100-150 mm of rain per year, mainly during the winter and early spring months. The arid climate combined with limited rainfall has shaped the landscape around the city, contributing to its dry, desert-like environment (Iran Meteorological Organization, 2022).

According to Figure 2, the central part of the city is primarily composed of Quaternary alluvium and riverbed deposits, formed by the Zayandeh River, which flows through the middle of the

city. The southern and southeastern areas are mainly composed of shale and sandstone, which represent the city's bedrock and the primary material of the surrounding mountain formations. This study focuses on the sandstone found in these areas, based on 12 samples collected from these sites, to provide an index of the geomechanical properties specific to Isfahan's sandstone.

The 12 sandstone samples collected from the Isfahan area were used to conduct CAI tests (Ghasemi, 2010) to determine their CAI values and hardness parameters. Following the CAI tests, the remaining portions of the samples were utilized for further geomechanical analysis. These included index tests like UCS (ASTM D7012) and point-load (ASTM D5731) tests to provide a comprehensive understanding of the material's geomechanical characteristics. These tests helped establish key properties of the sandstone, offering valuable insights into its behavior under stress and its suitability for construction and engineering projects in the region. The CAI test conducted in this study follows the principles established by the Centre d'Études et Recherches de Charbonnages de France in 1986 (Jacobs & Hagan, 2009). In this method, a Cerchar metal pin is rubbed across a freshly exposed surface of the rock sample (Al-Ameen & Waller, 1994). The resistance of the rock to the scratching action results in wear on the tip of the pin, and this resistance is used to determine a hardness index. The metal alloy used for the pin in the CAI test is specified as 4140H according to the US standards, or 1/7225 (42 Cr-Mo 4) in accordance with the German element standard. This ensures the consistency and reliability of the test results across different studies (Plinninger et al., 2003; Michalakopoulos et al., 2006). The pins are positioned at a 90-degree angle with maximum sharpness and are dragged across the marked surface, as described in the previous section, under a load of 70 N for 1 cm in 1 second. The results are then examined using a microscope and based on the wear observed on the pin tip, the rock's abrasiveness is classified. This method allows for accurate assessment of the rock's strength by analyzing the extent of abrasion on the pin (Thuro & Käsling, 2009).

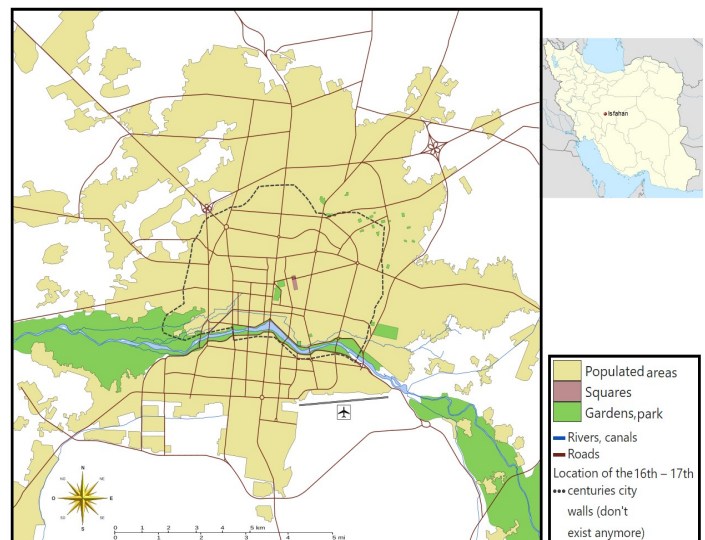


Fig. 2 Location of Isfahan city in Iran

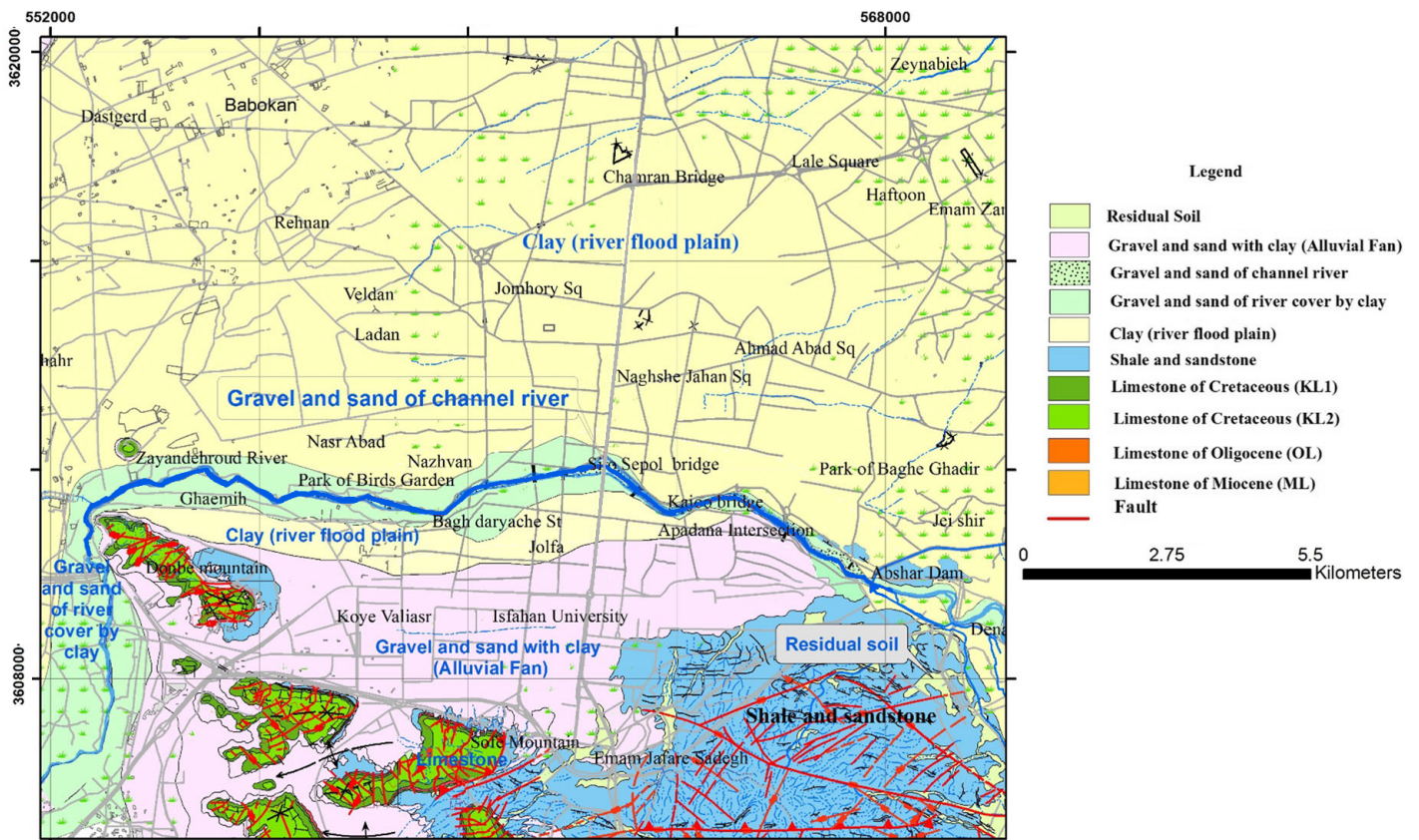


Fig. 3 Geological map of studied area (Geological Survey & Mineral Explorations of Iran, 2014; Mohammadi et al., 2020)

According to the guidelines from the Centre d'Études et Recherches de Charbonnages de France, the average value from five scratches is considered the representative CAI value for the mineral (Plinninger et al., 2002; 2003). Table 1 as well as Fig. 4, present the index values for various key minerals and rocks, along with their classifications based on the CAI index (Jacobs & Hagan, 2009). Additionally, Figure 5 illustrates the CAI value with UCS. These table and figures serve as a reference for understanding the abrasiveness of different geological materials, aiding in the classification and evaluation of rock strength in geotechnical applications.

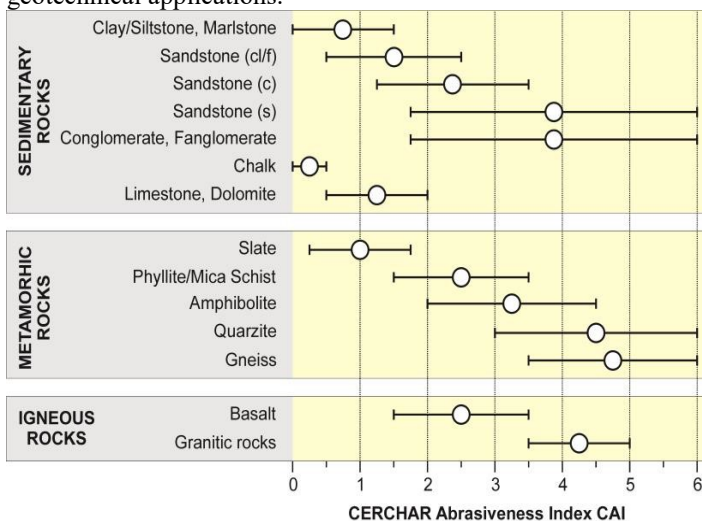


Fig. 4 Typical CAI values for different rock types (Büchi & Wyss, 1995; Plinninger & Restner, 2008)

Table 1 Rock classification based on CAI

CAI value	Rock abrasiveness class		
	CERCHAR (1986)	Michalakopoulos et al. (2006)	Plinninger and Restner 2008
0.3 – 0.5	Limited	Very low	Not very
0.5 – 1.0	Slightly	Low	Slightly
1.0 – 2.0	Medium	Moderate	Medium
2.0 – 4.0	Very	High	Very
2.0 – 6.0	Extremely	Very high/ quartzitic	Extremely

IV. RESULTS AND DISCUSSION

As mentioned earlier, 12 sandstone samples from the southern part of Isfahan were collected for CAI, UCS, and point load tests. The results of the CAI tests are shown in Figure 6. These CAI values were used to estimate the UCS values, as illustrated in Figure 5, and were compared with the actual UCS test results to confirm the accuracy of the index. Once confirmed, these values will be used to calculate rock hardness using Eq. 1 (Stanford and Hagan 2009).

$$CAI = -0.0766 HR + 5.80 \quad (1)$$

where, HR is rock hardness rating. According to the results, the estimated CAI value for the sandstones from Isfahan is 3.55, with a UCS of 35 MPa. Additionally, the estimated HR for the sandstone is 25.6. These values provide a clear understanding of the material's abrasiveness and strength, important for geotechnical assessments and engineering applications in the region.

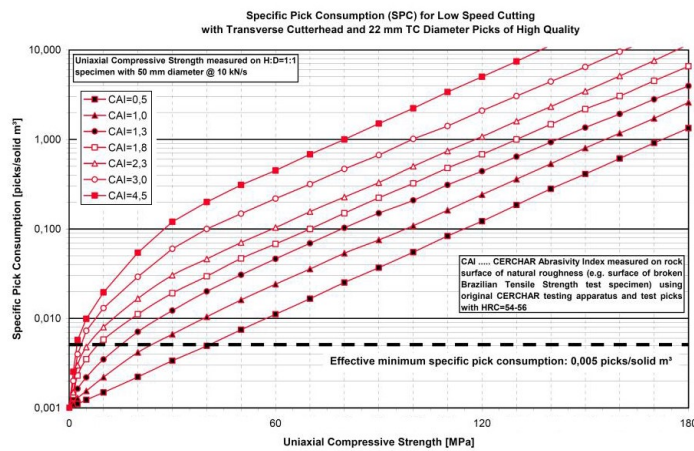


Fig. 5 CAI index value versus UCS for rocks (Plinninger & Restner, 2008)

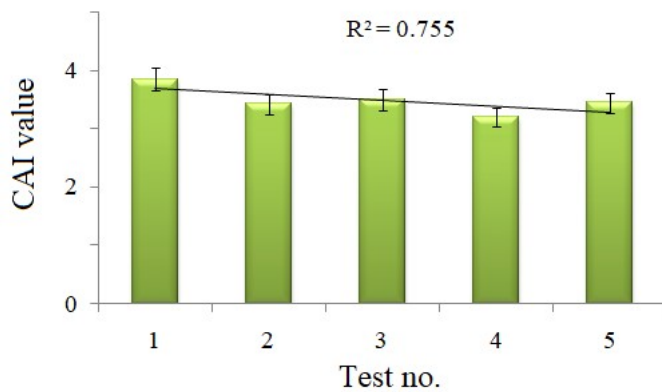


Fig. 6 CAI value variations in different attempts

V. CONCLUSION

The geomechanical characterization of Isfahan's sandstone reveals significant insights into its suitability for various engineering and construction projects. With a CAI value of 3.55, the sandstone demonstrates moderate abrasiveness, meaning it will cause moderate wear on excavation tools. This level of abrasiveness must be factored into project planning, particularly for operations involving extensive rock cutting, drilling, or tunneling. The findings suggest that while standard equipment may suffice, regular maintenance and tool replacement may be required to mitigate wear-related downtime. The UCS result of 35 MPa indicates that sandstone possesses adequate strength for many structural applications. This level of strength places the material within the category of moderately strong rocks, suitable for supporting foundational loads in construction. Given its strength, the sandstone can also withstand significant stress, making it appropriate for use in building foundations, road construction, and other infrastructural projects. However, additional considerations such as weather resistance and long-term durability should be evaluated in specific project contexts to ensure optimal performance. The HR of 25.6 further supports the assessment of the sandstone's mechanical properties, reinforcing its potential as a reliable construction material. The consistency between the estimated and actual UCS values confirms the

accuracy of the CAI-based estimations, proving the efficacy of using CAI for predicting material strength in future projects. Overall, these findings are crucial for construction professionals and engineers working in Isfahan, as they provide a data-driven foundation for material selection, tool usage, and cost-effective project planning, while ensuring that the inherent characteristics of the sandstone are appropriately managed.

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AUTHORS' CONTRIBUTIONS

Mahdi Aaghapour conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Ali Çelik assisted in the development of the methodology and performed validation checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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