Relationship Between Rock Textural Characteristics and Mechanical Properties

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The textural characteristics of rocks influence their petrophysical and mechanical properties. Such parameters largely control rock mass stability. The ability to evaluate both immediate and long-term rock behaviors based on the interaction between various parameters of rock texture, petrophysical and mechanical properties is therefore crucial to many geoengineering facilities. The mechanical properties of a rock largely depend on its petrographic or textural characteristics. Some quantitative associations between rock petrographic characteristics and mechanical properties have been found. Therefore, the effects of these relationships on the mechanical characteristics of rock, and their extents, must be well understood as a proper frame of reference if good rock cores are unavailable for reliable tests intended to characterize rock mass.

Rock Mechanical Properties Composition Texture Coefficient

1. Introduction

Rock behavior under in situ stresses is an essential element to be considered when undertaking earth engineering studies [1]. However, a rock mass is generally substantially heterogeneous with contrasting types of rocks; therefore, it cannot be regarded as a homogeneous medium. Furthermore, a single rock type can have distinct textural properties (e.g., mineral species, grain size, shape, and orientation). Thus, understanding the influence of rock's texture on its geomechanical behavior is crucial. Rock behavior is related to petrophysical properties, such as density, ultrasonic P-wave velocity, magnetic susceptibility, electric resistivity and magnetic remanence, and to mechanical properties, such as uniaxial compressive strength (UCS), tensile and shear strength, and elastic properties, e.g., Young's modulus and Poisson's ratio [2]. The mechanical properties and the composition of the rocks are commonly used to obtain critical information, such as rock or slope instability, failure mechanism, strength-deformation characteristic assessment, and other engineering purposes [3]. Moreover, the most influential factors on the strength and deformation behaviors of intact rocks include mineral composition, crystal size, rock fabric, grain size and shape, hydrothermal alteration, weathering, and anisotropy [4]. Discontinuities in the rock, such as macro- and micro-fractures, bedding planes, schistosity and faults, contribute to its weakening, and largely control its overall stress response [5]. Anisotropy is primarily caused by schistosity, foliation and cleavage. At high metamorphic grades, a rock can become layered, substantially heterogeneous and deformed [6]. In sedimentary rocks, different grain or clast sizes characterize bedding planes and lamination. Metamorphic rocks are generally physically weaker than magmatic rocks. Increasing microporosities along the grain boundaries and simplifying grain relationships result in decreasing strength properties [7][8].

2. Mineral Composition

The mechanical properties of rocks are markedly influenced by their mineralogical properties [9]. The strongest rocks are generally those that contain quartz as a binding material, followed by calcite (a carbonate species) and ferrous minerals (such as hematite and chromite), whereas rocks that contain clays and phyllosilicates (sheet silicates) for binding materials are weak [10]. Several researchers have investigated the links between the mineral composition and geomechanical properties of different rock types. **Figure 1** shows the main work of the experimental/empirical and numerical/simulation methods used for the evaluation of the effects of mineralogy and texture parameters on the geomechanical parameters of rock between 1960 and 2021. This chart represents the studies on sedimentary rock (yellow box), igneous rock (blue box), and metamorphic rock (red box). The red and green dashed lines indicate the nature of the study, that is, whether it has a substantial focus on geomechanical properties or rock texture. Researchers have recently devoted increasing attention to using simulation methods for the prediction of rock behavior with different mineralogical assemblages.

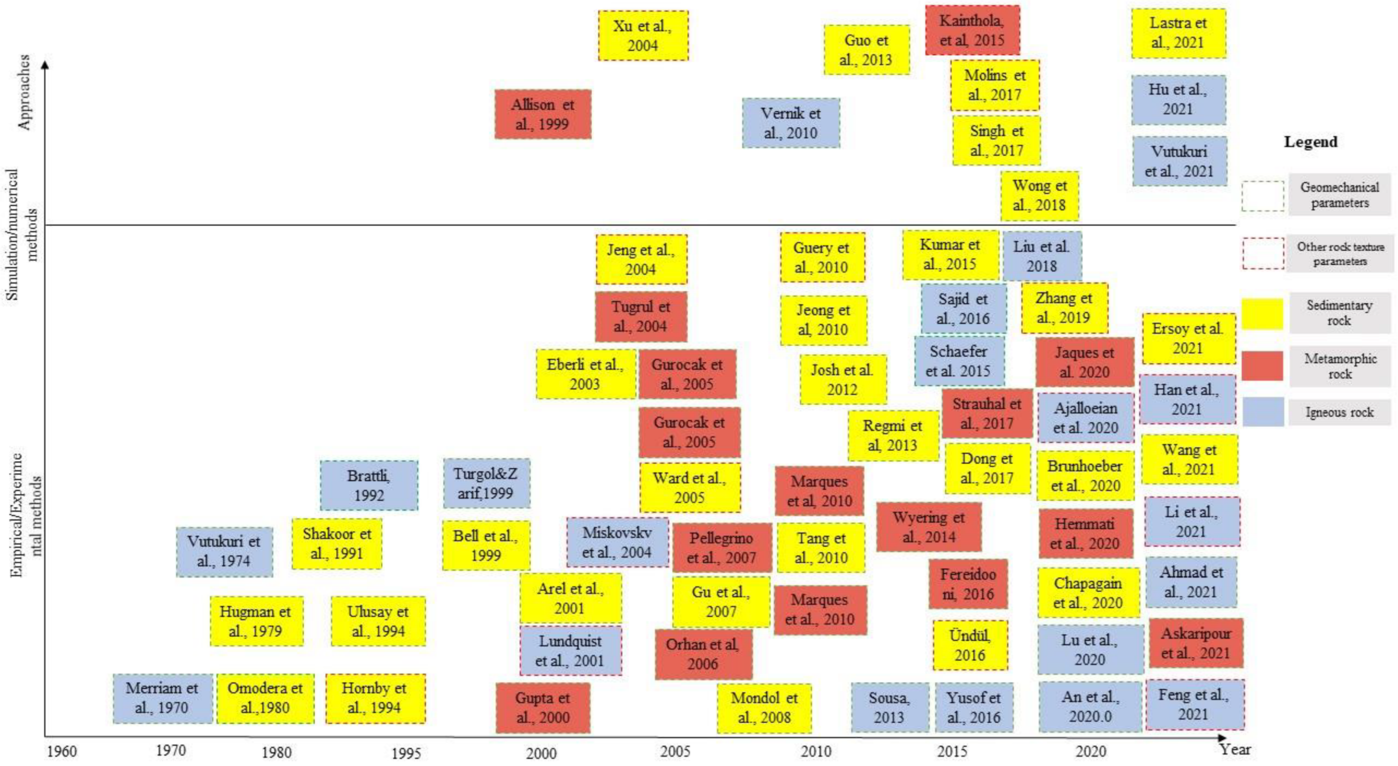

Figure 1. Main work on the effects of rock mineralogy on the geomechanical parameters of rock [3][5][9][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43][44][45][46][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61][62][63][64][65][66][67][68][69].

The main factors that affect the UCS of rocks based on their microtexture are mineral content, groundmass, and porosity [22].

3. Grain Size, Density, and Porosity

Grain size varies from very fine (125–250 μm) to coarse-grained (1–2 mm). Previous laboratory experiments have extensively investigated the relationships between mechanical properties and mean grain size, and demonstrated that grain size has a significant mechanical influence. Brace realized that rocks with fine mineral grains have high mechanical strength, implying that grain size has an impact on mechanical properties [70]. Hoek suggested that high stress is necessary to cause failures on grain boundaries in rocks with a tightly interlocking structure [71]. Mendes et al. discovered that the mineralogical properties of granite samples correlate well with their mechanical properties, and samples with fine grains have high strength [72]. Willard and McWilliams revealed that mineral cleavage, microfracture, and grain boundaries influence the ultimate strength of rock, as well as the direction of crack propagation [73]. Hartley indicated that intergranular bonding had a major impact on the mechanical features of sandstones, and concluded that it is possible to determine mechanical properties by counting the contacts between grains and by looking at the types of grains [74]. Onodera and Asoka indicated that strength is significantly reduced as the grain size in igneous rock increases [11]. Singh investigated the relationship between the mean grain size of the rock with UCS and fatigue strength [75]. The fatigue strength of the rock has an inverse relationship with its mean UCS because the uniaxial compressive strength varies with different grain sizes. Shakoor and Bonelli indicated that sandstone density, percent absorption, total pore volume, and grain-to-grain content are all closely related to compressive strength, tensile strength, and Young's modulus values [5]. The compressive strength, tensile strength, and Young's modulus were all high in the sandstone with high densities, low percent absorption, low total pore volume, and high percentages of saturated contacts. In addition, the percentage of angular grains had only a weak influence on strength and elastic properties. Ulusay et al. concluded that grain size, packing proximity, percent grain-to-grain contacts, and grain-to-matrix contacts have the largest impact on Young's modulus. Young's modulus increases with the increase in the first three parameters [25]. Increased grain-to-matrix contacts reduce stiffness; therefore, Young's modulus is inversely related to grain-to-matrix contacts. Akesson et al. showed that abrasion and fragility are dependent on the grain size, despite the important role of the shape and arrangement of the minerals [76]. Tugrul and Zarif found linear equations between the UCS and grain size of granite rock [39]. Ündül concluded that the UCS decreases as the total porosity increases. Furthermore, the Young's modulus decreases as the grain size of biotite rises [22]. A linear relationship exists between the mean grain size and the hardness value [77]. The mean grain size increases with mean hardness, while the normative hardness decreases with grain size. A decreasing mean grain size improves resistance to wearing and impact forces. Raisänen indicated that the abrasion value is linearly related to grain size [78]. In sedimentary rocks, all strength properties decrease with increasing porosity. Research on coal rocks has revealed a linear decrease in the UCS with an increase in porosity [79]. Yusof and Zabidi indicated that the uniaxial strength relationship is indirectly proportionate to the size of the grain, which thus decreases with the increase in grain size [17]. The researchers found the regression equations between the mechanical properties and the grain sizes of rocks primarily through experiments.

Porosity also plays a significant role in the geomechanical parameters of rock. Bell and Lindsay reported the highly significant relationship of porosity with UCS and tensile strength [38]. The UCS and tensile strength decrease as porosity increases. The total porosity and dry unit weight are linearly related. As porosity increases, the dry unit weight decreases [39]. Fahy and Guccione suggested a correlation between the compressive strength of rocks and the percentage of cement, and the mean grain size is as follows [80]:

$$\mathrm{UCS} = 167.7 - 0.52\ (\mathrm{total\ \ percent\ \ cement}) - 320.9\ (\mathrm{mean\ \ grain\ \ size})$$

where UCS is in MN/m^2, and mean grain size is in mm.

Shakoor and Bonelli studied the effects of the petrographic characteristics of sandstone on the mechanical properties of the rocks, and reported that sandstones with high density, low absorption percentage, low total pore volume, and a high percentage of sutured contacts exhibited high values of compressive strength, tensile strength, and Young’s modulus [5]. They proposed several empirical equations for the relationships of the petrographic characteristics of sandstone with the mechanical properties of the rocks.

Chatterjee and Mukhopadhyay developed a series of equations to link the petrophysical to the geomechanical properties of rock [81]. The samples were collected from the basement rocks of the Krishna-Godavari and Cauvery basins in India.

Tamrakar et al. studied the relationships of many petrographic characteristics of rocks with their geomechanical properties [82]. The samples were sandstone from the foothills of the Himalayas.

Ündül indicated that phenocrysts (i.e., conspicuous crystals that are substantially larger than the matrix in magmatic and volcanic rocks) and groundmass are regarded as the main factors influencing crack propagation [22]. An increase in phenocryst content leads to an increase in radial strain and an increase in Poisson’s ratio. Cracks tend to align parallel to the applied load as the groundmass content (low phenocryst content) increases. Increased groundmass reduces the Poisson’s ratio compared to samples with high phenocryst contents.

4. Texture Coefficient (TC)

The texture coefficient has often been used to quantify the characteristics of rock texture. In this approach, rock material textures depend on the geometrical relation between the mineral grains and the matrix [83]. Rocks comprising hard minerals tend to have rough surface textures and high strength properties. Soft minerals are found in clay minerals and organic matters. The rest of the rock-forming minerals are hard minerals. To define the texture coefficient, Howarth and Rowlands considered morphological characteristics such as grain size, grain shape, grain orientation, porosity, and matrix materials [84]. Various types of rocks show a linear increase in UCS as the texture coefficient increases, except for fault breccia (i.e., broken or partly disaggregated rocks in a fault zone). Ersoy and Waller found a positive linkage between UCS and texture coefficient for various sedimentary and igneous rocks [85]. A strong link in sandstone, siltstone, marl, shale, and limestone has been validated [83]. Most experiments have shown that UCS is increased linearly by raising the texture coefficient in various rock forms [85][86]. However, contradictory correlations are found between TC and strength [87]. The possible explanations for these contradictory correlations may be as follows. Complicated rock texture characteristics cannot be effectively expressed as a coefficient of texture by one index. For example, fault breccia, which comprises broken mineral grains filled with a fine-grained matrix, may have substantially different mineral properties than other types of rocks, such as sandstone, limestone, and granite, resulting in different relationships between UCS and grain size.

5. Rock Anisotropy

The anisotropy of a rock influences its behavior in engineering analyses. Aagaard investigated the effect of foliation angle on the diametrical point load index of two gneisses and mica schist rocks [88]. The point load index decreases as the foliation angle increases. Behrestaghi et al. indicated that quartzitic and chlorite schists with a low amount of mica exhibit high tensile strength and UCS at all foliation angles [89]. Nasseri et al. studied the impact of anisotropy on the UCS of quartzitic, chlorite, quartz mica, and biotite schists [90]. They showed that all samples displayed the maximum strength when β = 90°, due to the uniform distribution of stress throughout the anisotropy planes, compared with when the foliations are inclined. AL-Harthi studied 10 large blocks of Ranyah sandstone, which had two sets of discontinuities instead of one set of discontinuities [91]. Because of the superimposed effects of bedding and microfissures, an anisotropy curve in the form of a W curve was obtained.

Khanlari et al. noted that the metamorphic foliation angles of samples could influence rock strength directly [92]. The lowest rock strength was observed when the angle of foliation was from 0° to 30°. By contrast, the maximum value of rock strength was achieved when the foliation angle was 90°. Ali et al. investigated the behavior of banded amphibolite rocks in terms of strength and deformation anisotropy [93]. The results show that under UCS testing, the amphibolite had a U-shaped anisotropy with maximum strength at β = 90°, and minimum strength was reported when β = 30°. The results of the elastic deformation test show the absence of a relationship between the microstructure features of subtype amphibolite rocks (metamorphosed at high temperatures and pressures) that control modulus “shape anisotropy.” The researchers also studied the relationship between the anisotropy and tensile strengths of rocks. Several researchers have demonstrated that fractures in brittle materials can occur due to tensile stress. Therefore, the tensile strength is an important aspect of the failure resistance of rock. Hobbs reported that the maximum tensile strength is obtained when the angle of foliation is perpendicular to the load direction [94]. This phenomenon indicates that tensile strength is larger in low degrees of anisotropy than in high degrees of anisotropy. The low value may be attributed to the low cohesion between rock materials, or the presence of microcracks that directly connect to the anisotropy.

Shear strength refers to the strength of a rock, or the structural failure when the rock fails in shear. A rock that encounters a shear load slides along a plane, failing parallel to this direction. The effect of anisotropy on the shear strength of rock has been researched over the last few decades. McCabe and Koerner investigated the relationship between the anisotropy of mica schist samples and the shear strength parameters of rock [95]. The Mohr–Coulomb criterion was used to assess the relationship between rock anisotropy, cohesion, internal friction, and shear strength. The results indicate that the shear intensity value varies with the angle of foliation. The maximum and minimum values for shear strength were recorded when the foliation angle was β = 30°, β = 70°, and β = 50–59°. Furthermore, increasing the degree of foliation and the size of the mica flake decreased cohesion and the internal friction angle. Strength anisotropy remains important in the presence of confined conditions, as evidenced by a large number of triaxial tests on Delabole slates and Himalayan schists [96][97] With increasing confining pressures, strength anisotropy decreases [98]. Ramamurthy et al. investigated the anisotropy behavior of phyllites [99]. The compressive strength of phyllites increases non-linearly at all orientation angles of rock anisotropy. The results indicate that the variations in cohesion with σ_3 at a particular β are exactly the opposite of those in internal friction. For example, cohesion increases and internal friction decreases when σ_3 increases, and vice versa. Moreover, the variation in cohesion with σ_3 at a particular β is significant, whereas the variation in internal friction is insignificant. Nasseri et al. noted that maximum and minimum strength values for quartzitic, chlorite, and quartz mica schists are observed at β = 90° and β = 30–45°, respectively [90]. Maximum strength values for quartzitic and chlorite schists were observed at β = 90° throughout the range of confining pressures. The minimum strength is commonly 30° to 45°. However, quartzitic schist showed a 30% strength improvement at β = 30° due to confinement. For chlorite schist, this improvement was 15%, and for quartz mica schist it was 10%. Heng et al. studied the effects of anisotropy orientations on the shear strength and failure mechanisms of some shale samples [100]. The results demonstrate that the angle between the bedding planes and the coring orientation is an important factor in strength, cohesion, and internal friction, and the maximum and minimum values of shear strength were reached at β = 60° and β = 0°, respectively.

The foliation angle in anisotropic rock strongly affects the geomechanical parameters, and rock strength is a crucial aspect in the design of rock structures. The representative failure criteria are necessary for the analysis of these structures' stability. Therefore, the failure criteria of anisotropic rock will be discussed in the next section.

In summary, the mechanical behavior of a rock is predominantly determined by textural characteristics, such as grain size, shape and packing density (collectively expressed as "texture coefficient"), rather than by its mineral composition. Such information is generally readily available through routine geological and petrographic descriptions. Single and multivariable regressions between geomechanical parameters and texture were introduced. These regressions were developed in different but specific geological settings and rock types, and therefore cannot be universally applied to different types of rock that have contrasting mineral assemblages. A model that is applicable to a wide range of rock types and geological settings needs to be developed. Another possible future avenue for research would be to compare empirical methods with other methods, such as machine learning.

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