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Evaluating Microscale Failure Response of Various Weathering Grade Sandstones Based on Micro-Scale Observation and Micro-Structural Modelling Subjected to Wet and Dry Cycles

Kausar Sultan Shah[1], Mohd Hazizan bin Mohd Hashim[2*], Hafeezur Rehman[3], and Kamar Shah bin Ariffin[2]

1- Strategic Mineral Niche, School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, Penang, Malaysia
2- school of material and mineral resources engineering, USM, Malaysia
3- Department of Mining Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan.

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Abstract

The significance of rock failure can be found from the fact that microfracture genesis and coalescence in the rock mass results in macroscale fractures. Rock may fail due to an increase in the local stress, natural fractures, weathering inducing micro-crack genesis, coalescence, and propagation. Therefore, a comprehensive understanding of the micro-scale failure mechanism of various weathering grade sandstones based on micro-level observation and microstructure-based simulation is essential. The microscale failure response of various weathering grade sandstones is studied under the wet and dry cycles. Each sample is tested for the micro-structure and micro-fracture characteristics using the image analysis. Furthermore, the micrographs obtained are also used to create the microstructure-based models, which are then simulated in the ANSYS software. The findings indicate that the moderately weathered sandstones indicate less weight reduction than the slightly weathered sandstone. The results obtained also demonstrate that the wet and dry cycles have little effect on the particle shape and size. However, variation in the particle shape and size implies that this is a result of the prevailing interaction of rock and water particle. The microscale simulation reveal that both UCS and BTS decrease from 37 MPa to 19 MPa and 9 MPa to 4 MPa as the density of the micro-structure increases. The results reveal that the primary fracture deviation from the loading axis increases with increasing density in the micro-structural micro-structures, although this effect reduces with further increasing density in the micro-structures.

1. Introduction

Rock failures are addressed at the micro- and macro-scales, and failure initiation and propagation are complex phenomena highly influenced by the surrounding field [1, 2]. Rock failure at micro-scale is controlled by the variables such as the presence of grain boundaries cracks, intergranular cracks, intergranular cracks, multiple granular cracks, grains density and size, pore spaces, and orientation of micro-structures (microfractures and pore spaces) [3, 4]. Rock failure occurs due to the increased local stresses, and weathering induces microscale fracture genesis, coalescence, and propagation. At the microscale, natural, and stress-induced flaws create stress concentrations around pore spaces, micro-cracks, particle boundaries, etc., whereas at the macro-scale, bedding plane, fractures, folds, etc. play a vital role in the failure process leading to the failure of the rock mass. The significance of rock mechanics is deemed from the fact that microfracture genesis and coalescence in the rock mass results in the macroscale fractures [1, 5-7].

Corresponding author: mohd_hazizan@usm.my (M. H. Mohd Hashim).

Rock is made up of various minerals, and many defects and pores are developed during diagenesis. Hence, rock is considered a a non-uniform material due to the presence of microfractures and the variability, randomness, and diversity of the pore spaces [8]. Excessive micro-fractures and heterogeneity of rock pores lead to damage that affects the macro-mechanical characteristics of rock, and hence, severely impairs overall geotechnical stability [9, 10]. The interaction of rock and water is responsible for the growth of microfractures and pore spaces, which leads to rock instability. Therefore, rock-water interaction is critical for rock material stability. Due to environmental changes, however, absorbed water evaporates from rock. The wet and dry cycle is characterized by continual rock water absorption and evaporation, resulting in rock softening. The wet and dry process changes existing rock micro-defects that cause variation in rock micromechanical, damage, and geo-mechanical properties [11]. Chen *et al.* [12] have investigated the effect of wet-dry cycles on the strength and micro-structure of granite using mechanical equipment and scanning electron microscopy (SEM). The results showed that UCS, cohesion (c), elastic modulus (E), and angle of internal friction (φ) decreased as the number of wet-dry cycles increased. The SEM micrographs showed that the wet-dry cycle affects the micro-structures of granite, and the micro-structures are altered from smooth and integrated internal structures to microfracture initiation, development, and propagation. Yang *et al.* [13] have investigated the effect of wetting and drying cycles on the micro-structures of chlorite-amphibolite rock. The results show that Water–rock interaction changed the micro-structures of the rock sample surface from compact and uniform to flocculent and chaotic. Furthermore, the porosity of rock increases as the number of wetting and drying cycles increases. Wang *et al.* [14] have analysed the impact of wetting and drying cycles on the pore spaces of sandstone. The findings reveal that sandstone porosity increases with wet and dry cycles as new small pore spaces develop and existing pore spaces overlap.

The micro-scale behaviour of rock is essential to explain the diversity of macro-scale behaviour because the rock material characteristics are controlled by mineralogical composition, texture (grain shape and size), fabric (micro-flaws and mineral arrangement), weathering, and variation in tensile and compressive stresses [1, 15]. Among these factors, quasi-static loading and weathering of rock materials are major factors affecting the rock failure behaviour [16]. These two factors have been independently investigated by the researchers in mining and civil engineering [17-20].

Micro-flaws typically influence the initiation and propagation of micro-cracks. According to the literature, the porosity of a rock is more sensitive to weathering [11, 13]. The factor responsible for rock failure is water due to the water-rock interaction frequency and abundance of water in nature [11]. Research regarding rock properties evaluation based on wet and dry cycles has been reported. However, the effect of wet and dry cycles on sandstone subjected to various weathering grades needs comprehensive evaluation in terms of the geo-technical structure stability. Furthermore, the literature also presents scarcely the effect of quasi-static loadings on the sandstone damage at micro-scale subjected to various weathering grades. Therefore, a comprehensive understanding of the micro-scale failure mechanism of various weathering grade sandstone based on micro-level observation and microstructure-based simulation is essential. Consequently, the micro-scale failure response of various weathering grade sandstones was studied under wet and dry cycles. Each sample was tested for the micro-structure characteristics using image analysis. Furthermore, the obtained micrographs were also used to create microstructure-based models, which were then simulated in the ANSYS software.

2. Material and Methods

These samples were taken from the Sor-Range coal mines near Quetta, Pakistan. By cutting sandstone, the underground mines and access road were developed. The samples were collected from both underground and surface outcrops based on their weathering grades. In the laboratory, the effects of dry-wet cycles on the micro-fractures and micro-structures of various weathering grade sandstones were investigated. The wet and dry cycles were carried out in the following states: initially, the samples of each weathering grade were immersed in water for 48 hours, and then dried naturally. After that, the samples were dried in an oven at 50 $^{\circ}$C for an appropriate amount of time to evaporate the absorbed water. The sandstone samples were sorted into 5 groups based on their weathering grade, as shown in Figure 1, with 3 samples in each group, and were subjected to 0 cycles (describing the natural condition), 3 cycles, 6 cycles, and 9 cycles, respectively [11].

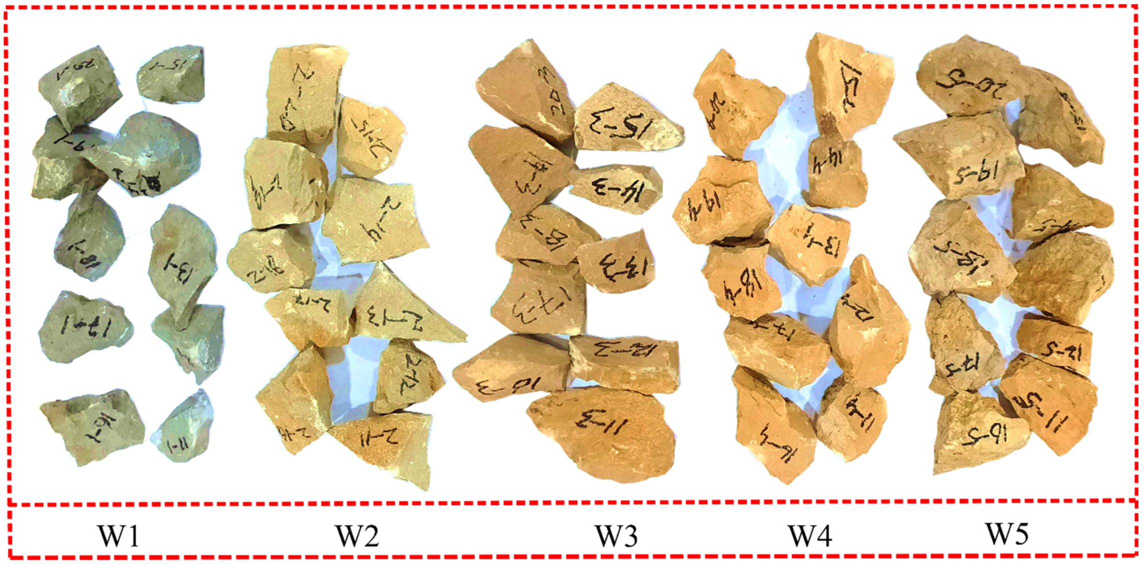


Figure 1. Sandstone samples of various grades for wet and dry experiments (W1-W5).

The first group (0 cycles) of samples was removed and prepared for image analysis to represent the natural state. At the end of each cycle, one group of samples was carefully removed, dried, weighted, and prepared for image analysis. The micrographs acquired from image analysis were used to understand the micro-fracture mechanism based on observation of surface morphology. These micrographs were also used to create microstructure-based models, which were then simulated in ANSYS under quasi-static loading. The flow chart of microstructure modelling and simulation is given in Figure 2.

FEM was also used to study the effect of wet and dry cycles on various weathering grade sandstone micro-structures. Therefore, the pore's structure is created in SpaceClaim from two-dimensional (2D) binary images acquired from ImageJ. For modelling pore's structure in space claim, the obtained PNG files were uploaded, traced, and modelled. The finite element simulation of micro-structures in sandstone was carried out using the ANSYS program. The sandstone various weathering grade models were simulated under quasi-static loading. The sandstone material data given in Table 1 was used to simulate the models. The density and Young's modulus were determined experimentally. The Poisson's ratio and Young's modulus were calculated based on the information already available in [21-24]. The ANSYS engineering data source contains the input data required for simulation relating to various types of sandstone. In this study, the material properties of sandstone used in finite element simulation are obtained using the experimental results, previous literature, and ANSYS engineering data sources. The optimal meshing size was determined by calibrating the first model using the experimental findings and comparing the results. The mesh size of 9 µm was adopted for microscale UCS modelling and simulation. In the simulation of microstructure-based BTS models, a mesh size of 4 mm was used. The model's top was loaded with 10,000 N in both the BTS and UCS simulations.

Despite the fact that the literature includes a variety of shape descriptors, this research work focuses on the roundness, circularity, and aspect ratio. This is because the images were analyzed using the ImageJ software, which also includes these three shape descriptors. These shape descriptors are acquired using qualitative dimensions such as area (μm^2), Feret diameter (µm), perimeter (µm), and major and minor axis (µm). Equations 4.1, 4.2, and 4.3 are used to calculate the roundness, circularity, and aspect ratio.

$$\text{Circularity} = 4\pi \times \frac{[\text{Area}]}{[\text{Perimeter}]^2} \tag{1}$$

$$\text{Roundness} = 4 \times \frac{[\text{Area}]}{\pi \times [\text{Major axis}]^2} \tag{2}$$

$$\text{Roundness} = 4 \times \frac{[\text{Area}]}{\pi \times [\text{Major axis}]^2} \tag{3}$$

Table 1. Sandstone material properties used in finite element modelling.

Weathering grade	Density (kg/m^3)	Poisson ratio	Young's Modulus (GPa)
W1	2565	0.19	21.3
W2	2391	0.25	17.1
W3	2330	0.23	17.8
W4	2273	0.30	12.5
W5	2172	0.33	12.0

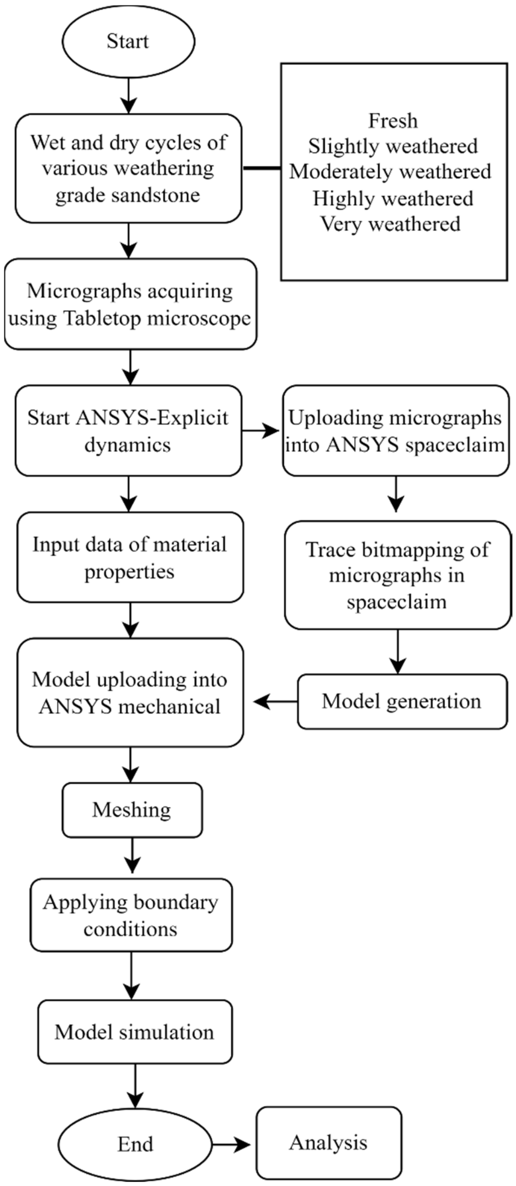


Figure 2. Flow chart of micro-structure modelling and simulation.

3. Results and Discussion
3.1. Interaction with water: weight loss

In order to understand the influence of wet and dry cycles on the weight loss of various weathering grade sandstone, the fluctuation in the weight is illustrated during different cycles (Figure 3). The fresh and moderately weathered sandstones indicate less weight reduction than slightly, very, and highly weathered sandstones. An increase in weathering grade will increase weight reduction because friability of the material increases with weathering grade [19, 25]. Slightly weathered sandstone presents more weight reduction than moderately weathered sandstone, as shown in Figure 3 *(b)* and *(c)*. Sandstone is mostly made up of feldspar and quartz, which are resistant to weathering [26]. However, some sandstone samples are chemically and physically unstable, making the sandstone unstable and erodible [27]. This instability and erodibility are caused by micro-defects that may be present due to progressive weathering and diagenesis [13, 28]. The very and highly weathered sandstone samples show a significant rise in weight reduction but randomly. It is attributed to the fact that the samples from the same grade of sandstone have a range of minerals, micro-fractures, and micro-structures, even when taken from the same location [29]. Therefore, SEM was used to characterize the micro-fractures and micro-structures of various weathering grade sandstones, as shown in Figure 4.

Figure 4 (a) shows the visible particles and a limited number of pore spaces, indicating that fresh sandstone is almost free from micro-fractures. As a result, fresh sandstone resists degradation, and the weight loss in the samples is attributed to loose material at the surface. The slightly weathered sandstone is characterized by noticeable fractures and a paucity of pore spaces. Figure 4 (c) demonstrates that moderately weathered sandstone has prominent pore spaces but the particles remain bonded together. The very weathered sandstone presents visible pore spaces, fractures, quartz, and clay material. Furthermore, the micrograph of highly weathered sandstone displayed a weak bond between particles as a result of extensive cracks. Figure 4 (e) illustrates that highly weathered sandstone contains visible fractures and quartz particle that resists degradation. In contrast, Figure 4 (f) shows that highly weathered sandstone contains loose particles and a substantial number of pore spaces. Therefore, both samples of highly weathered sandstone will react differently to the action of water.

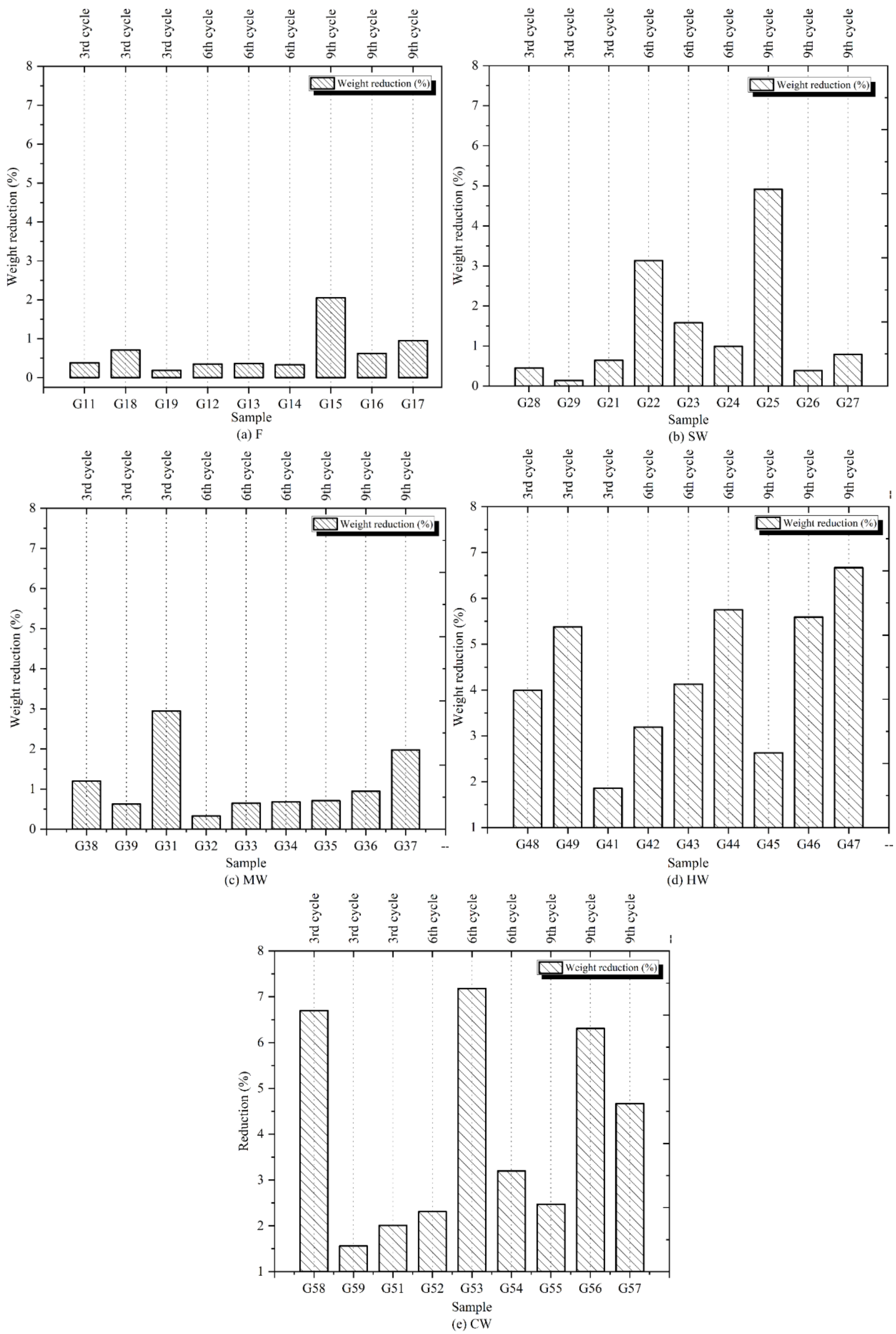
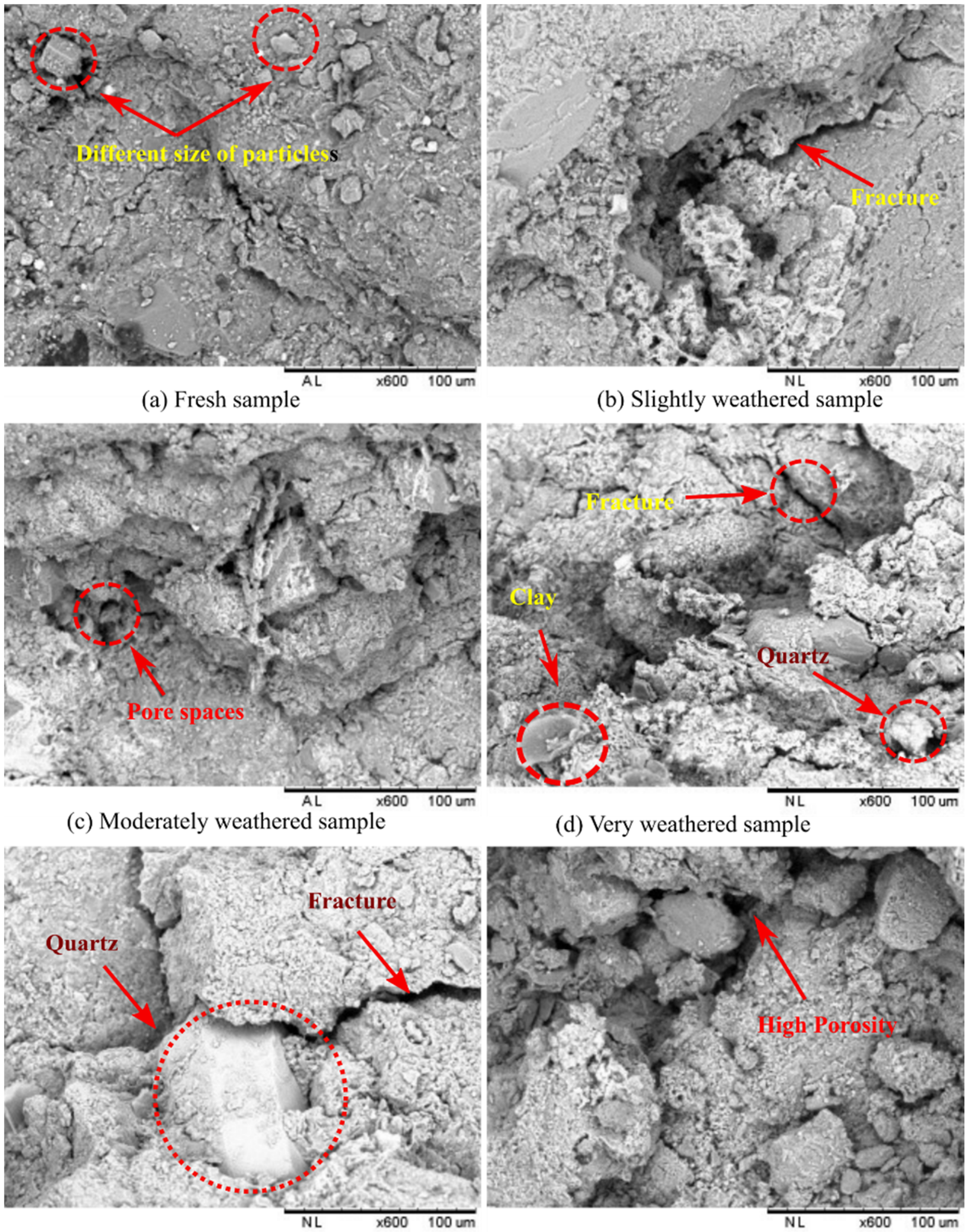


Figure 3. Effect of wet and dry cycles on weight reduction in different weathering grade sandstone; (a) fresh sandstone (b) slightly weathered sandstone (c) moderately weathered sandstone (d) very weathered sandstone (e) highly weathered sandstone.



(a) Fresh sample (b) Slightly weathered sample

(c) Moderately weathered sample (d) Very weathered sample

(e) Highly weathered sample (f) Highly weathered sample

Figure 4. Micrographs showing micro-fractures and micro-structures of various weathering grade sandstones.

3.2. Wet and dry cycles induced particle shape and size

Figure 5 presents the effect of wet and dry cycles on the particle size and shape of fresh and slightly weathered sandstone. The results indicate that fresh and slightly weathered sandstone particle shape and size deviate randomly during distinct wet and dry cycles. The trends followed by particle shape and size with relation to the number of wet and dry cycles provide obscure knowledge. However, the results indicate that the circularity and roundness of both fresh and slightly weathered sandstone first increase and then decrease with wet and dry cycles. The particle size of fresh sandstone decreases with an increase in the number of wet and dry cycles. In contrast, the particle size of slightly weathered sandstone deviates randomly. This randomness in particles is because the sandstone sample contains a significant proportion of feldspar and quartz, which resist degradation [26]. The results also revealed that the aspect ratio of fresh and slightly weathered sandstone first decreased and then increased as the number of wet and dry cycles increased.

Similar findings are observed for moderately, very, and highly weathered sandstone, as shown in Figure 6 and Figure 7. Circularity and roundness increase slightly and subsequently decrease with wet and dry cycles in moderately, very, and highly weathered sandstone. As the frequency of wet and dry cycles increases, both moderately and very weathered sandstone particle size decreases. In contrast, the particle size of highly weathered sandstone shows random results. These sandstone's aspect ratio drops and subsequently increases as the number of wet and dry cycles increases. The pre-rock water interactions produce strong bonds between particles that naturally weaken as weathering grade increases [25]. Water interaction weakens the bonding between particles in fresh, slightly, and moderately weathered sandstone and alters particle shape from angular to round. As the frequency of wet/dry cycles rises, the particle shape changes from round to angular due to degradation.

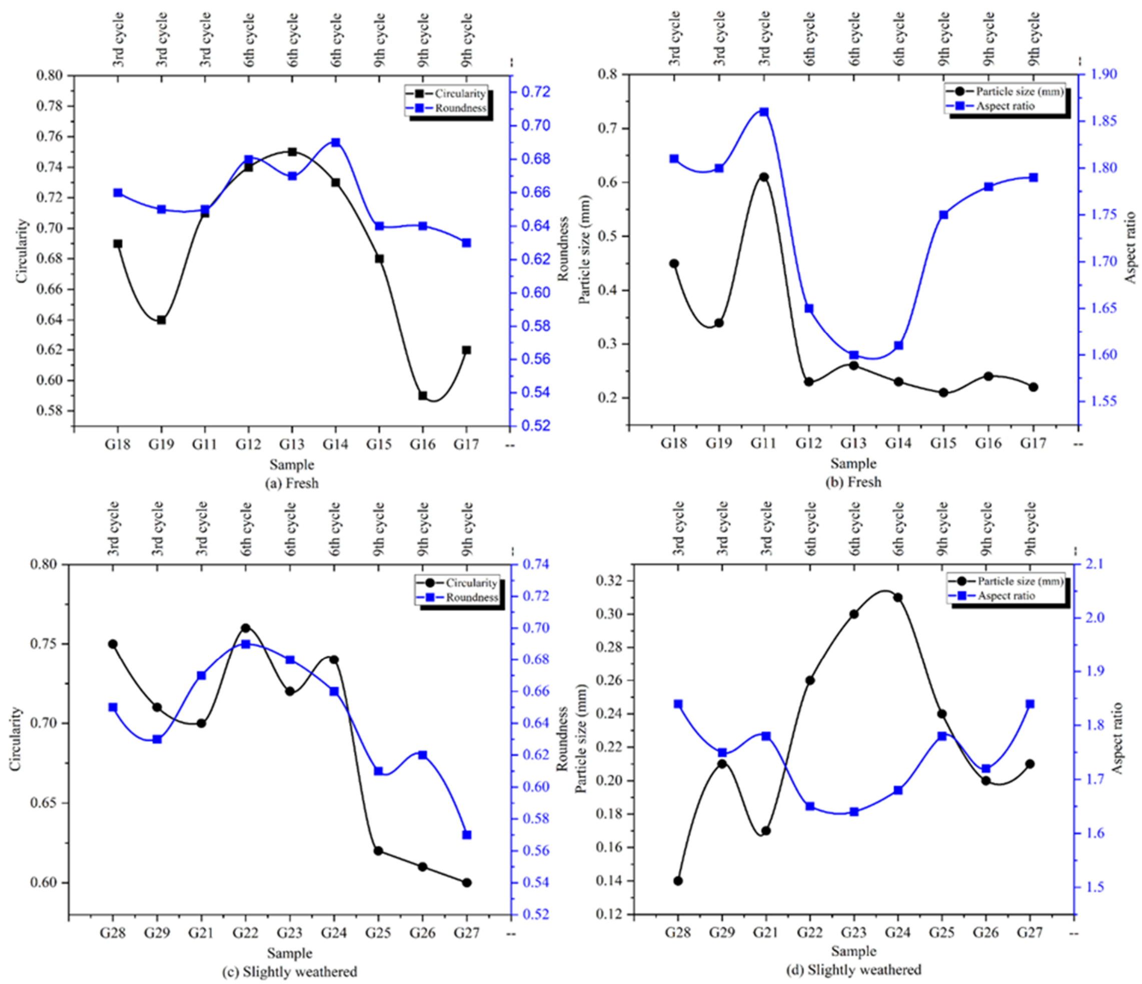


Figure 5. Particle shape and size of fresh and slightly weathered sandstone at different wet and dry cycles.

Following the analogous phenomenon of stress relief, the prolonged rock-water interaction causes the particle surface to degrade with time [11, 13]. Consequently, the particle roundness declines, and its angularity grows, eventually degrading the particle to mud. Additionally, this statement verifies the reduction in particle size as a result of wet and dry cycling. According to Yang, Wang *et al.* [13], rock micro-structures alter from tidy and compact to scattered and then muddy structures as the interaction between rock and water continues. Pore spaces have also changed their shape, size, and distribution. Additionally, the author noted that the particle shape evolved from flat to disordered.

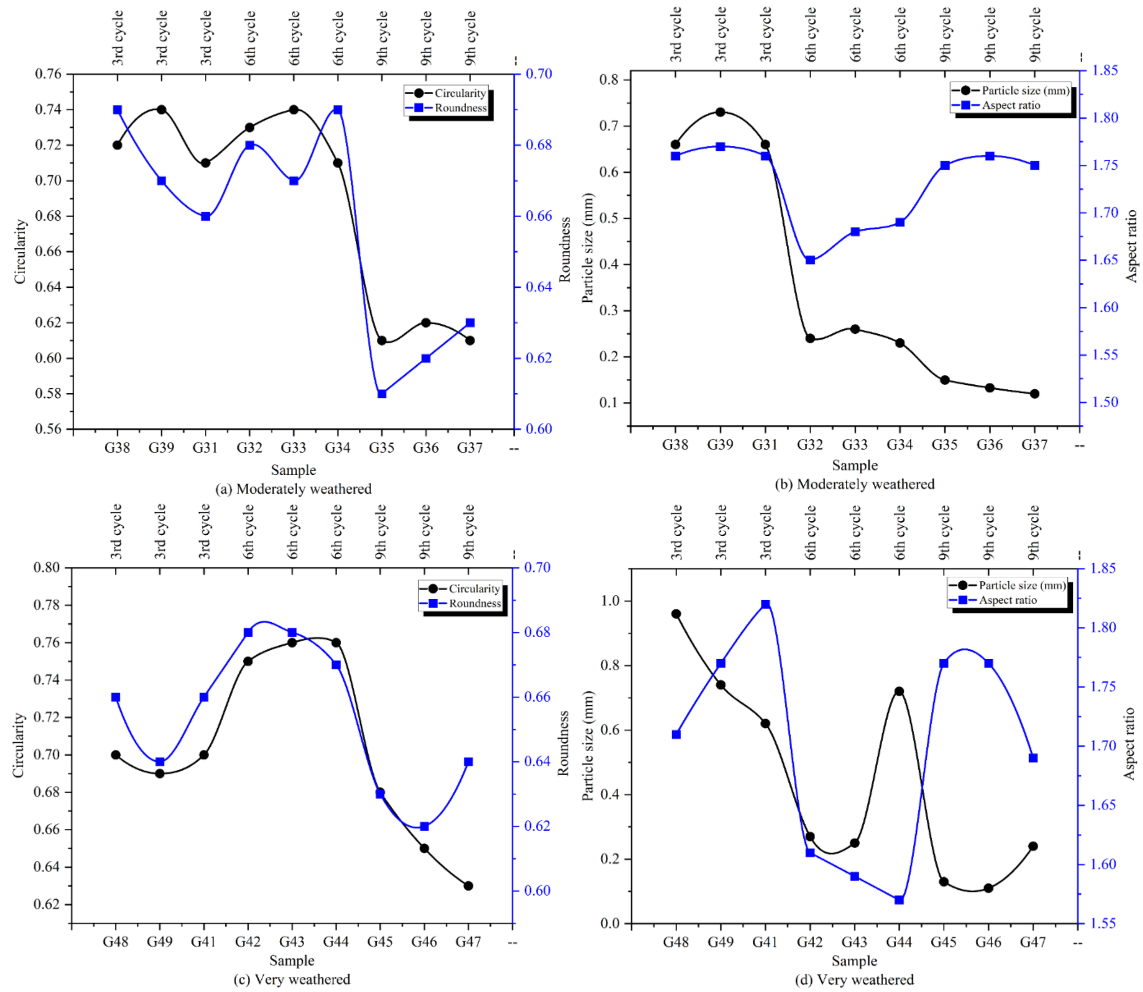


Figure 6. Particle shape and size of moderately weathered and very weathered sandstone at different wet and dry cycles.

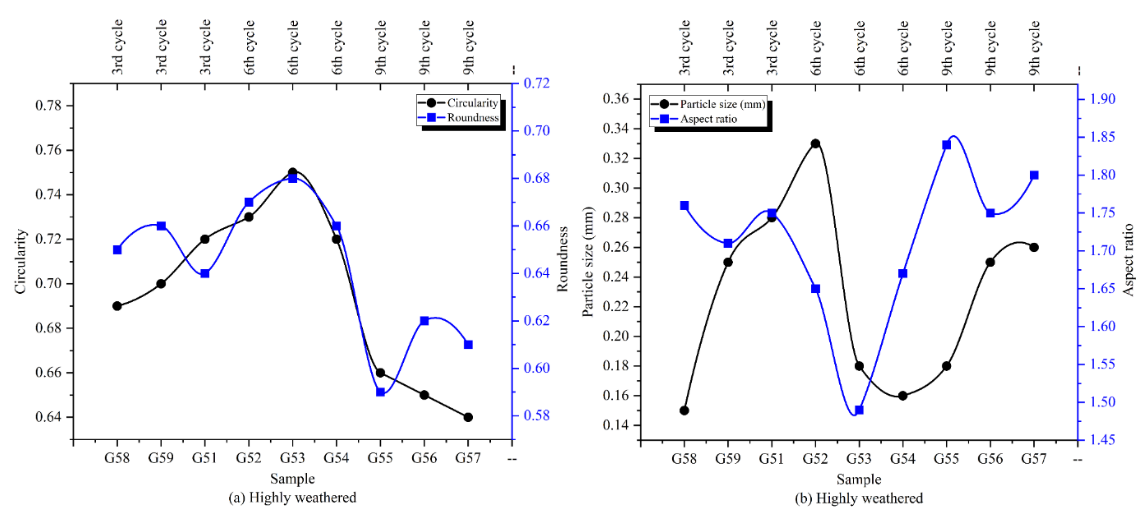


Figure 7. Particle shape and size of highly weathered sandstone at different wet and dry cycles.

3.3. SEM micrograph feature analysis

The micrographs of SEM for various weathering grade sandstones were observed before and after wet and dry cycles. The obtained samples were used to determine the effect of water interaction on sandstone micro-fractures and micro-structures.

The micrographs were analysed at the same magnification. Figure 8 and Figure 9 show the SEM micrographs of various weathering grade sandstone obtained at 100-time magnification (x100). The micrographs show that water action causes significant changes in sandstone micro-structure properties, which increases with weathering grade. The pore types of sandstone are mainly microcracks, microporosity, intergranular (primary), and dissolution (secondary) [30-32]. Figure 8 and Figure 9 demonstrate that the intensity of sandstone micro-structures and micro-fractures increases with water interaction. The visibility of pore spaces, fractures, and particles increases with wet and dry cycles in fresh, slightly weathered, and moderately weathered sandstone.

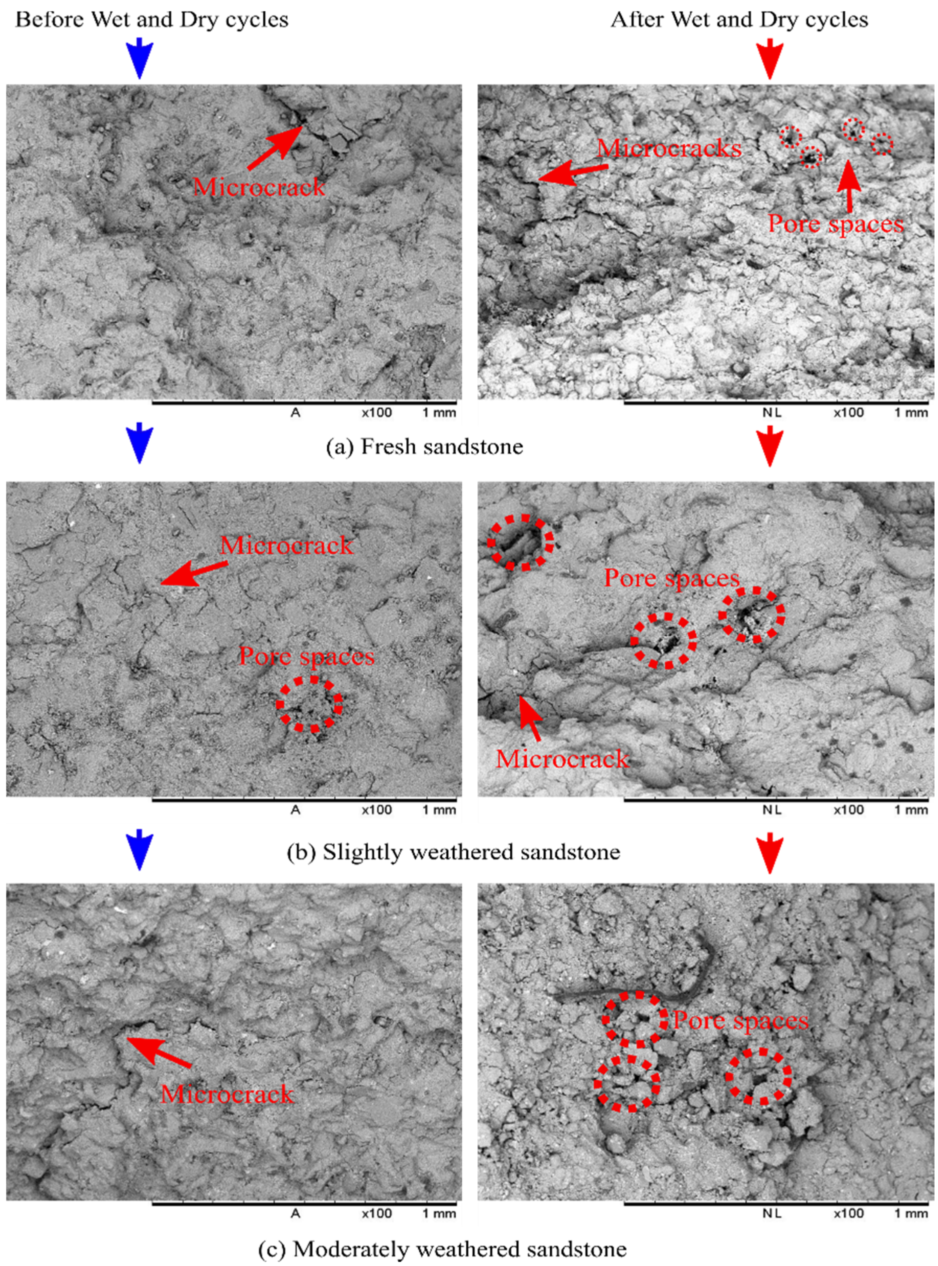


Figure 8. Effects of wet and dry cycles on micro-fractures and micro-structures of various weathering grade sandstone.

Whereas, in the case of very and highly weathered sandstone, the micro-structures altered from tidy to disordered and muddy as a result of progressive weathering. The pore shape, size, and distribution also altered considerably. Sandstone micro-structures had visible boundaries and no noticeable overlapping prior to rock water interaction. After interacting with water, the micro-structure boundaries of fresh sandstone become more visible. The overlapping of micro-structures increases as the weathering grade of sandstone increases. As the number of wet and dry cycles increases, the alteration of micro-structures and the emergence of new micro-structures occurs in the sample.

As a result, the sandstone microfractures change significantly from the natural state. Small pores coalesce and penetrate, resulting in the formation of large pores. In general, the morphology of the particles changed from round to angular and finally to mud. Furthermore, the porosity increases continuously, and the intensity of porosity alteration increases with weathering grade.

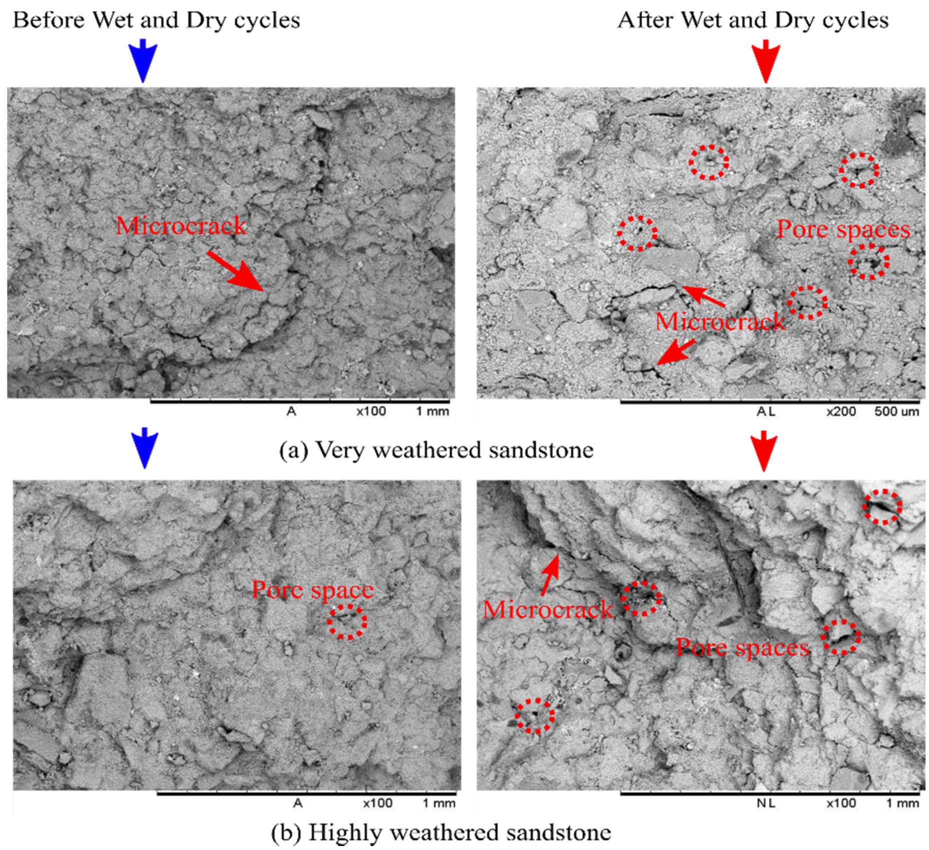


Figure 9. Effects of wet and dry cycles on micro-fractures and micro-structures of very and highly weathered sandstone.

3.4. Micro-scale simulation

A series of models were developed and simulated in order to examine the effect of pore spaces on the failure behaviour of sandstone under uniaxial compression. Figure 10 depicts the simulated sandstone models according to the weathering grades. As said earlier, the models are developed on the basis of micro-scale binary images of each sample. Furthermore, all of the samples are subjected to the same magnitude of loading (10,000 N). Figure 10 shows that the density and size of pore spaces increase as the weathering grade of sandstone increases. The simulation results illustrate that the stress is primarily concentrated on the pore space edges. This implies that the specimen will probably certainly fail in the direction of the micro-flaws. According to the simulation results, the UCS values of models decreases from 37 MPa to 19 MPa as the density and pore spaces size increases. The models with pre-existing pore spaces are built and simulated under tensile stresses to examine the effect of micro-flaws on the failure behaviour of various weathering sandstones.

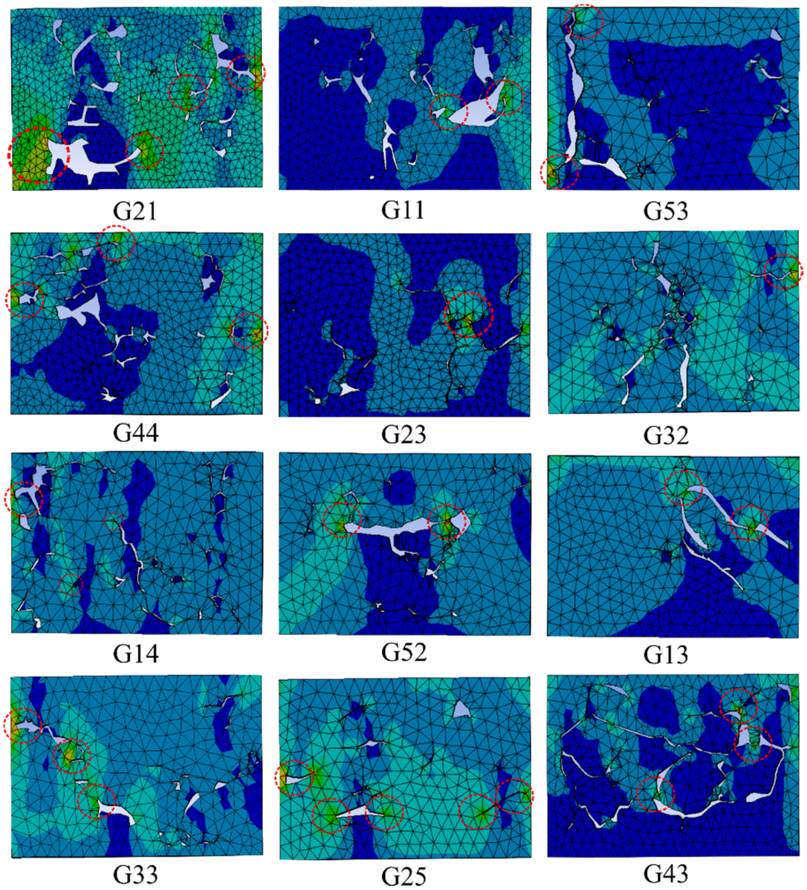


Figure 10. Uniaxial compression of samples under loading rate of 0.01 kN/s with pre-existing micro-flaws simulated in FEM. The red dotted circle denotes stress concentration on pore edges.

3.5. Micro-structure's density

The entire specimen is loaded in uniaxial compression, whereas a specific portion along the central loading line is loaded in Brazilian tensile strength testing. Therefore, rock conditions around the central loading line define the failure pattern and the overall tensile strength of the rock. The influence of micro-structures was examined in this work using the distributed micro-structures. The term "distributed micro-structures" refers to the micro-structures that are scattered throughout the specimen rather than being concentrated on the central loading line.

Figure 10 depicts the uniaxial compression of the micro-structure models, demonstrating that the density of micro-structure increases as the sandstone's weathering grade increases. Micro-scale modelling does not provide adequate information regarding sandstone failure. It is therefore imperative that the micro-structure features be analyzed under BTS testing to better understand the impact of micro-structures on sandstone. A series of BTS models were developed and simulated based on the weathering grade of sandstone (micro-structure density).

3.5.1. Effect of micro-structure density

In the Brazilian test, the tensile stresses acting normal to the loading direction causes an extension fracture along the loaded diameter. Besides the primary central fractures, fracture branches develop wedges near the loading platens [33]. Jaeger *et al.* [34] have found that the primary fracture start at the center of the disc during BTS testing and travell toward the platens to generate a primary fracture. Then the primary fracture produce a series of smaller fractures known as wedges.

Figure 11 shows the stress concentration on the sandstone models as a function of micro-structural density. The results indicate that a possible fracture pattern in sandstone is significantly affected by the micro-structure density. All simulations reveal that stress concentration starts at the disc center, and extends towards the loading platens. The possible fracture patterns deviate from the loading axis as the density of assumed microstructures changes.

The results also indicate that the stress concentration trajectory is uniformly distributed in the model without micro-structures. The BTS tests showed that the stress concentration of sandstone was affected considerably by stress-induced micro-structures. The numerical simulation results also demonstrate that when the density of micro-structure increases, the BTS values decrease from 9 MPa to 4 MPa. It is also worth noting that in addition to micro-structure density, other factors including micro-structure orientation, connection, and spacing have an impact on the failure pattern [35-37]. The effect of micro-structure density on the possible failure patterns is the sole subject of this research work.

In Figure 11, the failure patterns produced from numerical simulations demonstrate that the chances of primary fracture deviation rise with increasing micro-structure density. However, the results indicate that the stress concentrated along the loading axis in a model devoid of micro-structures, whereas the model with a low density of micro-structure also endeavor to fail into central line fracture. As the micro-structure density increases, the stress concentration begins to deviate from the loading axis. However, after a specific increment in micro-structure density, the model strives to fail along the loading axis, the stress trajectory demonstrates the presence of possible fracture branches.

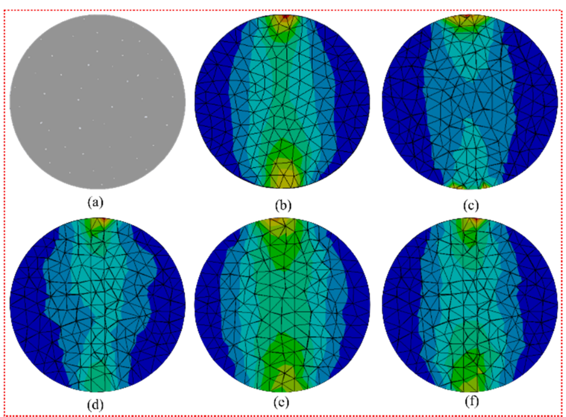


Figure 11. Simulation of Brazilian tensile strength (BTS) under loading rate of 0.01 kN/s with varied micro-structure density. (a) Micro-structures are shown. (b) shows the stress trajectory without micro-structures; (c), (d), (e), and (f) show stress trajectory with increasing microfracture.

The failure mechanism is generally attributed to pre-existing flaws such as cracks. This indicates that the pre-existing microcracks also play an important role in the fracture pattern of the specimen. Pre-existing cracks neighboring the opening propagate tensile fractures positioned sub-parallel in the form of spalling damage [38]. Wing crack propagation at the tip of pre-existing cracks is extremely susceptible to confinement [39, 40].

4. Conclusions

Microstructure observation and modelling were used to assess the microscale failure response of distinct weathering grade sandstones subjected to wet and dry cycles. The experimental and simulation results enable us to attain the following conclusions:

1. The sandstone deterioration increases with weathering grade; however, slightly weathered sandstone is more susceptible to weathering than moderately weathered. This is because an increase in weathering grade results in an increase in weight reduction, as the material's friability increases with weathering grade. Additionally, the research work found that wet and dry cycles had little effect on the shape and size of sandstone particles.

2. The microscale simulation demonstrated that when the density of micro-structures (pore spaces) increased, the chances of fracture deviating from the loading axis increased. However, at some point, the effect of micro-structure density is reduced on stress concentration because with an increase in the micro-structure density, the material specimens under loading do not fail instantly but degrade as a whole.

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Conflicts of Interest: The authors declare no conflict of interest.

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ارزیابی پاسخ شکست ماسه سنگ‌هایی با درجه هوازدگی مختلف بر اساس مشاهده در مقیاس میکرو و مدل‌سازی ریز ساختارها در شرایط تر و خشک

کوثر سلطان شاه[۱]، مهد حزیزان بن محد هاشم[۲*]، حافظ الرحمن[۳] و کمرشاه بن عارفین[۲]

۱- دانشکده مهندسی مواد و منابع معدنی، دانشگاه علوم مالزی، پردیس مهندسی، پنانگ، مالزی

۲- دانشکده مهندسی منابع مواد و معدنی، USM، مالزی

۳- گروه مهندسی معدن، دانشگاه فناوری اطلاعات بلوچستان، علوم مهندسی و مدیریت، کویته، پاکستان

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* نویسنده مسئول مکاتبات: mohd_hazizan@usm.my

چکیده:

اهمیت شکست سنگ را می‌توان از این واقعیت دریافت که پیدایش و ادغام ریزشکستگی در توده سنگ منجر به شکستگی در مقیاس بزرگ می‌شود. سنگ ممکن است به دلیل افزایش تنش موضعی، شکستگی‌های طبیعی، ایجاد ریزترک ناشی از هوازدگی شکسته شود. بنابراین، درک جامع مکانیسم شکست در مقیاس میکرو ماسه سنگ‌هایی با درجه هوازدگی مختلف بر اساس مشاهده سطح میکرو و شبیه‌سازی مبتنی بر ساختار میکرو ضروری است. شکست در مقیاس میکرو ماسه‌سنگ‌هایی با درجه هوازدگی مختلف در شرایط مرطوب و خشک مورد مطالعه قرار گرفت. هر نمونه برای شناخت ریز ساختار و ریزشکستگی با استفاده از آنالیز تصویر مورد مطالعه قرار گرفت. علاوه بر این، میکروگراف‌های به‌دست‌آمده نیز برای ایجاد مدل‌های مبتنی بر ریزساختار استفاده شدند که سپس در نرم‌افزار ANSYS شبیه‌سازی بکار رفت. یافته‌های بدست آمده نشان داد، ماسه‌سنگ‌هایی با درجه هوازدگی متوسط نسبت به ماسه‌سنگ‌ها با درجه هوازدگی کمتر کاهش وزن کمتری را نشان می‌دهند. همچنین نتایج به‌دست‌آمده نشان می‌دهد که با تر و خشک کردن نمونه تأثیر کمی بر شکل و اندازه ذرات دارند. با این حال، تغییر در شکل و اندازه ذرات نشان دهنده‌ی برهمکنش غالب سنگ و ذرات آب است. شبیه‌سازی در مقیاس میکرو نشان می‌دهد که هر دو UCS و BTS از ۳۷ مگاپاسکال به ۱۹ مگاپاسکال و ۹ مگاپاسکال به ۴ مگاپاسکال با افزایش چگالی ریز ساختار کاهش می‌یابند. بر این اساس انحراف شکست اولیه از محور بارگذاری با افزایش چگالی در ریزساختارهای افزایش می‌یابد، اگرچه این اثر با افزایش بیشتر تراکم در ریزساختارها کاهش می‌یابد.

کلمات کلیدی: شکست در مقیاس میکرو، درجه هوازدگی، ماسه سنگ، تر و خشک، شکستگی‌های ریز.