RGNZ/MGPB

Effects of porosity on the strength and mechanical behaviour of porous geo-materials under cyclic loading

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 622.323
DOI: 10.17794/rgn.2024.2.2

Original scientific paper

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Abstract

Most rocks in nature are porous and usually saturated with different fluids such as water, oil, and gas. The conventional and unconventional hydrocarbon reservoirs are mainly associated with sedimentary formations. The main rocks of these reservoirs are sandstone (porous rock), limestone and oil shale (tight rock), which are associated with varying porosity. Hence, porosity serves as a fundamental parameter for most reservoir rocks. In this research, the effect of porosity on the mechanical behaviour of geo-materials and its fatigue behaviour was investigated. For this purpose, a total of five geo-material sample groups with varying porosities were prepared and designated, i.e. groups A, B, C, D, and E. Group A exhibited the highest porosity 20-21.5%, while group E had the lowest porosity 2-3%, respectively. The conventional quasi-static strength tests and cycle loading tests with constant frequency and amplitude were performed on the samples and different results were obtained. The samples belonging to group E, with the lowest porosity (2-3%), exhibited the highest mechanical strength, elastic modulus and fracture toughness values and the lowest Poisson's ratio compared to those of higher porosity samples. During the cyclic loading period, the fatigue stress-life graph of the E group has the lowest slope compared to the other groups. It means that the slope of the graph increases as the porosity increases in all groups. Therefore, the E group has the lowest porosity and the longest fatigue life time, i.e. porosity and fatigue resistance have an inverse correlation.

Keywords:

fatigue life; porous geo-materials; fracture toughness; mechanical behaviour

1. Introduction

The rock materials associated with hydrocarbon reservoirs are porous and are usually saturated with different fluids, such as water, oil, or gas. In the oil industry, most hydrocarbon reservoirs are in sedimentary formations mainly consisting of sandstone or oil shale with various porosity percentages (**Cooper, 1998**). The effects of porosity as a fundamental parameter in oil production technology should be considered in most engineering applications. Therefore, understanding the mechanical characteristics of porous rock reservoirs may significantly impact engineering designs of the geo-mechanical structures. Additionally, another critical factor that plays a decisive role in mechanical design of the structure is the type and magnitude of the applied loadings. In most structural applications, forces are imposed on the system as dynamic loads. It is crucial to recognize that the mechanical response of rocks exhibits notable distinctions between dynamic and static loading conditions. As a result, the dynamic behaviour of rocks necessitates heightened attention and scrutiny to comprehensively understand and address its unique characteristics. The precise characteristics of dynamic failure in rocks are still not fully understood, and this lack of clarity is more pronounced when it comes to cyclic loading. Research indicates that the mechanical response of rocks varies under different loading rates. However, it is evident that rock failure can occur across all loading rates, albeit with distinct mechanisms involved. Therefore, the study of rock failure, rock mechanical behaviour under different frequency and rate of loading are very important in geomechanics (**Zhang et al., 1999**). According to past reports, more than 90% of mechanical failures are caused by fatigue (**Stephens et al., 2000**). Numerous investigations have been conducted to explore the phenomenon of fatigue and most of these studies focus on

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metals. In the following section, an overview is presented, encompassing significant experimental studies conducted on the topic of fatigue in geo-materials.

Jafari et al. studied the shear behaviour of rock-like samples under cyclic loading and showed that by increasing the frequency of the applied load, their shear strength reduced (**Jafari et al., 2004**). Chen et al. studied rock-like samples with different crack initiation angles (from zero to 90 degrees relative to the axis of loading) and showed that samples with a 45-degree crack initiation angle had the lowest fatigue life compared to the other samples (**Chen et al., 2005**). Bagde and Petroš investigated the fatigue behaviour of sandstone under dynamic uniaxial cyclical loading. The results showed that the fatigue strength of rock samples increased with a decrease in the frequency and amplitude of the load (**Bagde & Petroš, 2005**). Wang et al. studied the closure of rock joints under dynamic loading at different frequencies and found that the vertical displacement of joints of specific roughness decreased with an increase in loading frequency (**Wang et al., 2007**). Liu and He studied the effects of lateral pressure on the fatigue behaviour of rock samples via laboratory tests. The results of their research showed that lateral stress had a significant impact on the evolution of fatigue damage, so that an increase in lateral stress increased the axial strain of failure moment in the rock samples (**Liu & He, 2012**). Porosity has a significant impact on fluid and oil permeability, making it one of the most crucial factors to consider. Porosity increases the surface area of a material. The increased surface area can impact various material properties, such as fluid permeability, adsorption capacity, and surface reactions. In porous materials, the microscopic examination can reveal intricate networks of voids and pores, providing insight into the material's porosity and related surface phenomena. Microscopically, the interconnected voids and channels can act as pathways for fluid flow. The size and connectivity of pores can impact the permeability and diffusivity of the material (**Kuila & Prasad, 2013**). Nejati et al. studied the influence of fatigue loading on three different types of rock, i.e. onyx marble, sandstone, and limestone, with varying degrees of brittleness. They used acoustic emission sensors to evaluate the failure. The results showed that the increase in rock brittleness decreased the cracks created in the rocks under loading and decreased their fatigue life (**Nejati et al., 2014**). Le et al. investigated the effect of size on fatigue crack growth kinetics. A small-scale crack growth regime at the initial stage of cyclic loading is identified and the size of the crack tip front failure zone under uniform cyclic loading conditions is compared (**Le et al., 2014**). Ghamgosar et al. studied the fracture zone around the tips of the cracks and the mechanical behaviour of the samples under cyclic loading. In this study, two different types of loading were tested: stepped and continuous. The results showed that the type of loading had a great effect on the strength of the sample (**Ghamgosar et al., 2017**). In research exploring the fatigue behaviours of a uniaxial rock salt sample plastic deformation, crack shape and fatigue life of rocks under interval and intermittent cyclic loading were analysed (**Fan et al., 2017**). Wang et al. conducted a study on sandstone deriving a power law to describe the relationship between confining stress dependent porosity and the permeability of rocks under cyclic loading (**Wang et al., 2017**). In a study about jointed rocks, the influence of cyclic loading and joint geometrical parameters on fatigue properties of rocks, and revealing the fatigue progressive failure behaviour were investigated (**Liu et al., 2017**). Liu et al. investigated the shear mechanism of fatigue damage in rock joints with first-order and second-order triangular asperities under pre-peak cyclic loading conditions in a laboratory, their study showed that with a low number of cycles, fatigue damage occurs at the second order asperities in the upper and lower blocks (**Liu et al., 2018**). Another paper reviewed existing brittleness indices and proposes a new evaluation method based on energy transformation analysis. The new method captures the complete stress-strain behaviour of rocks and considers plastic energy dissipation and strength degradation during fracturing. The proposed brittleness index describes the transition from plastic to brittle behaviour on a continuous scale. It is verified using compression tests on carbonaceous lithofacies, demonstrating its superior performance compared to existing indices (**Rahimzadeh Kivi et al., 2018**). In a study investigating mean grain size and unconfined compressive strength (UCS) in weak reservoir sandstones by classifying the rocks into two categories of non-porous and porous crystals, it was found that the compressive strength of crystalline rocks decreases with an increase in grain size. However, for porous sandstones, grain size alone is not a reliable indicator of compressive strength due to other textural features, such as pore spaces and cementation. An experimental model is proposed that includes grain size, porosity and cement content to estimate the compressive strength of porous sandstones (**Atapour & Mortazavi, 2018a**). Another study discussed the effect of grain size on the index properties of weakly bonded synthetic sandstones. Laboratory tests were carried out on fifteen types of sandstone with different grain sizes and cement contents. The results show that grain size has a significant effect on porosity and apparent density. Porosity decreases with an increase in grain size while bulk density increases (**Atapour & Mortazavi, 2018b**).

In a different investigation involving cylindrical specimens, of Kota sandstone, dolomitic limestone and three weathering classes of Delhi quartzite were carried out. Fatigue characteristics of the rocks and the trend of elastic modulus degradation were investigated (**Arora et al., 2019**). In another study, a series of freeze-thaw cycling tests were conducted on sandstone samples, the results show that as the freeze-thaw cycles increase, the porosity of rocks increases approximately linearly (**Li et al., 2019**). Peng et al. studied the influences of the stress lower limit during cyclic loading and unloading on the deformation characteristics and laws of sandstones. The test results demonstrated that the stress lower limit can significantly affect the evolution of irreversible deformation (**Peng et al., 2019**). The state-of-the-art digital image correlation (DIC) method, which used classical digital photography, is employed to explore the detailed failure course of sandstone with physical uniaxial compression tests. The results show that there is a good relationship between the data obtained from digital image correlation and numerical analysis (**Chen et al., 2020**). In separate research conducted by the relevant researcher, the crack propagation and acoustic emission characteristics of three-point bending rock beams under monotonic and post-peak cyclic loads were studied using DIC and AE techniques. Some results showed that under the post-peak cyclic loading, the horizontal strain increases with loading and decreases with unloading (**Tang et al., 2020**). Yang et al. in a fatigue study that they conducted on the confining pressure of sandstone samples concluded that strength and deformation parameters depended strongly on the confining pressure and triaxial strength of the sandstone specimens under cyclic loading was approximately equal to that under monotonic loading, whereas the fatigue loading led to a reduction in triaxial strength (**Yang et al., 2020**). In a study about rock salt, the impact of combined creep and fatigue on the mechanical properties of rock salt was experimentally investigated and estimated in terms of the hysteresis behaviour, cumulative deformation, progressive damage, and fracture mechanism. The result showed that the axial, radial, and volumetric deformations of rock salt under combined creep and fatigue undergo a typical three-phase S-shaped course, which is like that observed under pure creep or fatigue (**Ma et al., 2021**). In another study that was conducted on the creep and fatigue couple, this result was obtained that the application of a short-term, low-stress level of creep load during fatigue loading can reduce the increase in deformation parameters, slow down the attenuation of elastic parameters, and restrain the decline in response level (**Shi et al., 2022**). In another study, the interaction between a notch and a micropore under uniaxial compression was investigated computationally and experimentally. The results showed that the failure pattern affects the uniaxial compressive strength, while the notch orientation and pore condition affect the failure pattern (**Vahab et al., 2022**). In a study, the effects of porosity and its geometry on the tensile properties of concrete were investigated using the Brazilian test and the three-dimensional PFC model. The results showed that the porosity geometry plays an important role in the fracture pattern. The porosity geometry was found to have a strong effect on the fracture stress and the UCS value of the rock. The numerical simulation shows that the fracture energy decreases as the dimension of the fracture increases (**Zhou et al., 2023**). In another study conducted on rock salt, it was concluded that fatigue loading increases creep deformation, and this effect weakens when the confining pressure increases (**Li et al., 2023**). During the study conducted on cyclic hydraulic fracturing, the result showed that long-period pulsating loading of pulsating hydraulic fracturing can cause significant damage in coal (**Yu et al., 2024**). A study on the influence of specimen size on fracture properties has shown that mechanical properties are affected by both particle size and specimen size on a micro-scale. The effects of changes in specimen size on fracture properties depend on factors such as specimen and crack geometry. For semi-brittle materials, changes in specimen size affect properties such as FPZ dimensions, stress intensity, strength, load capacity, and deformation. Increasing specimen dimensions decrease strength but increase failure load, crack distance, and width (**Dolatshahi & Molladavoodi, 2023**). In separate research conducted by the relevant researcher, the uniaxial cyclic loading test was conducted and the variation law of mechanical strength characteristics with the unloading rate was obtained the result showed that the various types of energy of the sample increase nonlinearly with the increase of the number of cycles, and the plastic damage energy drops as the unloading rate increases (**Liu et al., 2024**).

As it is clear from previous studies, many and varied fatigue researches have been carried out on rock, but the simultaneous effects of porosity and cyclic loading have been rarely considered. On the other hand, most of the research studies are related to the fatigue behaviour of metals which mostly ignored the porosity effects of the solid. Therefore, in this research, experimental investigations were conducted to study the effects of porosity and cyclic loading on the mechanical behaviour of geomaterials. The experimental method was laborious and time consuming because of the preparation of rock-like material specimens with various porosity percentages. However, five types of specimens were prepared and tested in a rock mechanics laboratory. The uniaxial compressive and indirect Brazilian tensile strength tests were conducted to study the effects of porosity on the strength and mechanical behaviour of porous geomaterial specimens. Then, the cyclic loading effects are investigated on the Brazilian discs in the indirect tensile strength apparatus. The range of porosity in the specimens are closely like those of actual rock samples of the hydrocarbon reservoir rocks in general, the porosity of hydrocarbon reservoir rocks can range from less than 5% to more than 30%. However, the average porosity of most productive oil and gas reservoirs falls within the range of 10% to 20% (**Tiab & Donaldson, 2012**).

2. Materials and methods

The specimens are prepared from Portland cement, fine sand, water, and proper additives. Five types of geo-material specimens are prepared considering various porosity percentages. The specimens are prepared in the rock mechanics laboratory and submerged in water for 28 days at room temperature which have been further elaborated on in the subsequent section.

2.1. Preparation of porous geo-materials specimens

The laboratory tests should be conducted on specimens with various porosity, and the other parameters should be constant during the tests. Therefore, appropriate specimens are prepared to measure the effects of porosity on the mechanical behaviour and strength of rocks. However, finding or preparing rock specimens that meet the specific conditions for testing is a challenging task for engineers. To overcome the limitations and facilitate the necessary tests, rock-like specimens were prepared in the laboratory using proper mixtures of cement, fine sand, water, and other concrete additives. To control porosity and prevent aggregate settling in the specimen, aggregates of the same type but with varying porosities were used. These aggregates were carefully selected based on the desired porosity level, and their proportions were calculated and combined accordingly. Additionally, concrete admixtures were utilized to further regulate the porosity. These additives were thoroughly mixed in a specialized mixer designed specifically for this purpose. The mixer operated at high speed and introduced the necessary air into the slurry. By employing this blending technique along with the distinct properties of the materials used, the resulting specimens exhibit the intended porosity, possess adequate strength for testing, and display a consistent texture throughout their length without any settling of aggregates.

These specimens were designed to have five different levels of porosity, enabling investigation of the effects of the desired parameters. In accordance with applicable standards, the ratio of the pore space to the height of the specimen was kept below 0.1 (**"The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014," 2015**). Different mix designs were employed to create the specimens, and their performance was assessed. Ultimately, the optimal mix design was identified based on the maximum distribution of porosity and the absence of pore space deposition. Finally, five distinct levels of porosity were chosen, with approx-

Figure 1: The materials used for preparing specimens i.e. sand, sand sketch, cement, water, concrete additive

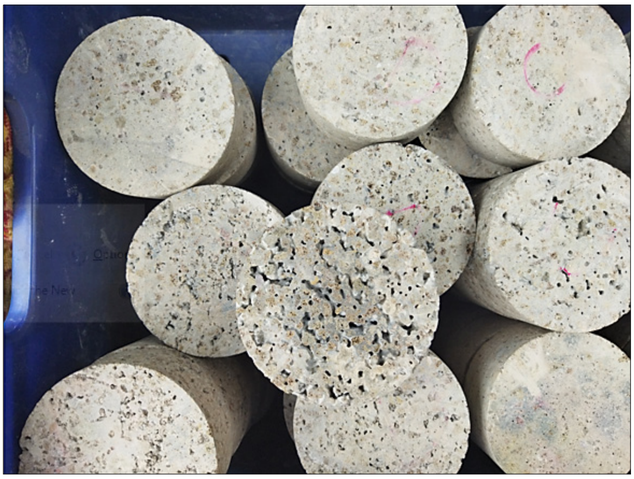

Figure 2: The specimens were created in accordance with the intended mixing plan

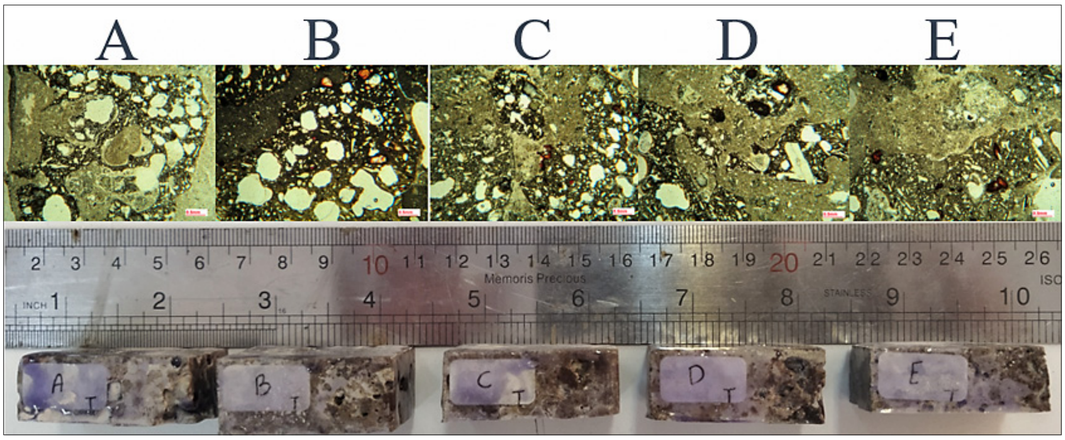

Figure 3: Thin sections prepared from the specimen including 5 groups

Table 1: Porosity and density of 5 specimen groups

No.	Group name	The number of specimens	Density (t/m^3)	Porosity (%)	STDEV	Average of porosity (%)
1	A	15	1.83	20-21.5	0.63	20.64
2	B	15	1.87	15-15.4	0.19	15.15
3	C	15	1.96	9.7-10.5	0.32	10.14
4	D	15	2.1	4.5-5.1	0.25	4.95
5	E	15	2.2	2-3	0.5	2.47

imate percentages of 20%, 15%, 10%, 5%, and 2%. These levels were then categorised into five groups, denoted as A, B, C, D, and E, respectively. The ultimate mix design that was chosen incorporated a water-cement ratio of 0.5, a sand-cement ratio of 2, and the appropriate inclusion of concrete additives. This blend adequately met both criteria to an acceptable extent. **Figure 1** shows the materials utilised for creating the specimens in the laboratory. The ideal specimens were submerged in water for 28 days, allowing them to achieve the desired level of strength. The concrete's 28-day strength is a measure of its compressive strength after this curing period. This parameter is used to assess the overall strength and quality of the concrete (**Chung et al., 2021**).

Then the specimens are casted and prepared as shown in **Figure 2**. Their porosity was accurately measured using a specific measurement method. The subsequent section describes the measurement method employed and the corresponding porosity values obtained.

2.2. Porosity measurement

There are various methods available for measuring porosity in different materials. Some common porosity measurement methods include: (1- the water saturation method, 2- image analysis, 3- mercury intrusion porosimetry, 4- gas adsorption, 5- X-ray computed tomography, 6- ultrasonic testing, 7- neutron radiography) (**Qiu et al., 2015**). In this study, the water saturation method was employed to determine the porosity of the specimens. Additionally, to obtain a more precise understanding of the porosity level and the distribution of voids on the specimen's surface, the image analysis method of geological thin sections was utilized.

This method involves saturating the specimens with a liquid and measuring the change in weight or volume before and after saturation. The difference in weight or volume provides an indication of the porosity of the specimens. The desiccator was employed as the device to achieve specimen saturation. By creating a vacuum within its chamber, the desiccator facilitates the flow of water into the empty pores of the specimen, leading to its saturation. The measurement involves calculating the weight change of the sample before and after it is immersed in a fluid. This method is based on Archimedes› principle, which states that the buoyant force exerted on an object submerged in a fluid is equal to the weight of the fluid displaced by the object (**Lin, 2015**). The following is a general formulation of the porosity measurement method using Archimedes' principle:

The pore volume (Vp) was calculated as the buoyancy force (Fb) per unit of water. This was determined by measuring the weight difference before and after immersion:

$$Vp = Fb / \rho_{water} \tag{1}$$

To ensure uniformity of porosity and materials among different groups, the specimens underwent preparation and examination in the form of thin sections prior to test-

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ing. The focus of this study involved utilizing a polarizing microscope to assess the optical properties of minerals and deduce their compositions. **Figure 3** shows the thin sections prepared from the specimen.

This following the completion of porosity testing and validation, the resulting values have been calculated and are presented in **Table 1**.

To ensure a comprehensive analysis of the fatigue test results, it is essential to possess a solid comprehension of the mechanical parameters of the specimen prior to conducting the test. To achieve this understanding, specimens with standardized geometric dimensions were prepared for the purpose of performing both the uniaxial compressive strength test and the indirect tensile test.

2.3. Uniaxial compression test

The uniaxial compressive test, also known as the unconfined compressive strength (UCS) test, involves subjecting cylindrical rock specimens to compression along their longitudinal axis. This test, which is considered the oldest and simplest method, remains highly convenient and valuable for determining the properties of rocks (**Peng & Zhang, 2007**). The specimens that were prepared had a cylindrical shape, with a standardized length of approximately 140 mm and a standardized diameter of 54 mm (**"The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014," 2015**). **Figure 4** shows the prepared specimens and the used uniaxial testing machine.

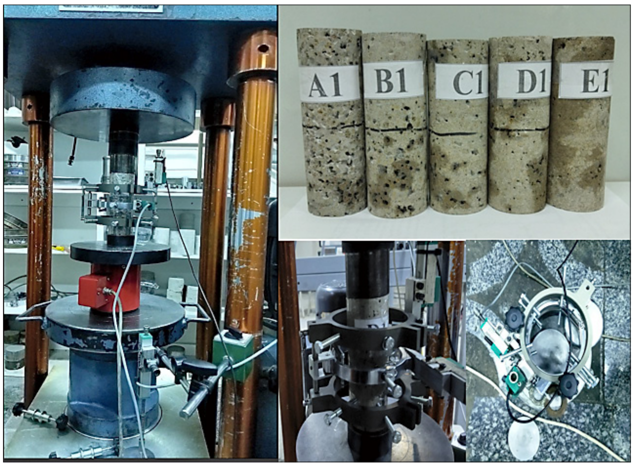

Figure 4: Uniaxial testing machine with displacement data logger and the prepared specimens

In this research, the uniaxial compression test is used to measure the mechanical parameters of the porous geo-material specimens. This information comprises measurements and calculations that are associated with the material's behaviour throughout the testing process. Some of the key data and mechanical parameters obtained from these tests are as follows.

2.3.1. Compressive Strength

The compressive strength is one of the primary exit parameters in the uniaxial compression test. It represents the maximum stress or load that the material can withstand before failure occurs under compression (**Cheng & Geng, 2023**), (**Xiao et al., 2023**). **Figure 5** shows a correlation between porosity and the uniaxial resistance of the specimen. The diagram indicates that as the porosity of the specimen increases, the uniaxial resistance decreases. This relationship suggests that higher porosity leads to a reduction in the material's ability to resist compressive forces in the uniaxial direction.

2.3.2. Elastic Modulus

The elastic modulus, also known as Young's modulus, is a measure of the material's stiffness or rigidity. It represents the ratio of stress to strain within the elastic range of the material (**Aladejare et al., 2022**). The elastic modulus is an important parameter for assessing the material's behaviour under compression and its ability to return to its original shape after deformation. **Figure 6** shows a relationship between porosity and elastic modulus of the specimen. The result showed that as the porosity of a material increases, the elastic modulus tends to decrease.

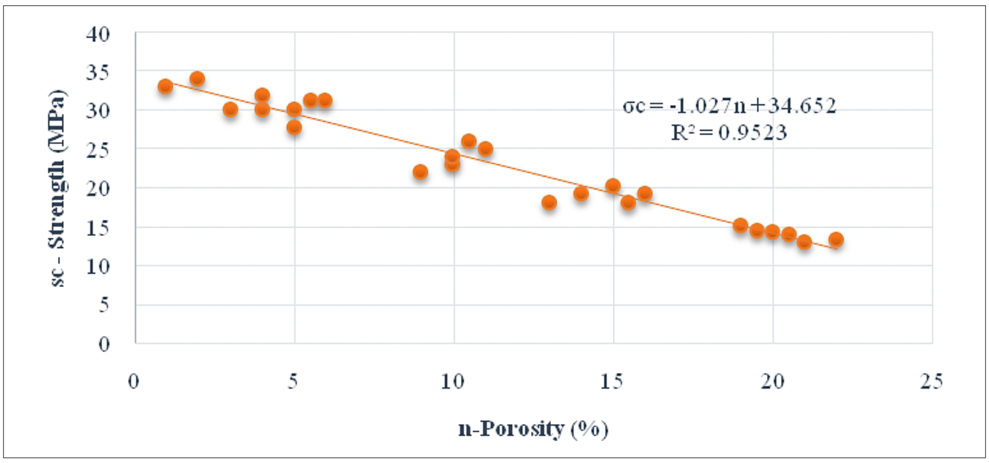

Figure 5: Relationship between porosity and uniaxial compression strength

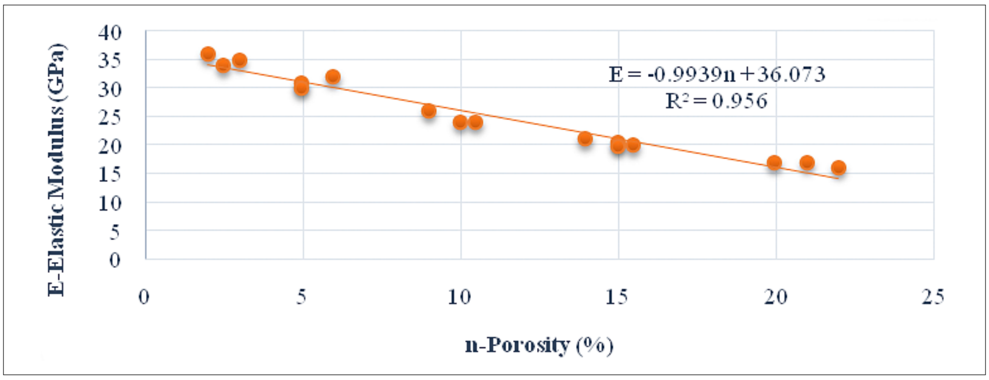

Figure 6: Relationship between porosity and elastic modulus

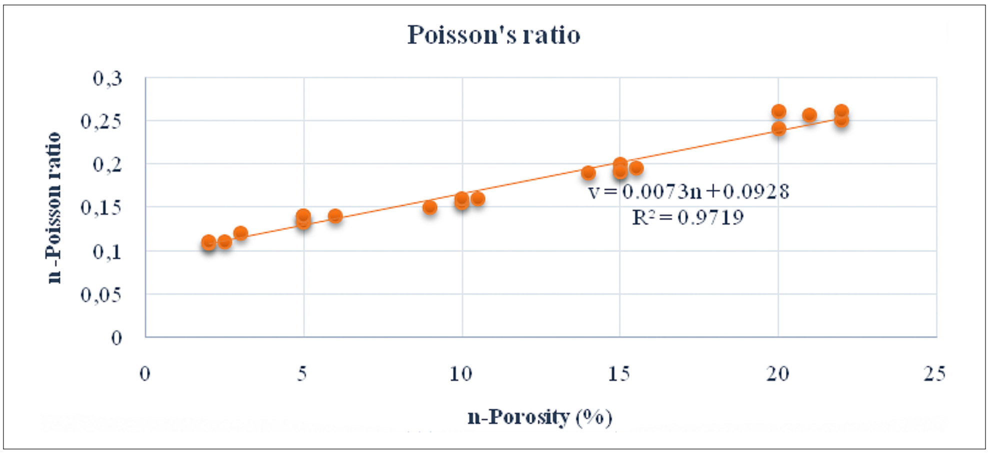

Figure 7: Relationship between porosity and Poisson's ratio

2.3.3. Poisson's ratio

It is a mechanical property that characterizes the relationship between the lateral (transverse) strain and the axial (longitudinal) strain of a material when subjected to an applied load (**Poplavko, 2019**). **Figure 7** indicates a direct relationship between porosity and Poisson's ratio. Specifically, as the porosity of the specimens increases, Poisson's ratio also increases. Therefore, Poisson's ratio and porosity exhibit a positive correlation.

2.3.4. Fracture Toughness

The fracture toughness (KIC) is typically quantified using several parameters, including the area under the stress-strain curve. These parameters provide a means to compare the toughness of different materials (**J.-L. Li et al., 2023**). **Figure 8** shows the obtained strain stress diagram, as it is known that the toughness of the specimen decreases with the increase of porosity.

Correlation between the percentage of porosity and the area of the stress-strain diagram is evident from **Figure 8**. With the increase in porosity percentage, the area of the stress-strain diagram decreases, which indicates a decrease in toughness. **Figure 9** shows this relationship.

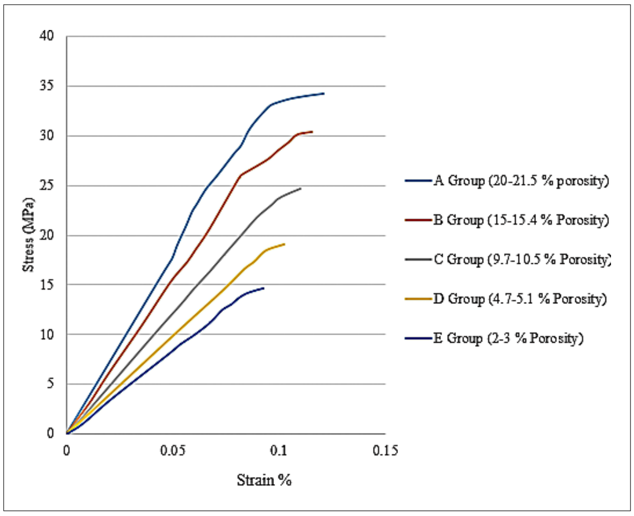

Figure 8: The Stress-Strain diagram of the specimens

By conducting the uniaxial compression test and calculating the mechanical parameters, a comprehensive understanding of the specimens was acquired, providing insights into the impact of porosity on their behaviour to a certain degree. In the following, the fatigue test performed on the specimens will be investigated.

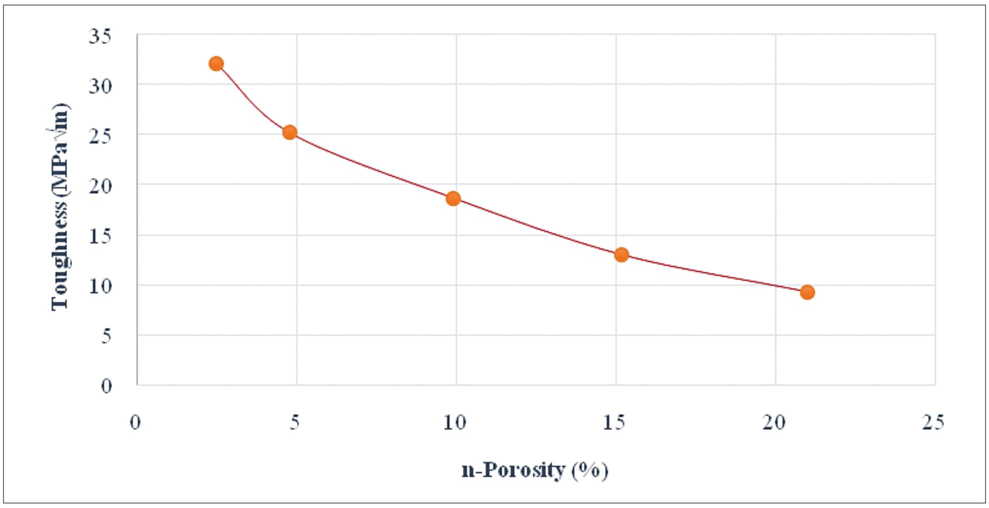

Figure 9: The correlation between porosity and fracture toughness

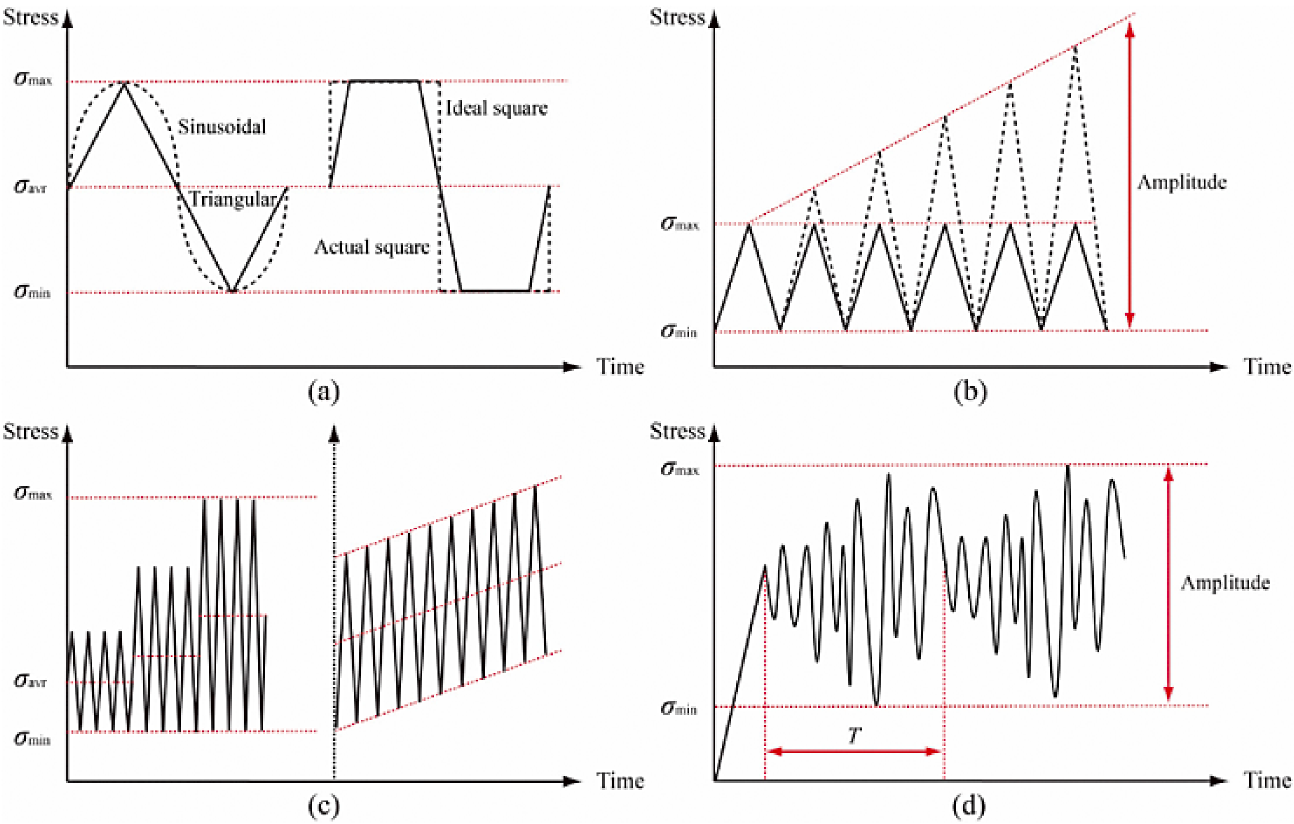

Figure 10: Schematics of cyclic stress waveform and loading path: (a) regular triangular, sinusoidal, actual and ideal square waveforms; (b) waveforms with constant and stepwise increasing amplitudes; (c) waveform with multi-level cyclic amplitude and that with increasing average stress and constant amplitude; and (d) random cyclic loading (**Liu & Dai, 2021**).

2.4. Cyclic loading test for measuring the fatigue life of the specimens

A cyclic loading test is a type of mechanical test performed on materials and structures to assess their resistance to repeated or cyclic loading. Various law and equations exist that enable the estimation of the lifespan of a specimen, considering its specific shape and material properties. Paris law is an empirical relationship that describes the growth rate of a fatigue crack in a material subjected to cyclic loading. It relates the crack growth rate (da/dN) to the stress intensity range (ΔK), where da is the change in crack length per cycle of applied stress and dN is the number of stress cycles (**Janssen et al., 2004**).

The Paris law equation is typically expressed as:

$$\frac{da}{dN} = C(\Delta K)^{\wedge} m \tag{2}$$

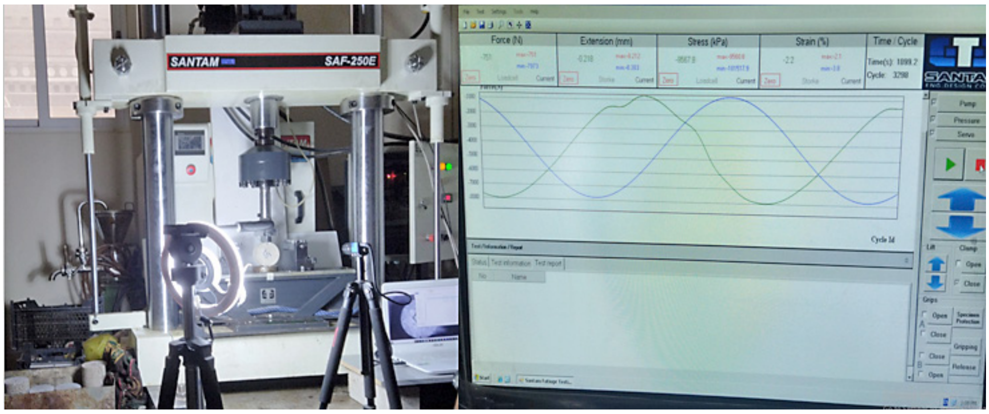

Figure 11: The device employed in the experiment and the path loading on the specimens

The value of the stress intensity factor (K) is influenced by various factors, including the geometry of the specimen, the size and location of the crack or notch, and the magnitude and distribution of loads applied to the material. Consequently, it can be expressed as:

$$K = \sigma\sqrt{\pi a}\, f(a/W) \quad (3)$$

In this equation, the function f(a/W) represents a dependence on the crack length (a) relative to the specimen width (W), which is specific to the geometry of the specimen and σ denotes the applied stress (**Tada et al., 1973**). The fatigue life of the specimen can be determined using the Paris law, which involves the following integral to calculate the lifespan (**Alizadeh et al., 2023a**).

$$N = \int_{N_i}^{N_f} dN = \int_{a_i}^{a_f} \frac{da}{f(\Delta K_f)} \quad (4)$$

In cyclic loading there are several types of cyclic loading path that can be applied during fatigue testing included: (a) regular triangular, sinusoidal, actual and ideal square waveforms; (b) waveforms with constant and stepwise increasing amplitudes; (c) waveform with multi-level cyclic amplitude and that with increasing average stress and constant amplitude; and (d) random cyclic loading. **Figure 10** shows the schematic path of this type of loading (**Liu & Dai, 2021**).

The path loading used in this research was the sinusoidal loading path that refers to a cyclic loading pattern which follows a smooth and periodic sinusoidal waveform. This loading path is characterized by a gradual increase of stress or strain from a minimum value to a maximum value, followed by a gradual decrease back to the minimum value. The stress or strain varies sinusoidally over time, creating a repetitive pattern. **Figure 11** shows the type of applied load and the device employed in the experiment.

The experimental method that was considered in the research to investigate the behaviour and fatigue life was the stress life method. The stress life fatigue test is a widely used method for evaluating the fatigue behaviour of materials and components. The primary advantage of the stress life fatigue test is that it provides valuable information about the fatigue strength and fatigue life characteristics of a material. The specimens utilized in cyclic loading tests exhibit various shapes, which are determined by the specific test purpose. **Figure 12** shows some types of specimen shape. The specimens that become ready for testing had disk shape with dimensions of 9 cm in diameter and 4 cm in thickness (**AC10520925, 2008**).

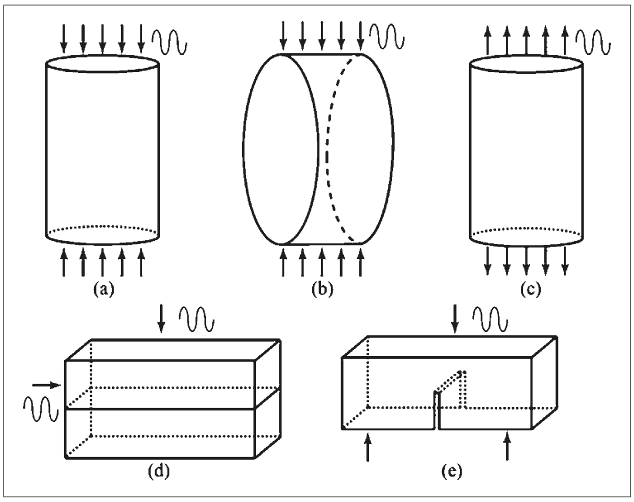

Figure 12: Schematics of different cyclic loading tests: (a) cyclic uniaxial compression; (b) indirect cyclic tension; (c) direct cyclic tension; (d) cyclic shear test; and (e) cyclic flexural test (**Liu & Dai, 2021**)

The specimens that become ready for testing had disk shape with dimensions of 9 cm in diameter and 4 cm in thickness, as shown in **Figure 13**.

Typically, failure initiation and the formation of micro-cracks in a specimen occur when it reaches approximately 60% of its ultimate strength (see **Figure 14**), and this process gradually progresses over time. Therefore, to observe failure during periodic loading tests, the stress applied to the specimen must exceed this threshold since the specimen does not fracture under stress levels below this value.

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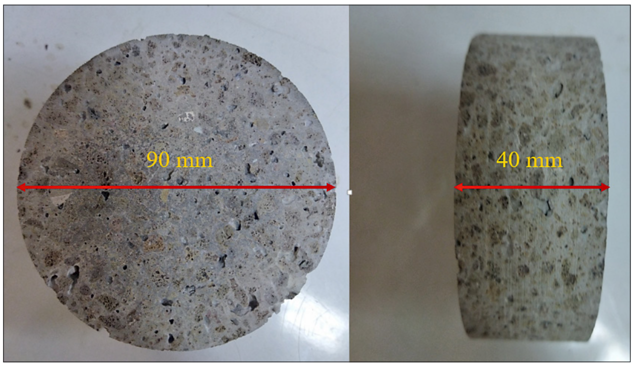

Figure 13: The specimen prepared for fatigue test with a diameter of 90 and a thickness of 40 mm

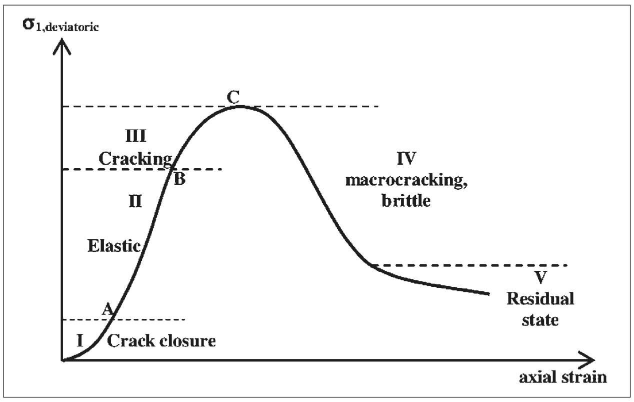

Figure 14: Complete rock strain stress diagram with its stages (**Goodman, 1991**)

In the experiment, the minimum stress ratio applied to the specimen was 0.75% of its ultimate strength. This choice was made because the specimen with an applied load below this value had an extremely long failure life, making it practically impossible to accurately measure its life at a loading frequency of 3 Hz. **Table 2**. Shows the ratio of stress and number of applied cycles in the table defines P/P_{max} as the ratio of applied Brazilian stress to the maximum Brazilian stress of the specimen.

Table 2: Different ratio of load and number of failure cycle

A Group		
P/P_{max}	Stress (MPa)	Cycle Number
1	*1.78*	*1*
0.95	*1.691*	*104*
0.85	*1.513*	*507*
0.80	*1.335*	*2030*
0.75	*1.157*	*10506*

Subsequently, the life stress graph was calculated and drawn for each group. **Figure 15** shows the stress life diagram for each specimen group.

During this research, the specimens with different porosity were subjected to several tests, and different results were obtained from them. In the following, these findings will be further analysed.

3. Discussion

Porosity, an essential parameter, plays an important role in shaping the mechanical behaviour and fatigue characteristics of rocks. The presence of pores or voids in rocks affects the overall strength, deformation properties and ability to resist fatigue failure. Previous laboratory research on fatigue has mainly focused on metals, and because rocks and metals behave differently, the findings may not be directly applicable to rocks. Consequently, uncertainties still exist in understanding the behaviour of rocks. The parameter that was investigated in this research is porosity. One distinguishing feature of this research, as compared to others, in the field of fatigue on porous materials is that real porosity was created in geo-material specimens and was fatigue investigated.

As shown in **Figure 5**, the results indicate that increasing porosity reduces the resistance of the porous specimens. The diagram shows that a decrease of about 20 percent of porosity can increase the compressive strength by about 300 percent, which shows the great importance of porosity in reducing the strength of the specimen. Other studies conducted so far in the field of porosity confirm this result (**Zhang et al., 2020; Yang et al., 2022; Li et al., 2021; Fang et al., 2022**). Porosity introduces weaknesses in the material's structure. The presence of void spaces or pores can act as stress concentrators, creating localized areas of vulnerability. These areas can experience higher stress levels compared to the surrounding matrix, making them prone to deformation, cracking, or failure. As a result, the material's overall resistance to applied loads or stresses can be diminished. **Figure 6** shows a relationship between porosity and elastic modulus of the specimen the elastic modulus is a measure of a material's stiffness or rigidity, and it quantifies the material's resistance to deformation under an applied stress. In porous specimens, the presence of void spaces interrupts the continuity of the solid material, leading to a reduction in the effective load transfer and, consequently, a decrease in the elastic modulus. This finding has been corroborated by recent research as well (**Helms et al., 2023**). As it is clear from **Figure 7**, Poisson's ratio also increases with the increase of porosity of the specimens. The increased porosity introduces more pathways for lateral deformation, allowing for greater lateral strain to occur when the material is loaded. This results in a higher ratio of lateral strain to axial strain, which corresponds to an increase in the Poisson's ratio. One of the most important parameters that was investigated in this research was toughness, as it is clear from **Figure 9**, with the increase of the porosity of the specimen, its toughness decreases. Toughness is a measure of a material's ability to absorb energy and

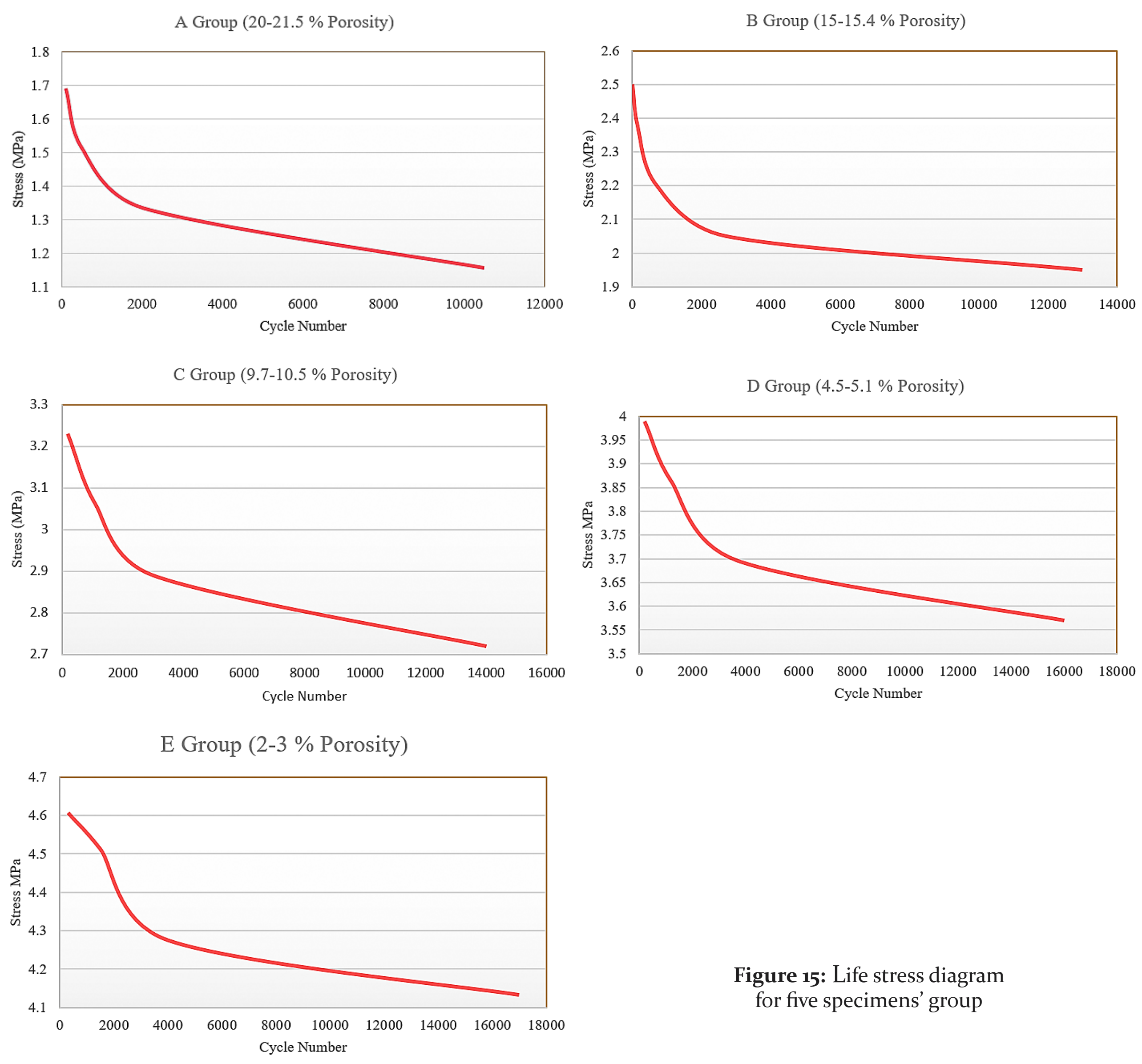

Figure 15: Life stress diagram for five specimens' group

deform plastically before fracturing. With the increase of porosity of the specimens, the void spaces act as stress concentrators, making the material more prone to crack initiation and propagation, ultimately reducing its ability to absorb energy and deform plastically before fracturing. Equations 1, 2, and 3 describe the relationship between fracture toughness and fatigue life. A higher fracture toughness value indicates greater resistance to crack growth, which translates to a longer fatigue life. Conversely, reducing the fracture toughness value makes the material more susceptible to crack growth, leading to a shorter fatigue life.

The primary test conducted in this research was the periodic loading examination carried out on the porous specimens. The prepared disk-shaped specimens underwent indirect tensile loading, and stress life diagrams were generated for each individual specimen. The data presented in **Figure 15** reveals that when porosity decreases, there is a corresponding decrease in the slope of the life stress graph. This decline indicates an improvement in the specimen's capacity to withstand periodic loading, leading to increased resistance and extended fatigue life. To facilitate this comparison, a graph was constructed based on the ratio of the applied load to the final load of the specimen **Figure 16**. This graph provides a visual representation of how porosity influences the fatigue life of the material under consideration. As it is clear from **Figure 16**, group E has the lowest porosity and the longest fatigue life. As porosity increases, the material›s structural integrity and resistance to cyclic loading diminish. The presence of voids or pores within the material acts as stress concentration points, promoting the initiation and propagation of cracks. Consequently, the material becomes more susceptible to fatigue failure, leading to a decrease in its fatigue life. Fatigue crack development is one of the most important

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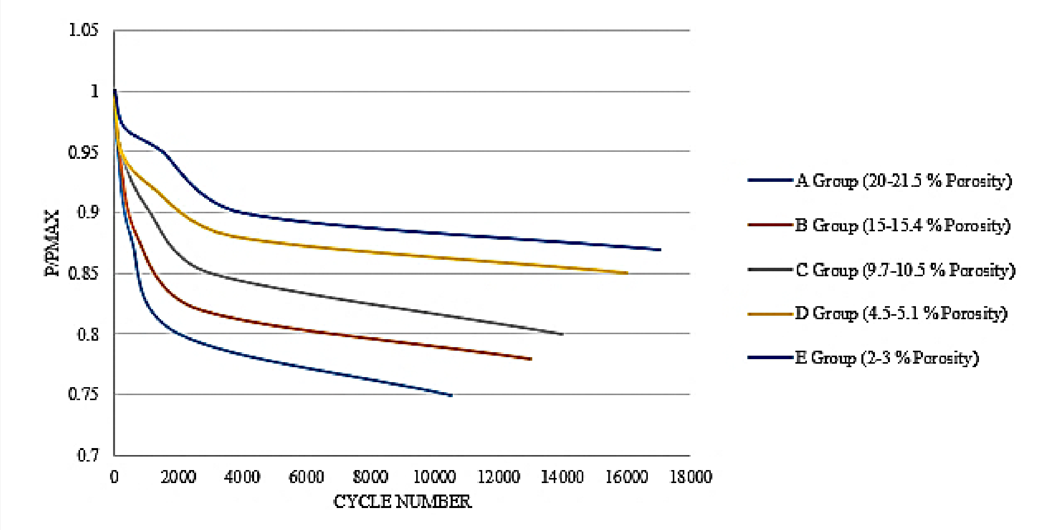

Figure 16: Life stress ratio diagram for five porous specimens' group

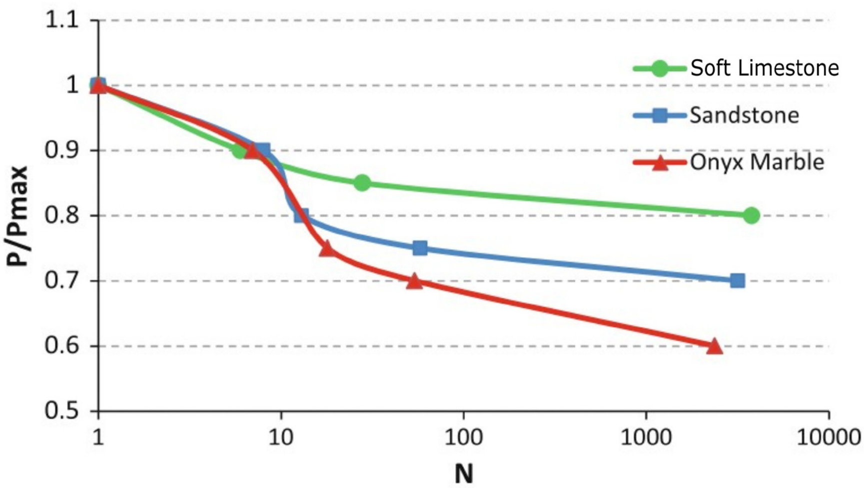

Figure 17: Fatigue life comparison of the rock types (**Nejati et al., 2014**)

fields of fatigue behaviour research that has been studied by various researchers (**Alizadeh et al., 2023b**).

Some other research studies have been done in the field of fatigue life in rock, the stress life graph for the specimens has been drawn and compared, for example, in the research that was done on the effect of brittleness on fatigue, the stress life graph for three types of specimens with different crunches were obtained and analysed, as seen in **Figure 17**, which shows the life stress diagram for specimens with different brittleness (**Nejati et al., 2014**).

Soft Limestone group specimen has a more plastic behaviour than Onyx Marble. The researcher concluded that the more plastic the behaviour of the specimen, the more energy absorption the specimen has and the longer the fatigue life. These results confirm the result of the present research. The results obtained from the tests conducted in this research on the porous specimens were expressed and discussed. Subsequently, a summary of the results is provided below.

4. Conclusion

The effect of porosity on the mechanical behaviour and fatigue of geo-materials specimens was investigated. Geo-material specimens were prepared in a laboratory through special mixing of cement, sand, and special additives. Five distinct specimen groups, named A, B, C, D, and E, were generated with varying porosity levels ranging from approximately 20-21.5% to 2-3%, respectively. The quasi-static strength and fatigue tests with constant frequency and amplitude were performed on the specimens and the life stress graph was obtained for each group and compared. The main conclusions may be described as:

The specimens of group E, which had the lowest porosity (2-3%), exhibited the highest strength and elastic modulus values and the lowest value of Poisson›s ratio.

There is an inverse correlation between porosity percentage and mechanical strength, elastic modulus, and a direct correlation between porosity and Poisson›s ratio of geo-materials.

The E group specimens (2-3% porosity) have the highest value of fracture toughness and A group (20-21.5% porosity) have the lowest value, so with the increase of porosity, the toughness of the geo-material specimens decreases.

By increasing the porosity of the specimens, the empty spaces act as stress concentrators and make the material susceptible to crack initiation and propagation, and ultimately reduce its ability to absorb energy (plastic deformation) before fracture and hence reduce the fracture toughness.

The Stress Life graph of the E group has the lowest slope compared to other groups. Therefore, with the increase of porosity, the slope of the graph increases in the specimens. In other words, the group E has the lowest porosity and the longest fatigue life.

By increasing the porosity, the fatigue life decreases, which means that the material's structural integrity and resistance to cyclic loading decreases.

The presence of voids or pores makes the geomaterial more susceptible to fatigue failure, leading to a decrease in its fatigue life.

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SAŽETAK

Utjecaj poroznosti na čvrstoću i mehaničko ponašanje poroznog geomaterijala uslijed cikličkog opterećenja

Većina je stijena u prirodi porozna i obično zasićena različitim fluidima kao što su voda, nafta ili prirodni plin. Konvencionalna i nekonvencionalna ležišta ugljikovodika najčešće se nalaze u sedimentnim formacijama. Glavne su stijene tih ležišta pješčenjaci (porozna stijena), vapnenci i naftni šejlovi (slabo propusna stijena), koje su karakterizirane različitom poroznošću. Stoga je poroznost osnovna karakteristika većine ležišnih stijena. U ovome je istraživanju ispitivan utjecaj poroznosti na mehaničko ponašanje geomaterijala i njezin utjecaj na zamor materijala. U tu je svrhu pripremljeno pet skupina uzoraka geomaterijala različite poroznosti, tj. skupina A, B, C, D i E. Pri tome su uzorci skupine A imali najveću poroznost (20 – 21,5 %), dok su uzorci skupine E imali najmanju poroznost (2 – 3 %). Uzorci su podvrgnuti konvencionalnim kvazistatičkim testovima čvrstoće i cikličkoga opterećenja s konstantnom frekvencijom i amplitudom te su dobiveni različiti rezultati. Uzorci iz skupine E, skupine s najnižom poroznošću (2 – 3 %), u odnosu na uzorke veće poroznosti, pokazali su najveću mehaničku čvrstoću, modul elastičnosti i lomnu žilavost te najniži Poissonov koeficijent. Tijekom cikličkoga opterećenja graf zamora materijala uzoraka skupine E, u usporedbi s uzorcima ostalih skupina, ima najmanji nagib krivulje. Ispitivanje je pokazalo da se nagib krivulje povećava s porastom poroznosti u svim skupinama. Stoga uzorci skupine E imaju namanju poroznost i najveću otpornost na zamor materijala, tj. poroznost i otpornost na zamor obrnuto su proporcionalni.

Ključne riječi:
zamor materijala, porozni geomaterijal, lomna žilavost, mehaničko ponašanje, cikličko opterećenje

Author’s contribution

Abolfazl Dalirnasab (PhD Student in Rock Mechanics): provided the specimens, experiments, data curation, validation, wrote the original draft. **Mohammad Fatehi Marji (Professor in Rock Mechanics):** provided the supervision, formal analysis, software, participated in revision and editing. **Hamid-Reza Nejati (Associate Professor in Rock Mechanics**): supervised the experiments, participated in data preparation and refinements; consultant. **Mohsen Mohebbi (PhD in Rock Mechanics)** helped in the computer modelling and numerical simulations of the experiments.