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An experimental Investigation of fault gauge material under confined conditions

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Abstract

This research presents a thorough experimental investigation of the fault gouge material conducted in a laboratory setting. The objective of this study is to gain insight into the behavior of the fault gouge material, namely by analyzing and characterizing the hydraulic properties of the samples under investigation. The aforementioned findings possess potential utility in diverse underground openings such as deep mines, CO_2 storage sites, nuclear waste repositories, etc. in the presence of faults or major discontinuities.

Representative fault gauge material samples were prepared artificially in the laboratory and a series of experiments were conducted to characterize the fault gauge material behavior. The size distribution and material composition reported in the literature were used as a basis in the preparation of artificial fault gauge material. The use of artificial samples enabled a more controlled experimentation and served as a foundation for understanding the inherent complexities associated with fault gouge samples.

The study primarily centres on conducting a correlation analysis between permeability and the variables of confining pressure and different fluid variations. The research seeks to clarify the complex connections between permeability and environmental conditions by conducting flooding experiments with water. This research offers useful insights into the design and safety issues of underground openings and storage sites. Geotechnical and geological research benefits from this study of fault gouge material's mechanical and hydraulic behavior, which optimizes underground storage facilities and deep mining activities.

The findings from the study have the potential to provide valuable insights into the design and operation of subsurface storage facilities, thereby enhancing both theoretical comprehension and practical application. The experiment demonstrated that confining pressure significantly decreased sample permeability. The permeability of fault gouge material determines fluid flow in underground applications, and studying fluid movement in fractured geological formations helps design and secure subsurface storage systems.

Keywords

Fault gouge material, artificial sample, permeability, variation in confining pressure

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1 Introduction

One of the key elements in carbon storage operations and other underground openings such as deep mines, nuclear waste repositories, or major discontinuities is played by fault zones, which are a common integral part of geological formations. Therefore, understanding fault behavior under in-situ conditions is essential to managing the risks and maintaining the safety of such projects (Zambrano 2019). The primary objective of this research is to provide useful insights that will enable us to utilize underground storage responsibly and efficiently considering fault gouge material characterization.

In general, fault gouge, a finely fragmented blend of minerals located within fault zones, exhibits distinctive mechanical and hydraulic characteristics that substantially impact fault behavior. Although fault gouge plays a crucial role in the integrity of geological storage, there is still a lack of thorough knowledge about its behavior in storage settings. This study aims to fill the existing gap in knowledge by methodically analysing the behavior of fault gouge materials under different levels of confining pressures.

Classical friction/shear behavior studies reported in literature usually concern interfaces between two adjacent blocks of rock that are either directly in contact with each other or are separated by a thin layer of granular gouge. For instance, the gouge layer's (clay or quartz) thickness varies by a few millimeters in most investigations (Marone et al. 1990; Delle Piane et al. 2016). According to Giorgetti et al. (2019), the existence of a thick gouge layer decreases the amount of stress needed to reactivate a fault, implying that extensive shear zones exhibiting distributed deformation may possess lower strength than predicted by theoretical models. The authors proposed that the conventional depiction of fault planes as ideal planes with zero thickness might not accurately capture the complexities found in natural faults with intricate structures. Thick interfaces are typically seen in natural fault zones; mature faults are defined as having a cataclastic to ultracataclastic core that is a meter thick, surrounded by less damaged layers that are several hundred meters thick (e.g., Micarelli et al. 2003; Chambon et al. 2006). The influence of such thick gouge layers on the effective mechanical behavior of faults remains largely unexplored in laboratory studies. In the current research, the dimensions of the studied fault gouge samples are about 15 cm (0.15 m) in length, and they form cylindrical core samples with a diameter of 3.8 cm (0.038 m). By altering the confining pressure exerted on the sample, the effects of large in-situ stress magnitudes encountered in such circumstances can be simulated in a laboratory setting.

An essential aspect of comprehending the mechanical properties and behavior of fault gouge material during fault slide events is its particle-size distribution. It should be emphasized that there is no unique and universal particle size distribution of the fault gouge material. However, there are different studies on governing laws as well as on the different ranges covered. One of the interesting studies in the literature is made by Sammis and Biegel (1989), in which a wide range of 5 μm (5×10^{-6} m) to 40 cm (0.4 m) of a natural fault-gauge analyzed, and it was identified that within a range of 5 μm (5×10^{-6} m) to 10 mm (0.01 m) particle sizes of fault gouge displays self-similarity. In general, geological characteristics can affect fault gouge material size distribution, and there is essentially no unique composition for all fault gouges.

2 Methodology

The research is intended to address a lack of research findings about the characterization of fault gouge material. To do this, a methodical experimental program is put into practice. To ensure uniformity and repeatability of the experimental program, fault gouge material for the current research was prepared artificially in the laboratory. To determine important factors such as the confining pressure of fault gouge materials, a set of core flooding studies has been planned. This involves establishing the relationship between confining pressure and the permeability of the fault gouge material. The proposed extensive experimental program can greatly enhance our knowledge and characterization of the fault gouge material.

2.1 Artificial Fault Gouge Sample Preparation

Fault gouge materials typically consist of saturated cataclastic rocks, with a broad size distribution, which typically obeys a power law particle size distribution. Although natural fault gouges exhibit some cohesiveness, a number of important characteristics can be explained by viewing them as differently sized granular materials, including their discontinuum nature, highly varied mechanical properties, lower cohesiveness relative to intact rock, which results in higher deformability, and their irregularly shaped constituent particles (Chambon et al. 2006). Consequently, the goal of this research is to generate artificial gauge material samples for the experimental program using unconsolidated conglomerates. A representative mix utilized to prepare the samples for pilot experiments is shown in Fig. 1.

Fig. 1 A sample of mix used in the preparation of fault gauge material.

The samples were made of crushed rocks and soil. In general, the fault gouge material is a mixture of soil and rock Mass (SRM). Considering the published literature, it has been deduced that high rock block content (RBC), increases the strength of the resulting SRM. Also, based on Tao et al. (2022), the size of the particles greatly impacts on micro-mechanical properties of the faults. Table 1 illustrates the fault gauge material particle size distribution demonstrated by Tao et al. (2022).

Table 1 Fault gouge material particle size distribution (Tao et al., 2022)

				Rock				Soil
Particle size, mm ($\times 10^{-3}$ m)	>40	30-40	25-30	25-20	15-20	10-15	5-10	<5
Distribution, %	6.15	1.88	2.15	11.33	3.5	11.76	9.86	53.37

The Tao et al. proposed size distribution (Table 1) has been used as a reference in the proposed experimental program. However, during the sample preparation for our pilot test setup, it was determined that it is necessary to eliminate large particles to accommodate a larger quantity of particles in the fault gouge material cross-section. Table 2 presents the trial size distribution used in the pilot test and is the basis for the experiments proposed in the current research study.

Table 2 Fault gouge material particle size distribution proposed in the current research

		Rock				Soil	
Particle size, mm ($\times 10^{-3}$ m)	>12.5	8-12.5	6.3-8	4-6.3	0.5-4	0.25-0.5	0.25<
Distribution, %	0	6.0	7.4	15.2	24.8	34.2	12.4

To ensure that the experiments can be repeated, fault gouge materials are prepared artificially in the lab. The desired composition of the material mix can be acquired from the sieve analysis. Additionally, as many scholars have agreed, 5 mm is used in this study as a reference value for distinguishing soil and rock particles. To get a more homogeneous sample, the final mixture must be well mixed.

2.2 Experimental program on fault gouge material under in-situ conditions

To prepare the fault gouge samples, a systematic and rigorous sequence of operations was followed. Firstly, a sieve analysis was performed to classify particles according to their size.

Fig. 2 The setup used for the sieving process.

The available sieving facility of the Mineral Processing Laboratory at Nazarbayev University was used for the preparation of samples. The setup used for the initial sieving of the chosen fault gouge sample is depicted in Fig. 2. Subsequently, particles of different sizes are mixed to achieve the desired composition.

Fig. 3 A view of the wet fault gouge sample mixture.

Afterward, the mixture is humidified to facilitate the molding of the sample as shown in Fig. 3 with about 20 mL (2×10^{-5} m^3) of water. Then the wet mix was poured into plastic molds and compacted using a three-ton capacity jack. A view of the prepared sample before placement into the core flooding system is shown in Fig. 4.

Fig. 4 The prepared fault gouge sample photo.

Accordingly, the lubricated sample with oil (covered with the plastic coating) was carefully inserted into the core holder, with screens in place to prevent fines migration into the test system. Following this, confining pressure is set to replicate subsurface conditions with the following confining pressure values 200 psi (about 1.38×10^6 Pa), 500 psi (3.45×10^6 Pa), 1000 psi (6.90×10^6 Pa), and 1500 psi (10.34×10^6 Pa). Testing flow rate values in the 0.3 – 0.9 cc/min (5×10^{-9} – 15×10^{-9} m^3/s) range with a step of 0.2 cc/min (about 3.33×10^{-9} m^3/s) were established, and the pressure difference was pointed out. Then, to estimate the permeability of the fault gouge sample, Darcy's Law was applied as shown in Eq.1.

$$k = \frac{q \cdot \mu \cdot L}{A \cdot \Delta P} \tag{1}$$

The following denotations are used for the fault gouge material sample:

k	Permeability
q	Flow rate
μ	Fluid viscosity
L	Length
A	Cross-sectional area
ΔP	Pressure differences

This designed experimental program ensures the controlled creation of fault gouge samples, allowing for a systematic investigation of their permeability under varying confining pressures, thereby contributing to a detailed understanding of their behavior in the context of depth variation of the underground storage.

3 Results and Discussion

Due to the varied geological characteristics of different storage locations, such indicators as pressure, and depth display fluctuations. Thus, to generate a valid model and analysis, these relevant parameters must be analyzed. The effective stress, which represents the difference between mechanical stress and pore pressure fields, is of utmost importance. The presence of underground water systems makes pore pressure an essential parameter as well. In general, deeper storage sites are preferred for CO_2 projects, for example, with higher formation safety and storage capacities since they are subjected to greater pressure changes. Consequently, the characterization of fault gouge material depends on these parameters.

The intended experimental plan is formulated to be implemented within a core flooding system, where confining pressure is manipulated while ensuring consistency in other elements such as flow rate, fault gouge material composition, and outlet pressure. Thus, using this method of experimental execution, it is possible to evaluate fault gouge material behavior under in-situ conditions.

According to the trends observed, the outcomes of the pilot trials conducted on the Coreflooding System have been regarded as satisfactory and in harmony with the field observations from the qualitative point of view. A set of data obtained was plotted and displayed in Fig. 5. There was numerous pilot tests conducted for testing this composition. In Fig. 5 there is an elevation of pressure difference with more fluid PV (pore volumes) injected. The reason is that there is fines migration and blockage of the protective outlet screens that are inserted for avoiding blockage of the tubes. Thus, it was concluded to keep a consistent and low injection flow rate to preserve fines in their places and avoid their migration.

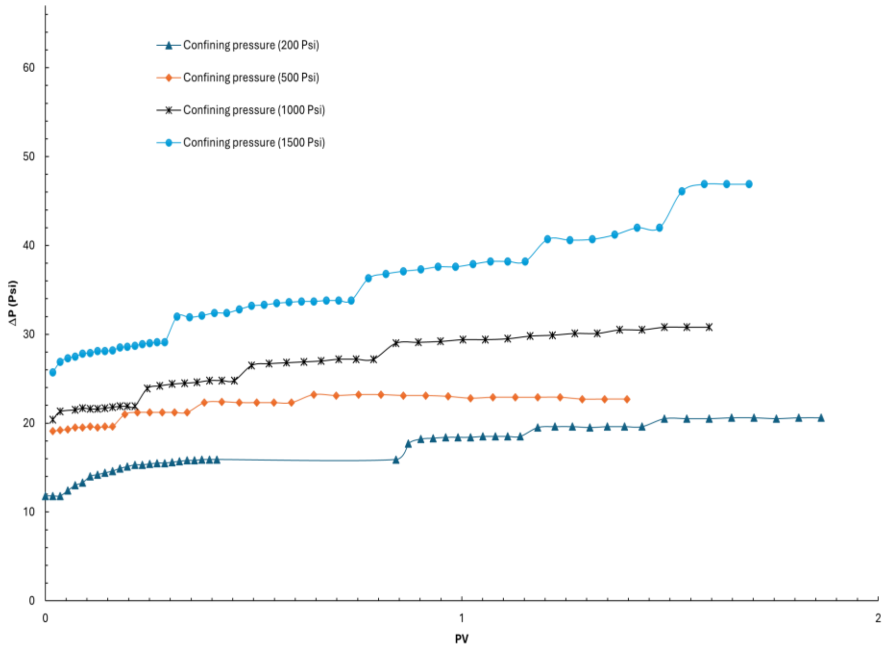

Fig. 5 Coreflooding results of the fault gouge sample.

In general, applying the confining pressure in the range from 200 psi (1.38×10^{6} Pa) up to 1500 psi (10.34×10^{6} Pa) relatively shallow and middle-depth storages up to about 1500 m below ground level attempted to be replicated. The experiments were conducted at the following flow rates 0.3 cc/min (5×10^{-9} m^3/s), 0.5 cc/min (8.33×10^{-9} m^3/s), 0.7 cc/min (11.67×10^{-9} m^3/s) and 0.9 cc/min (15×10^{-9} m^3/s). To ensure a consistent flow, the rate was maintained at a low level. The Darcy Law was subsequently applied to analyze the data. The obtained results under these conditions are illustrated in Tables 3a and 3b. Confining pressure and permeability relationships were noted at all flow rates and permeability reduces as confining pressure elevates. For instance, it can be seen from the Table that when the flow rate is equal to 0.3 cc/min (5×10^{-9} m^3/s) permeability decreases from 6 md to 3.3 md (5.92×10^{-15} m^2 to 3.26×10^{-15} m^2), <u>decreases to 1.8 times,</u> when changing confining pressure from 200 psi (1.38×10^{6} Pa) to 1500 psi (10.34×10^{6} Pa), respectively. Let us compare the declining trend at different flow rates, when the flow rate is 0.5 cc/min (8.33×10^{-9} m^3/s) this decline in permeability is about <u>1.8 times</u> from 8.5 md (8.39×10^{-15} m^2) to 4.7 md (4.64×10^{-15} m^2) as well, while when the flow rate is 0.7 cc/min (11.67×10^{-9} m^3/s) it <u>equals 1.9 times</u> and for the 0.9 cc/min (15×10^{-9} m^3/s) this decrease in permeability is almost <u>2.2 times</u>. Thus, the recorded data also indicates that permeability varies for different flow rates at a fixed sample and confining pressure, as seen from the Table below, which might refer to disturbance of the fine particles and alterations in the pore structure at elevation of injection flow rate. This behavior is likely for samples that are not highly consolidated, proving that the studied sample is a discrete media with a mixture of differently sized particles.

Table 3a Recorded permeability (md) of the fault gouge sample at altering values of confining pressure and flow rate

Flow rate (cc/min) \ Confining P (Psi)	200	500	1000	1500
0.3	6	4.9	4.3	3.3
0.5	8.5	7.5	6.4	4.7
0.7	11.3	9.9	8.1	5.8
0.9	13.8	12.5	9.2	6.1

Table 3b Recorded permeability ($\times 10^{-15}$ m^2) of the fault gouge sample at altering values of confining pressure and flow rate (Table 3a converted to SI units)

Flow rate ($\times 10^{-9}$ m^3/s) \ Confining P ($\times 10^6$ Pa)	1.38	3.45	6.90	10.34
5	5.92	4.84	4.24	3.26
8.33	8.39	7.4	6.32	4.64
11.67	11.15	9.77	7.99	5.72
15	13.62	12.34	9.08	6.02

In this experimental program, several confining regimes were tested and correlated with altered flow rates. Confining pressure and permeability relationships are noted at all flow rates, and permeability drops as confining pressure increases. Similarly, in general, this research is planned to conceptually correlate permeability with confining pressure, to correlate permeability with flow rate, and further studies to correlate fluid types, and different fault gouge compositions (namely by altering clay share) are planned to be conducted. Thus, the results of the studied samples are considered as a basis for further research.

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