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RESEARCH PAPER

Effect of Cyclic Loading on Anhydrite Mechanical and Petrophysical Properties: an Iranian Underground Gas Storage Caprock

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ABSTRACT

Underground gas storage (UGS) in depleted reservoirs holds the highest amount of working gas. In this study, Anhydrite caprock of an Iranian depleted reservoir was studied due to an increase in the number of seismic activities around this field. Anhydrite mechanical properties degrade due to cyclic loading effects resulted from the natural gas injection-production mechanisms. Anhydrite specimens were cored from the outcrop samples. The similarity of Anhydrite outcrop and drilling cuttings was confirmed using X-ray diffraction and SEM EDAX mineral analysis. The effect of cyclic loading on Anhydrite specimens has not been studied previously. The specimens loaded 10, 20, and 30 times in the range of 18, 21, 24, and 25 MPa respectively. Anhydrite unconfined compressive strength (UCS) reduced between 3.5 to 23.9 percent under the cyclic loading experiments. The UCS is more sensitive to the intensity of loading rather than the cyclic times. The specimens CT images were obtained before and after the cyclic loading tests. Also petrophysical properties of the specimens were measured. The study of the specimens' damage indicated that the anhydrite loading threshold was greater than 40 percent of the original UCS.

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1. Introduction

Hydrocarbons are valuable because they are capable of releasing large quantities of energy during the combustion and in this way make them hazardous to move and store in high volumes. The CEDIGAZ projections indicate a 1.4 percent annual increase in the natural gas consumption by 2040 [1]. The sustainability of the natural gas chain requires special attention to the storage of this product such as the conventional storage methods for the hydrocarbon including surface storage in metal and concrete storage, and underground storage in various forms. Underground Gas Storage (UGS) is the unique efficient process to store large quantities of natural gas in an underground inventory [2]. Underground storage of natural gas due to economic advantages and proximity to the target market has replaced the traditional way of constructing pipelines for the gas transportation, while the rapid development of the natural gas market has increased the importance of storage. Underground storage in depleted reservoirs account for the largest share among different types of storage with benefits associated with the cognition and being in the neighborhood of

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the main lines. Underground Gas Storage (UGS) is a cost effective means of installing peak shaving capacity close to gas consumers [3]. Many studies have modeled depleted reservoirs. Some of them have investigated the use of depleted reservoirs to store the carbon dioxide [1, 4, 5].

Storage cycles result in pore pressure fluctuation inside the reservoir rock which change the petrophysical and mechanical properties of that strata and indirectly change the induced stresses affect the caprock and cause the change in caprock integrity properties. Caprock provides a seal for trapping hydrocarbon or other fluids from migrating into the confining layers. In other words, whatever any symptom indicating a change in caprock integrity should be considered during the lifetime of an underground storage facility. Thus, the induced stresses resulted from a change in pore pressure inside the reservoir should be considered respectively [6].

The effect of cyclic loading on different rock type properties' have been widely studied, for the time-lapse of milliseconds [7] to months [8], is divided into dynamic [9-11] and static [7, 12] cyclic loading. Despite increasing studies, the effect of cyclic loading on Anhydrite as the main caprock of carbonate reservoirs has not been fully considered. The study of Anhydrite loading has been restricted to single cycle loading and the effect of UGS cyclic injection-production stages has not been taken into account [8, 13].

The effect of cyclic loading on different materials such as rock salt [7, 8, 14-16], granite [13, 17], sandstone [9, 11, 18, 19], and shale [20] have been studied, yet main works on mechanical properties of anhydrite have been restricted to Table 1 which include only anhydrite basic mechanical properties. However,, these studies mainly focused on the combination of evaporites including anhydrite and not separately. In this study, the effect of cyclic loading on Anhydrite mechanical and petrophysical properties was studied to fill the gap in understanding the alteration of Anhydrite under cyclic loading conditions.

2. Research Method

The tests described herein were carried out on Qom anhydrite. Anhydrite is the caprock of Iranian underground gas storage (UGS). Qom anhydrite was chosen since it is an evaporite rock type with low porosity and permeability, making it a suitable caprock for Qom formation. Besides, an increase in the number of seismic activity due to the storage operation makes its strength alteration an important issue.

The fluctuation of pore pressure inside the reservoir affects the reservoir and its surrounding rocks. To investigate the effect of pore pressure on caprock, anhydrite outcrop samples were prepared and the samples were tested under cyclic loading condition, where the effect of cyclic loading including both the number of cycles and the magnitude of loading were taken into account.

Table 1. Anhydrite geomechanical properties

Property	Unit	Researchers					
		Robertson et al. [21]	Schwerdtner et al. [22]	Smith et al. [23]	Hangx et al. [24]	Malenda et al. [25]	Mehrgini et al. [26]
Density	Kg/m^3	2890 - 3000	2960 – 2980	-	-	2930	2820-2880
Vp	m/s	-	5630	-	-	-	5027-5399
Vs	m/s	-	3150	-	-	-	2908-3014
UCS	MPa	-	-	75	98	110-180	34.4-38.2
E	GPa	53.6 – 81.0	91 – 160	-	38	80-104	3.66-4.39
ν		0.20 - 0.36	0.13 – 0.274	-	-	0.42	0.19-0.22
C	MPa	-	-	12.4	-	-	5.9 – 7.02
ϕ	(°)	-	-	53	-	-	44.2 – 46.6
T	MPa	-	-	-	-	-	4.67 – 5.3

The similarity of the caprock and outcrop anhydrite was confirmed using the geological reports, X-ray diffraction (XRD) by Philips PW-1800, and Hitachi S-400 scanning electron microscope (SEM) EDAX analysis. Based on the combination of XRD and SEM EDAX results, the anhydrite outcrop the same as caprock is mainly composed of calcium sulfate with minor traces of Celestine and Boron minerals. Calcium sulfate can be hydrated near-surface; hence, choosing anhydrite outcrop for sampling was confirmed by the Schmidt hammer rebound (SHR) test in the range of 30 to 43 [27, 28]; therefore, the weathering effect on outcrop samples was minimized.

Anhydrite blocks cored to a set of 2.15 inches (NX) cores, gathered from the outcrop. The coring was perpendicular to layering and performed with water. Anhydrite mechanical properties were measured as shown in Table 2 including unconfined compressive strength (UCS), elastic modulus (E), Poisson ratio (v), and tensile strength (TS). The mechanical properties obtained using Qom anhydrite were in good accordance with previous studies. The sample preparation and testing procedure for obtaining mechanical properties confirmed the requirement of the ISRM (1981) standard.

Static cyclic tests were carried out on 18 core samples with a diameter of 1.5 inches. Samples with a diameter to length ratio of 1:2 were obtained from two anhydrite outcrop blocks to reduce the effect of anisotropy. All the cyclic tests were performed using the Azmoon-50 KN servo-control testing apparatus with a loading rate of 0.004 mm/s during the cyclic loading tests.

These cyclic loading tests were used to study the changes in samples UCS shown in Table 2. The axial load specified as a sinusoidal compressive load and the number of cycles were divided into 10, 20, and 30 times at each loading level. The highest stress ratio (ratio of the maximum stress in the cyclic test to the anhydrite UCS) varied between 0.3, 0.35, 0.4, and 0.42. The specimens loaded to the maximum stress level and then cyclic loading tests were performed at the given amplitude and frequency and finally measured the UCS of cyclically loaded samples. All of the tests were conducted at room temperature.

3. Results and Analysis

Cyclic loading changed the micro and macro properties of the specimens, thereby altering specimens' mechanical and petrophysical properties. The decrease in the mechanical properties is related to the number of cycles and intensity of loading. In fact, the greater the intensity of loading and the number of cycles, the lower the specimens' remaining strength. Higher cyclic intensity alters the specimen's mechanical property notably based on the specimens' damage properties.

Table 2. Qom anhydrite mechanical properties obtained from the laboratory tests

Property	Density	Vp	UCS	E	v	C	ϕ	T
Unit	Kg/m3	m/s	MPa	GPa		MPa	°	MPa
Qom Anhydrite	2890 – 2940	5450 - 5800	57 - 63	25 - 35	0.22 - 0.25	11	34	8.03

Table 3. Specimens cyclic loading test condition

	Number of Cycles		
Cyclic Magnitude	10 Times	20 Times	30 Times
18 MPa	B3	B40	B2
21 MPa	B1	B4	B5
24 MPa	B8	B6	B7
25 MPa	A7	A5	A8

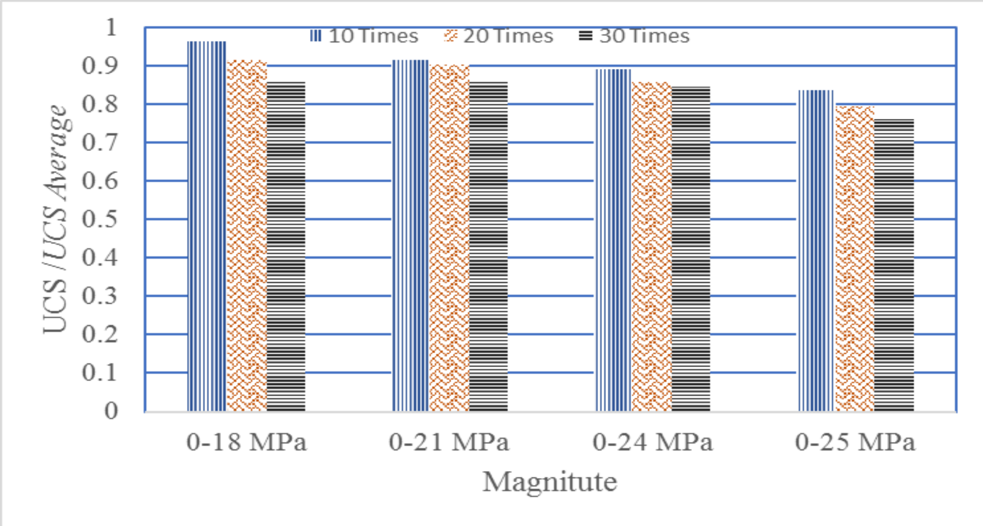

Figure 1. Anhydrite UCS alteration due to cyclic loading

3.1. Anhydrite UCS alteration due to cyclic loading

The study of anhydrite specimens subjected to cyclic loading as shown in Figure 1 indicates that specimens UCS alters. the UCS reduction is more sensible to the intensity of loading than the number of cycles.

Anhydrite specimens subjected to the cyclic loading with intensity changing from 0.3, 0.35, and 0.4 UCS showed UCS reduction. For loading intensity equal to 0.42 UCS, this reduction is of higher degree. The comparison of UCS alteration between 40 and 42 percent UCS intensity indicated that the critical threshold for anhydrite under the cyclic loading is approximately 0.42 original UCS.

The intensity of loading has also more effect on UCS reduction in comparison with the number of cycles (Figure 2). It shows a sharp change in UCS alteration under 25 MPa loading intensity (0.42 UCS) based on CT study resulted from crack initiation through all length of specimens, while for lower loading intensity during 10, 20, and 30 cycles of loading the crack growth was restricted to the middle parts of the specimens. This result is in good accordance with data obtained from porosity and permeability measurements.

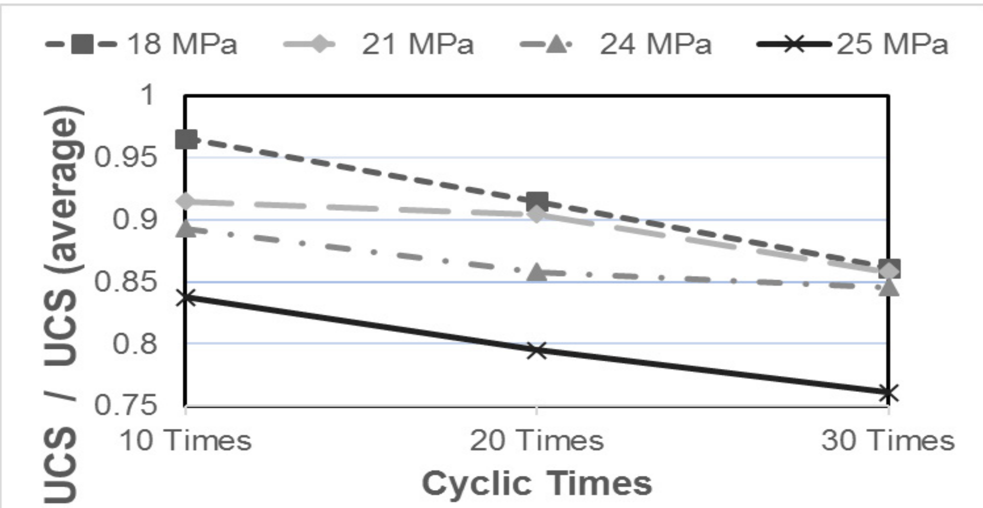

Figure 2. Effect of loading magnitude on UCS reduction for different number of cycles

3.2. Anhydrite petrophysical alteration due to cyclic loading

Anhydrite specimens were CT imaged before and after the cyclic loading test using PROMAX 3D D-054SB-C CT imaging unit with a 100-micrometer resolution. In addition, specimens petrophysical properties such as porosity and permeability were measured using Petro Ahoura U.S.S PERM apparatus. The CT images were used to study the observed cracks after the cyclic loading tests. The cracks initiated in the length of specimens after the different cyclic loading stages.

The study of anhydrite specimen petrophysical properties due to cyclic loading as shown in Figure 3 indicated that the specimen's porosity mainly increased even though the permeability of specimens did not increase. The positive values indicate an increase in the amount of measured feature while the negative values indicate a reduction of that feature. As long as the cyclic loading did not similarly change both porosity and permeability of specimens, the reduction in the mechanical properties is minor, but when the intensity of loading is greater than the critical threshold the change in porosity also affects the permeability of the specimens. The minor change in the specimens' petrophysical properties is due to the discontinuity of the initiated cracks inside the anhydrite specimen - based on CT images – but when the crack growth included all length of the specimens, showing critical intensity threshold, both porosity and permeability increased.

CT image obtained before and after the cyclic loading tests showed that the cracks initiate inside the specimens under the cyclic loading conditions and this growth affects the petrophysical properties. Under higher than 40 percent UCS loading magnitude the cracks propagate through all length of A8 specimen and the opening of cracks happens in the middle part of the specimen as shown in the right part of Figure 4. In lower loading intensity such as B4 specimen, the length of the cracks is less than the specimen's length as shown in the left part of Figure 4. The result obtained from the CT image is in good accordance with those of the petrophysical properties. Figure 5 shows the change in CT number in the length of specimen B4 before and after the cyclic loading test. CT number was presented with solid lines shown on the left axis and the percentage of CT number change with the hollow line on the right axis. The change in CT number indicating crack initiation happened in the center part of the specimen, confirming that an increase in the porosity of specimen did not affect the permeability.

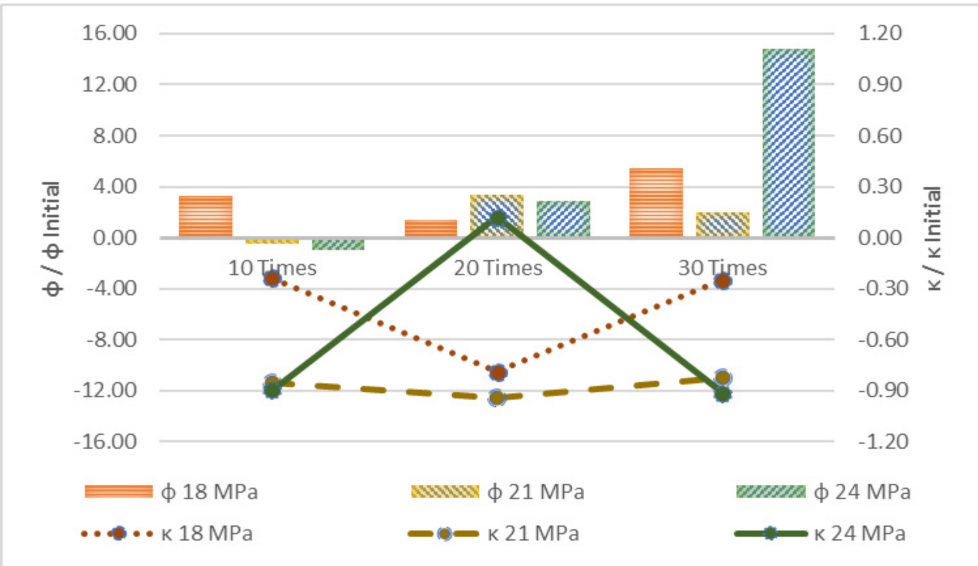

Figure 3. Effect of cyclic loading on petrophysical properties of anhydrite specimens

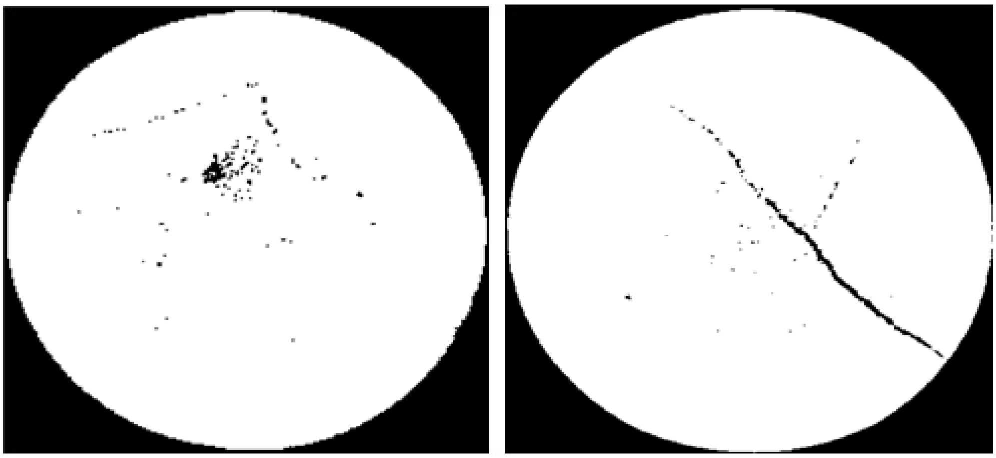

Figure 4. Specimens B4 (left) and A8 (right) CT image after cyclic loading

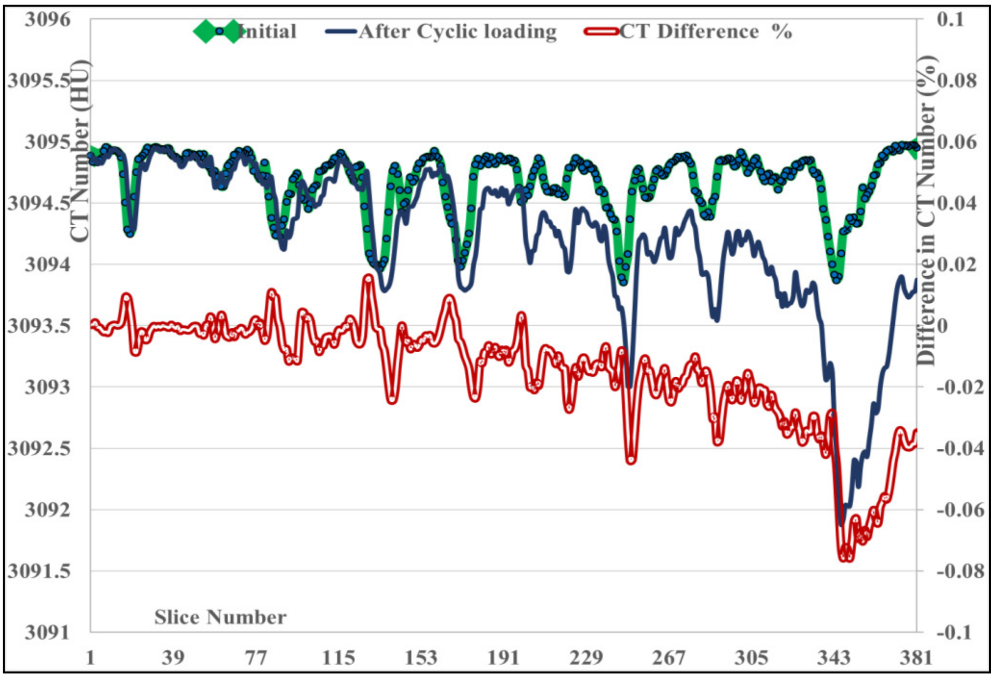

Figure 5. CT number in the length of Specimen B4 before and after the cyclic loading test

4. Conclusion

UGS operation affects the reservoir rock and caprock. This pressure fluctuation in the form of cyclic loading affects the mechanical and petrophysical properties of the caprock. Based on this study, Qom anhydrite mechanical and petrophysical properties changed due to the cyclic loading. The effect of the intensity of cyclic loading was more dominant in comparison with the loading cycle times. The anhydrite critical loading threshold measured about 42 percent of its UCS, indicating an increase in the present storage pressure higher than 33 percent of the current storing pressure which increases the risk of crack growth inside the anhydrite caprock. The cyclic loading threshold happened with UCS reduction to 0.85 percent of the initial value. Even though the current storing scenario changed the caprock properties, a 17 percent increase in the current storing pressure has nearly the same effect on the long-term condition.

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مقاله تحقیقاتی

تاثیر بارگذاری تناوبی بر خصوصیات مکانیکی و پتروفیزیکی انیدریت: بررسی یکی از مخازن ذخیره سازی زیرزمینی ایران

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چکیده

بیشترین میزان گاز کار در مراکز ذخیره سازی زیرمینی در مخزن های تخلیه شده ذخیره شده است. به دلیل افزایش فعالیت های لرزه ای در اطراف یکی از مخزن های ذخیره سازی زیرزمینی ایران، پوش سنگ انیدریتی این میدان مورد بررسی قرار گرفت. بارگذاری تناوبی ناشی از مکانیزم تزریق و برداشت متناوب گاز در مخزن های ذخیره سازی بر رفتار مکانیک سنگی انیدریت تاثیر می گذارد. مغزه های انیدریت از نمونه های تهیه شده از رخنمون تهیه گردید. مشابهت نمونه های رخنمون و خرده ای های حفاری انیدریت به کمک تست سنجش اشعه ایکس و تحلیل عناصر تایید گردید. اثر بارگذاری تناوبی بر خصوصیات انیدریت مورد بررسی قرار نگرفته است. مغزه های تهیه شده ۱۰، ۲۰ و ۳۰ بار در محدوده ۰ تا ۱۸، ۲۱، ۲۴ و ۲۵ مگاپاسکال بارگذاری گردیدند. مقاومت تک محوره نمونه ها کاهش ۳/۵ تا ۳۲/۹ درصدی داشتند. تاثیر شدت بارگذاری بیش از تعداد دفعات بارگذاری می باشد. حد فشار بارگذاری بحرانی انیدریت بیش از ۴۰ درصد مقاومت تک محوره استاندارد نمونه های انیدریتی گزارش می گردد.

نحوه استناد به این مقاله:

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