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Experimental Evaluation of Hydrochloric Acid Treatment on Sandstone Reservoir Properties

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ABSTRACT

Matrix acidizing is a popular stimulation method in oil and gas well that increases the permeability of sandstone reservoirs by dissolving minerals that block pore spaces. The success of this process is dependent on the mineral composition of the rock and the type of acid used. In this work the effects of HCl on sandstones from Sitakundo were studied in the laboratory. Pre and post acidize analysis is performed to observe alteration in porosity, permeability and uniaxial compressive strength (UCS). A significant enhancement in porosity from 11-13 to 22-25% and more than 70% permeability increase were achieved, ensuring an effective dissolution of minerals and an enhancement of porous structure. This implies that the UCS was reduced by 14% approximately as a result of mechanical weakening consequent to the dissolution of cementing materials. These results underline the two fold effect of acidizing - increasing flow capacity while decreasing rock strength and open avenues to more optimized acid treatment design for effective & stable reservoir stimulation.

Keywords: Matrix acidizing, hydrochloric acid, Porosity, Permeability

1. Introduction

Matrix acidizing is a comprehensive stimulation technique in upstream oil and gas operations, which is used to clean the near-wellbore damage and reestablish the reservoir permeability. This procedure is performed by pumping acid solutions or acidizing solutions into the wellbore to dissolve particles and minerals that are blocking the flow of fluid, which effectively increases the size of the pores, the permeability, and the hydrocarbon production [1]. The purpose of matrix-acidizing in sandstone reservoirs is to dissolve siliceous minerals (clays, feldspars, and quartz) that are obstructing the flow of hydrocarbons. This treatment helps to overcome formation damage from drilling, clay hydration and fines migration to increase reservoir productivity and well life [2]. Nevertheless, executing matrix acidizing in sand is challenging. These consist of the subsequent precipitation of the reaction by-products, uncontrolled spending of the acid, and acid spending in a non homogeneous manner; each of these factors may decrease the stimulation's efficiency and/or harm the reservoir [3]. Sandstones with substantial clay content are especially troublesome, since it has been identified that acid–clay reactions could give rise to clay swelling, migration, and/or to the formation of insoluble precipitates that could cause plugging of pores and reduction of permeability [4].

Sandstone deposits are sedimentary rocks, clastic in nature. Compaction of quartz and feldspar grains formed by sandstone, with quartz having a higher percentage of sand composition. Consequently, their porosity, permeability, and overall reservoir quality depend on their depositional environment (fluvial, deltaic, or marine) [5]. Hydrochloric acid (HCl) is the acid of choice in the pre-flush in acidizing treatments for the removal of carbonate scale and for the displacement of formation brine. This step provides a low-pH environment that prevents precipitation reactions and allows the next HF treatment to concentrate on the siliceous minerals. The concentration of hydrochloric acid (HCl) has an important influence on the process of dissolution of minerals and on the changes in porosity and permeability of sandstone reservoirs. At lower acid concentrations, a slow dissolution phenomenon occurs, so acid can penetrate deeper, and a milder but more uniform increase in porosity is obtained. Conversely, high concentrations of HCl result in fast reactions close to the wellbore and create localized dissolution zones, thus resulting in a limited increase of permeability. Thus, an optimum HCl concentration must be found to attain the optimal combination of reaction rate and acid penetration depth, thereby promoting the development of interconnected pore networks and improving fluid flow characteristics. Appropriately selected acid concentrations are thus vital for maximizing reservoir stimulation efficiency while mitigating potential near-wellbore damage [6].

The practice of acidizing to enhance performance has evolved over a century. It was first introduced in the early 20th century, primarily for carbonate formations, where hydrochloric acid (HCl) was injected to dissolve carbonate minerals and improve permeability [7]. Since the mid-20th century, sandstone matrix acidizing has become an integral practice in the petroleum industry, with continuous advancements in acid formulations to suit various mineralogical and temperature conditions [8]. The type and concentration of acids like HCl, HF, or organic acids need to be closely matched to the mineralogical and petrophysical properties of the reservoir. An inadequate acid system could cause under dissolution of damaging minerals or over precipitation, both leading to a reduction in formation permeability [9].

Some recent work has explored enhanced acid systems to address the limitations of traditional mud acid. For example, mud acid combined with buffering agents (e.g., phosphoric or formic acid) can keep the pH stable during the treatment, which can result in a more uniform dissolution and a deeper penetration. [10]. Fluoroboric acid (HBF4) has also been suggested to be a system of retarded acid that is hydrolyzed slowly to liberate HF, which allows a controlled reactivity and deeper penetration, especially in high temperatures of more than 65°C. [2]. Such innovations have expanded the applicability of acidizing to a wider range of reservoir conditions.

Though there have been significant advances in acidizing, the treatment of sandstone reservoirs, especially at high temperatures and in the presence of clays, is still facing many difficulties. Typical HF-based mud acids are too reactive at temperatures above 200°F, leading to early acid-spending, low depth of penetration, and, in severe cases, damage to the formation. Moreover, HF reactions may weaken the mechanical strength of a sandstone, decreasing its compressive strength, porosity, and permeability, and inducing fine migration and corrosion-related problems [11].

These limitations emphasize the importance of finding new acid systems or tailored solutions that can provide effective stimulation with no adverse effects on the reservoir integrity. Consequently, this study is devoted to the development and optimization of acid systems for sandstone matrix acidizing, focusing on the enhancement of the performance in severe thermal and mineralogical environments. The study starts with a thorough review of current acidizing methods and reaction mechanisms and continues with several controlled laboratory studies on acid–rock reactions. The experimental results are analyzed to identify key parameters influencing dissolution efficiency, secondary precipitation, and overall stimulation effectiveness. Based on these insights, recommendations are proposed to guide the formulation of more effective, thermally stable, and environmentally sustainable acid systems for sandstone reservoir stimulation.

2. Methodology

This study investigated the effects of acid treatment on sandstone samples, focusing on changes in mechanical integrity and dissolution behavior. The methodology comprised four main stages: (i) sample collection and preparation, (ii) acid solution formulation, (iii) acid–rock interaction testing, and (iv) post-treatment characterization. The overall experimental workflow is illustrated in Fig. 1

After collecting the samples and sizing them properly in the lab. The diameter and length of each sample were measured. Then they were washed to get rid of loose particles and dried in an oven at 60°C for 24h to dispel the moisture content.

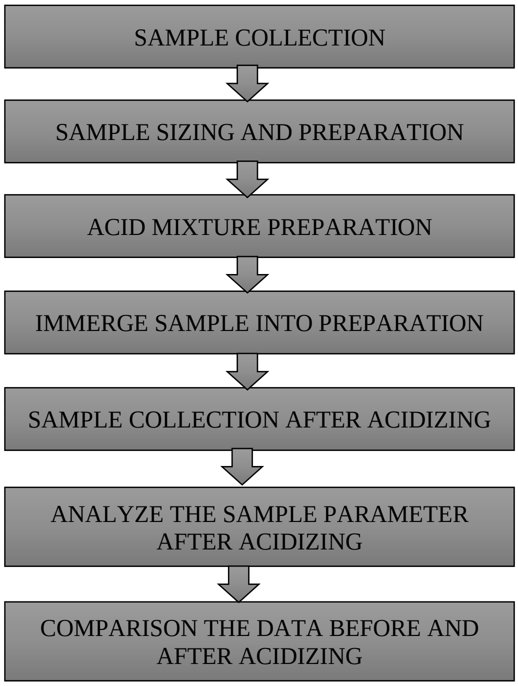

Fig. 1. Flow chart of the Methodology

The 24-hour duration for HCl acid immersion in this study was selected based on preliminary trials and literature evidence to ensure adequate interaction between the acid and the sandstone matrix.

Shorter exposure times may result in incomplete mineral removal and limited permeability gains, while excessively long immersion could cause over-dissolution, weaken the rock framework, and reduce unconfined compressive strength (UCS) [12].

2.1 Sample Preparation

A representative set of sandstone core samples from the Sitakundo formation was taken to the Core Laboratory at the Chittagong University of Engineering and Technology (CUET) and was subjected to testing. (Fig. 2, Fig. 3). The block was sectioned into normal cylindrical cores using a precision core drill. Dimensional data length and diameter were obtained with a vernier caliper to standardize all testing specimens. (Table 1). After removal of surface debris by cleaning, the samples were oven dried at 60 °C for 24 h to a constant mass before the acid application to ensure that no moisture remained.

Table 1: Sandstone physical properties

Sample Number	Weight (g)	Length (cm)	Diameter (cm)
1	134.22	4.8	3.5
2	136.75	4.8	3.5
3	83.05	6.5	2.5
4	81.70	6.5	2.5

Fig. 2. Sample collected from Sitakundo

Fig. 3. Prepared core samples before acid treatment

2.2 **Acid Solution Preparation**

The acidizing fluid was formulated to simulate typical sandstone matrix acidizing conditions. A hydrochloric acid (HCl) solution was prepared at a concentration of 15 wt.% relative to the total solution volume, consistent with standard field practice for sandstone stimulation.

All solutions were prepared using analytical-grade reagents under controlled laboratory conditions with appropriate safety measures.

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2.3 **Acid–Rock Interaction Procedure**

Each oven-dried sandstone sample was fully immersed in the prepared acid solution for 24 hours at ambient laboratory temperature. The immersion duration was selected based on prior studies and standard matrix acidizing procedures to ensure sufficient reaction between the acid and siliceous minerals. The reaction progress was visually monitored throughout the exposure period.

After the treatment, the specimens were taken out of the acid bath, rinsed with distilled water to neutralize the remaining acid, and finally oven dried again at 60 °C for 24 h to remove any remaining moisture. The acidized samples were subsequently sealed in bags and stored for mechanical and visual evaluation (

Fig. 4).

2.4 **Acid–Rock Interaction Procedure**

The mechanical integrity of the sandstone before and after acid treatment was evaluated using an Unconfined Compressive Strength (UCS) apparatus. Each sample was subjected to axial compression at a constant displacement rate until failure, and the maximum load at failure was recorded. The UCS values were compared to assess the extent of strength reduction resulting from acid–rock interactions.

Fig. 4. Core samples after acid treatment

3. Results and findings

A comprehensive analysis was conducted to evaluate the effect of matrix acidizing on the physical and mechanical properties of the sandstone. The important comparative factors were a decrease in weight, an increase in porosity, an increase in permeability, and a variation in uniaxial compressive strength (UCS). The results provide a full picture of the chemical–mechanical coupling between acid–rock reactions and reservoir quality improvement.Baseline values of porosity, permeability, and mechanical strength were measured for each sand before acid treatment. The acidizing was performed by dipping the specimens in the prepared HCl solution at room temperature for 24 h, to ensure complete contact with acid-reactive minerals. After finishing the treatment, the samples were washed, dried in an oven, and tested again to measure the change in critical reservoir parameters.

3.1 **Weight Loss Analysis**

Weight loss provides an indirect measure of mineral dissolution and acid–rock reactivity. As presented in Table **2**, all samples exhibited noticeable mass reductions following acidizing, indicating active dissolution of acid-soluble components such as calcite, dolomite, and clay minerals.

Table 2: Weight change in percentage after acidizing

Sample Number	Weight Before (g)	Weight After (g)	Weight Loss (%)
1	134.22	127.51	4.99
2	136.75	129.11	5.58
3	83.05	80.13	3.51
4	81.70	78.51	3.90

The highest weight loss (5.58%) occurred in Sample 2, suggesting a higher content of acid-reactive minerals in its matrix. The observed weight reduction confirms that acidizing effectively removed mineral obstructions and fines within the pore network, which directly correlates with the observed improvement in reservoir flow properties.

3.2 **Porosity Analysis**

Porosity is a critical parameter controlling reservoir storage capacity and fluid mobility [13]. The acid treatment significantly enhanced the porosity of the tested samples.

Table 3 summarizes the porosity values before and after acidizing. As shown, the porosity of Sample 1 and Sample 2 nearly doubled after acid exposure, increasing from 12.65% to 24.50% and from 11.96% to 21.77%, respectively. This substantial increase indicates that acid dissolution of intergranular cements and fine particles generated additional pore space and enhanced the connectivity of existing pore networks. Visual inspection of the post-acidized samples confirmed a more porous surface texture and reduced grain cohesion, consistent with mineral removal and pore enlargement.

Table 3: Porosity changes before and after acidizing

Sample Number	Before Treatment (%)	After Treatment (%)	Porosity Change (%)
1	12.65	24.50	11.85
2	11.96	21.77	9.81

3.3 **Permeability analysis**

Permeability represents the rock's ability to transmit fluids and is a key indicator of stimulation effectiveness [14]. Measurements before and after acidizing revealed a pronounced increase in permeability for all tested samples (Table 4). The results demonstrate that permeability improved by approximately 72% for Sample 3 and 81% for Sample 4 after acidizing. This improvement is attributed to the dissolution of mineral bridges and fines that previously obstructed flow channels. The correlation between weight loss and permeability enhancement further validates that mineral dissolution directly facilitated better pore connectivity and fluid flow pathways.

The permeability was measured in this test at the beginning and at the end of the matrix acidizing treatment to assess the degree of improvement in fluid flow paths by the acid. The computation was based on Darcy's Law, which is generally written as equation (1)

$$K=\frac{Q.\mu.L}{A.\Delta p} \quad (1)$$

Where, K = Permeability (mD), Q = Flow rate of fluid (cm³/s), and μ= Viscosity of the fluid (cp) [15].

Table 4: Permeability before and after acidizing

Sample Number	Before Treatment (mD)	After Treatment (mD)	Permeability Change (%)
3	414.5	715.2	300.7
4	435.1	8787.6	352.5

3.4 **UCS Analysis**

Although acidizing enhanced porosity and permeability, it also degraded the mechanical stability of the rock. The acid treatment resulted in a marked weakening of the samples, as demonstrated by the UCS tests. For instance, the UCS of Sample 2 was reduced from 73.96 MPa to 63.57 MPa, signifying a loss of 14% in compressive strength. The ultimate load-carrying capacity was also reduced from 172.5 kN to 148.3 kN.

This loss of strength is the result of cementing minerals being dissolved and grain-to-grain bonds being weakened through acid–rock reaction. While this weakening may raise some potential issues for wellbore stability, it is an inherent trade-off in matrix acidizing--increased permeability and porosity come at the cost of a certain amount of mechanical integrity. Therefore, the acid strength and the acid exposure times should be optimized to achieve a compromise between stimulation efficiency and formation stability.

4. Discussion

The overall findings are that matrix acidizing can enhance reservoir quality indicators, porosity, and permeability, and reduce rock strength at the same time. The removal of carbonate and silicate cements by dissolution also unplugs pores and increases the flow of fluids. But too much selling or the wrong type of acid concentration can result in undercutting and weakening.

These results are in general agreement with earlier reports that have shown that tailored acid systems can provide significant improvement in the flow of tight sandstones under treatment conditions are well controlled. As the experimental strategy in this work is significantly different from other studies in that pure hydrochloric acid (HCl) was utilized for an extended 24 h acidizing duration as opposed to mixed acids for short-term applications, full interaction between the acid and rock matrix can take place. The enhanced porosity (up to 11.85%) and permeability (up to 81%) showed that acidizing has great potential to be a reservoir stimulation technique, but the corresponding strength loss calls for accurate design parameters.

The ~14% reduction in UCS is due to moderate weakening of the sandstone from HCl dissolution of cementing minerals. In field-scale acidizing, such strength reduction is usually acceptable and not expected to jeopardize wellbore stability information having sufficient overburden and being intact. But in weak, fractured, or heterogeneous rock, even a modest drop in UCS might raise the risk of near-wellbore collapse and sand production.

Nevertheless, in weak, fractured, or heterogeneous formations, a modest UCS reduction may result in aggravating the risk of near-wellbore collapse and sand production. To sum up, the findings inform the double-sided effect of matrix acidizing: on one hand, it improves reservoir productivity via enhancing pore connectivity and flow capacity; on the other hand, it requires cautious operation to maintain formation integrity and prevent long-term damage to the structure.

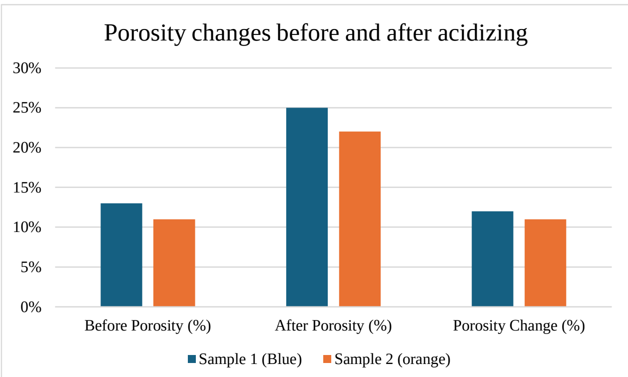

Fig. 5. Porosity variation through the samples

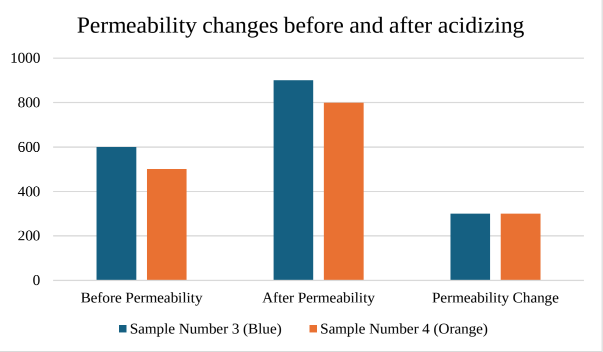

Fig. 6. Permeability variation through the samples

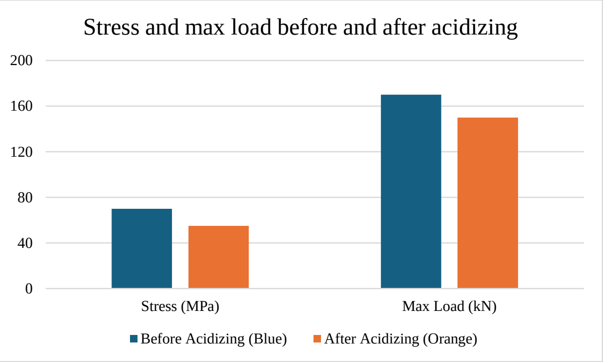

Fig. 7. Change of stress before and after acidizing

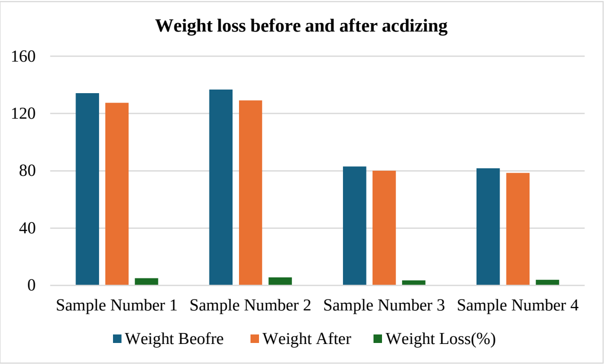

Fig. 8. Variation in weight loss before and after acidification

5. Conclusion

In this research, the influence of matrix acidizing on the physical and strength characteristics of sandstone was experimentally studied by using typical core samples taken from the Sitakundo area. Hydrochloric acid (HCl) solutions were employed for the laboratory-scale acidizing treatments, which were carried out under conditions simulating those in the field. Several important parameters, such as sample weight, porosity, permeability, and unconfined compressive strength (UCS), were determined, before and after acidizing, to evaluate the net effect of acid–rock reactions.The results demonstrated clear and consistent trends across all tested samples. Post-acidizing analyses revealed measurable weight reduction due to mineral dissolution, significant increases in porosity and permeability, and a corresponding decrease in UCS values. These findings confirm that matrix acidizing effectively enhances reservoir quality by improving pore connectivity and fluid flow capacity, primarily through the removal of acid-soluble minerals and fines that impede permeability. However, the concurrent reduction in mechanical strength indicates a trade-off between improved reservoir productivity and potential risks to formation stability.

Overall, the study highlights the dual nature of acidizing treatments in sandstone reservoirs—enhancing reservoir performance while altering mechanical integrity. The experimental observations provide valuable insight into the mechanisms governing acid–rock interactions and their implications for reservoir stimulation design. Future work should focus on optimizing acid formulations, treatment durations, and thermal conditions to maximize stimulation efficiency while minimizing structural weakening and long-term damage to the formation.

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