

## Research Article

# Investigation of Using Various Quantities of Steelmaking Waste for Scavenging Hydrogen Sulfide in Drilling Fluids

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Effective in situ scavenging of hydrogen sulfide ( $H_2S$ ) while drilling a sour formation is critical for limiting the prevalent related impacts and safety hazards. Thus, it is necessary to develop a specialized additive that can selectively react with  $H_2S$  and remove it without generating harmful byproducts or impairing drilling fluid performance. Additionally, waste management and utilization will transfer the waste from being an environmental and economic burden to a valuable commodity. Accordingly, we report herein the management of steelmaking waste through its utilization as a novel  $H_2S$  scavenger for water-based drilling fluids, as well as the evaluation of the effects of the steelmaking waste dosage (1, 2, and 3 g) on the mud  $H_2S$  scavenging capability and key properties. The  $H_2S$  scavenging capacity of the waste-containing mud was investigated and compared to that of the base mud and fluids containing the commercial scavengers (triazine- and iron gluconate-based materials). In addition, the mud rheology, alkalinity, and filtering performance were studied in the presence and absence of the waste, and the findings were compared to those of commercial scavengers. This study showed that adding 1, 2, and 3 g of the steelmaking waste to the base drilling fluid significantly improved the  $H_2S$  scavenging capacity by 105, 399, and 503%, respectively, while the triazine- and iron gluconate-based materials increased the capacity by 179 and 131%. Similarly, when the proportion of the steelmaking waste increased, the rheological parameters, comprising apparent viscosity, plastic viscosity, and yield point, slightly increased. The inclusion of the steelmaking waste reduced mud pH to 10.4, 9.8, and 8.5 with a content of 1, 2, and 3 g, respectively, compared to 11.0 for the base mud, 11.1 for triazine-based material, and 7.9 for iron gluconate-based scavenger. When 1 and 2 g of the steelmaking waste were added, the obtained filtrated liquid volume was preferably lower than the base mud and even the commercial scavengers-contained muds. As a result, 2 g of steelmaking waste could be added for enhanced mud performance. Nevertheless, higher amounts of the steelmaking waste could be used instead to achieve maximal  $H_2S$  scavenging capability, with an extra alkalinity controller added to ensure attaining the practical recommended properties.

## 1. Introduction

The presence of hydrogen sulfide ( $H_2S$ ) gas is a frequent problem encountered when drilling subsurface hydrocarbon formations. This gas is naturally found in oil and gas reservoirs and is formed either by geological or microbiological processes [1–4].  $H_2S$  invades the drilling system through either invading formations containing  $H_2S$ -contaminated fluids, the metabolism of sulfate-reducing bacteria that survive in anaerobic conditions, or the thermal degradation of

sulfur-containing drilling fluid additives [5–8].  $H_2S$  gas is the most reduced form of sulfur, having a rotten-egg-like odor that can be recognized by smell at low concentration levels as 0.5 ppm; however, at high  $H_2S$  concentrations, the human ability to smell this lethal gas is lost.  $H_2S$  is denser than air with a specific gravity of 1.2 and is extremely corrosive, toxic, flammable, and reactive [9].

The transfer of this toxic gas to the surface poses a serious threat to personnel health and safety, with varying consequences depending on the duration and intensity of exposure.

The agencies, such as the National Institute for Occupational Safety and Health (NIOSH), define standard regulations and guidelines for H<sub>2</sub>S exposure limits, which are updated on a regular basis. NIOSH, for instance, specifies a 10-minute exposure limit of 10 ppm, and a concentration of 100 ppm is considered an emergency life-threatening level. [8–12]

The interaction of H<sub>2</sub>S gas with metallic components of equipment during drilling operations may cause brittle failure, sour, or pitting corrosion. Metal brittle failure is caused by hydrogen embrittlement and stress cracking, occurring from H<sub>2</sub>S reaction with steel in equipment [8, 13–15]. Increasing the acidity of the contained fluids and generating corrosive iron sulfide result in the sour corrosion of equipment [3, 14, 16–21]. The iron sulfide scale that sticks to steel surfaces causes pitting corrosion, which reduces equipment life [22, 23]. When H<sub>2</sub>S is introduced into the drilling fluid, it changes the viscosity, fluid loss, and density of the mud, causing a well kick problem as well as a drop in pH that makes the mud more corrosive to metallic equipment [3, 19, 24, 25]. Also, during an H<sub>2</sub>S-containing kick, the H<sub>2</sub>S remains in liquid form (because H<sub>2</sub>S can liquefy at pressures as low as 350–400 psi) until it reaches the surface, where it changes to gaseous form with a rapid and massive volume increase, posing a difficult well control situation [8].

As mentioned above, H<sub>2</sub>S is encountered during the drilling operations in significant amounts, posing serious safety challenges and equipment damage. As a result, the safe and immediate tackling of any released H<sub>2</sub>S during the drilling operations is essential [26, 27]. A range of specialized additives have been used to selectively react with H<sub>2</sub>S and effectively scavenge it without forming any undesired byproducts or deteriorating the drilling fluid properties. Since H<sub>2</sub>S reacts with strong oxidizers and metals, oxidizers such as hydrogen peroxide and potassium permanganate were used as H<sub>2</sub>S scavengers. Hydrogen peroxide is a nonselective reactant that causes an uncontrollable scavenging process, making it inappropriate for use in drilling fluid [3, 19, 28, 29]. Potassium permanganate has a better mud rheological effect, but it is ineffective with heavy mud weight [30–34].

Metal-based compounds are particularly appealing among other H<sub>2</sub>S scavengers due to their low cost, efficacy, and safety. These compounds react with H<sub>2</sub>S to produce insoluble metal sulfides, which are thermally stable and do not reproduce H<sub>2</sub>S during drilling conditions, making them safe H<sub>2</sub>S scavengers. Copper, zinc, and iron-containing compounds make up the majority of metal-based H<sub>2</sub>S scavengers utilized in drilling operations [19, 24, 29, 35–37]. Table 1 describes the common metal-based scavengers used so far in drilling operations.

Although various scavengers have been used in the petroleum industry, each has its limitations, including reaction kinetics, scavenging methods, conditions, cost, environmental concerns, and effects on mud properties. As a result, research is still ongoing in order to obtain an optimal and feasible scavenger that can remove H<sub>2</sub>S completely and quickly without forming any deleterious byproducts.

Massive amounts of waste are produced during the steelmaking process, with waste production projected to reach 2–4 tons per ton of steel generated [59–62]. The produced wastes

were previously used in drill cutting disposal [63, 64], asphalt concrete binder [65–67], cement production [68–71], and heavy metal adsorption [72–74]. Steelmaking waste has recently been introduced as a viscosifier additive in drilling fluids by combining it in various ratios with bentonite [61]. Steelmaking waste is abundant and available as a byproduct from many steel factories. Waste management, on the other hand, poses significant economic and environmental challenges.

The purpose of this study is to incorporate steelmaking waste into water-based drilling fluids and investigate the effect of the steelmaking waste level in the drilling mud on H<sub>2</sub>S scavenging capabilities and mud properties. The novelty of this study stems from utilizing the steelmaking waste as an H<sub>2</sub>S scavenger for efficient and safe drilling operations, converting waste from a cost and environmental burden to a beneficial product.

## 2. Materials and Experiments

**2.1. Materials.** Water-based drilling fluid samples were prepared in laboratory using an actual field mud formula. Using fresh water as the base fluid, 350 cm<sup>3</sup> of drilling fluid samples were prepared. The prepared mud formulations were presented in Table 2. A small amount of antifoam agent was added. To acquire the desired mud viscosity, xanthan polymer was used, while the starch was employed primarily to limit fluid losses and to aid in viscosity build-up. To prevent the formation shale from swelling, the sodium chloride was utilized. Caustic soda was used to maintain the desired alkaline pH value. Then, fine and medium calcium carbonate particles were used as bridging agents and densifiers. The prepared drilling fluid samples had a density of 9.8 ppg. The drilling fluid with the aforementioned compositions served as the base mud for this study. Drilling fluid services companies provided commercialized H<sub>2</sub>S scavengers (i.e., triazine- and iron gluconate-based scavengers), which were utilized as benchmarks for comparison. To investigate the effect of incorporating steelmaking waste, different amounts (1, 2, and 3 g) were added to the base mud. The names of the drilling fluid samples used in this study were abbreviated as follows:

BASE: base mud without scavenger; TRZM: triazine-based mud; IGM: iron gluconate-based mud; SWM1: 1 g-steelmaking waste-containing mud; SWM2: 2 g-steelmaking waste-containing mud; and SWM3: 3 g-steelmaking waste-containing mud.

The triazine-base scavenger is obtained as a liquid, has a density of 1.073 g/cm<sup>3</sup>, a pH of 10.5, and an average concentration of 60 vol.%. The iron gluconate-base scavenger is a water-soluble powder with a density of 0.7 g/cm<sup>3</sup>, a pH of 4.5, and an average concentration of 60 vol.%. The mineralogy, chemical composition, and particle size distribution of steelmaking waste were determined using the X-ray Diffraction (XRD), X-ray fluorescence (XRF), and particle size distribution analyzer. Steelmaking waste characterization revealed that it contains 26.5% zincite, 14.3% orthopyroxene, 8.8% lawrencite, 3% siderite, and other minerals. The key metal oxides content was identified as 43.3% ZnO, 33.8% Na<sub>2</sub>O, and 2.9% Fe<sub>2</sub>O<sub>3</sub>. The average particle size distribution ( $D_{50}$ ) of the waste was found to be 11.77 μm.

TABLE 1: Various metal-based scavengers used in drilling operations.

Chemical compound	Chemical reaction	Remarks
Copper carbonate	$\text{CuCO}_3 + \text{H}_2\text{S} \longrightarrow \text{CuS}\downarrow + \text{H}_2\text{O} + \text{CO}_2\uparrow$	It has a quick and efficient reaction, but the copper electrodeposition causes corrosion on the metal surface [28, 29, 38–40].
Copper nitrate	$\text{Cu}(\text{NO}_3)_2 + \text{H}_2\text{S} \longrightarrow \text{CuS}\downarrow + 2\text{HNO}_3$	It improves the mud rheology and filtration performance with a lower corrosion affinity [27, 41].
Zinc oxide	$\text{ZnO} + \text{H}_2\text{S} \longrightarrow \text{ZnS}\downarrow + \text{H}_2\text{O}$	They are amphoteric in nature, with predictable reactivity but larger concentrations may deteriorate mud rheology and produce flocculation and fluid loss, particularly at high pH levels [6, 37, 38, 40, 42–48].
Iron oxide	$\text{Fe}_3\text{O}_4 + 6\text{H}_2\text{S} \longrightarrow 3\text{FeS}_2\downarrow + 4\text{H}_2\text{O} + \text{H}_2$	They work better at low pH levels and help to densify the drilling fluid [24, 40, 49–55].
Iron gluconate	$\text{Fe}(\text{C}_6\text{H}_{12}\text{O}_7)_2 + \text{H}_2\text{S} \longrightarrow \text{FeS}\downarrow + 2\text{C}_6\text{H}_{12}\text{O}_7 + \text{H}_2\text{O}$	It is an ecofriendly compound with a quick reaction; however, it significantly lowers the pH and is ineffective with heavy mud weight [56–58].

TABLE 2: The prepared drilling fluid formulation.

Additive	Quantities					
	BASE	TRZM	IGM	SWM1	SWM2	SWM3
Fresh water	316 cm <sup>3</sup>	316 cm <sup>3</sup>	316 cm <sup>3</sup>	316 cm <sup>3</sup>	316 cm <sup>3</sup>	316 cm <sup>3</sup>
Defoamer	0.08 cm <sup>3</sup>	0.08 cm <sup>3</sup>	0.08 cm <sup>3</sup>	0.08 cm <sup>3</sup>	0.08 cm <sup>3</sup>	0.08 cm <sup>3</sup>
Xanthan	1 g	1 g	1 g	1 g	1 g	1 g
Starch	6 g	6 g	6 g	6 g	6 g	6 g
Sodium chloride	34 g	34 g	34 g	34 g	34 g	34 g
Caustic soda	0.25 g	0.25 g	0.25 g	0.25 g	0.25 g	0.25 g
Calcium carbonate (fine)	24 g	24 g	24 g	24 g	24 g	24 g
Calcium carbonate (medium)	36 g	36 g	36 g	36 g	36 g	36 g
Triazine-based scavenger	—	1 g	—	—	—	—
Iron gluconate-based scavenger	—	—	1 g	—	—	—
Steelmaking waste	—	—	—	1 g	2 g	3 g

2.2. *Experiments.* The effect of incorporating different quantities of the steelmaking waste on H<sub>2</sub>S scavenging capacity, rheology, alkalinity, and filtering characteristics of the mud was studied and compared to those of the base mud and commercialized scavengers.

The H<sub>2</sub>S scavenging experiments were carried out at ambient conditions. In each experiment, a volume of 10 cm<sup>3</sup> from each mud sample was placed in a burette with a gas intake from a cylinder containing 100 ppm of H<sub>2</sub>S, while the burette outlet was attached to a MultiRAE gas detector having a minimum detection limit of 0.1 ppm. At the gas entry, a flowmeter with a flow controller was employed to control the gas flowrate at 150 cm<sup>3</sup>/min. The H<sub>2</sub>S concentration in the outlet gas was continually recorded until it reached saturation (i.e., 100 ppm, which is equal to the inlet gas concentration). The test setup is depicted in Figure 1.

When the scavenger is entirely consumed (i.e., saturation is reached), the following equation [30] can be used to estimate the scavenging capacity (in mg H<sub>2</sub>S/l mud) of each mud sample.

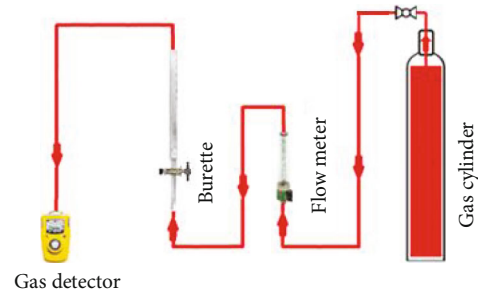


FIGURE 1: Setup for the H<sub>2</sub>S scavenging experiment.

$$\text{Saturation capacity} \left( \frac{\text{mg}}{\text{l}} \right) = \frac{Q \times \rho \times 10^{-6}}{V} \times \int_0^{t_s} (C_{\text{in}} - C_{\text{out}}) dt, \quad (1)$$

where  $Q$  is the inlet gas flowrate (150 cm<sup>3</sup>/min),  $\rho$  is the H<sub>2</sub>S density (1.391 mg/cm<sup>3</sup>),  $t_s$  represents the saturation time in

TABLE 3: Results of H<sub>2</sub>S scavenging experiments.

Mud sample	Breakthrough time (min)	Saturation time (min)	Saturation capacity (mg H <sub>2</sub> S/l mud)	Scavenging improvement (%)
BASE	20	46.5	84.3	—
TRZM	42	146	235.5	179
IGM	29.5	163	194.8	131
SWM1	61	116	172.8	105
SWM2	168	216	421	399
SWM3	213.5	363	508.3	503

minutes (when the H<sub>2</sub>S concentration in the outlet gas stream reaches 100 ppm),  $V$  is the used volume of drilling fluid (10 cm<sup>3</sup>),  $C_{in}$  is the H<sub>2</sub>S concentration in the burette's inlet (100 ppm), and  $C_{out}$  represents the time-dependent concentration in the outlet gas stream (ppm).

It is important for drilling fluids to have capable rheological performance, which was assessed by evaluating the apparent viscosity (AV), plastic viscosity (PV), yield point (YP), and gel strengths adhering to the American Petroleum Institute standard procedures at 120°F [75]. Additionally, the pH values of the prepared mud samples were determined at room temperature.

A filtration test was carried out at 250°F and a differential pressure up to 300 psi in order to assess the filtering performance and to analyze the obtained filter cake. The filtration media used in the test was a 40 μm saturated porous ceramic disc. The filtrated liquid was collected for 30 minutes, and its volume was determined. The thickness of the filter-cake was then measured.

### 3. Results and Discussion

**3.1. H<sub>2</sub>S Scavenging Test.** Table 3 summarizes the findings of the H<sub>2</sub>S scavenging experiments, and Figure 2 shows the timely recorded concentrations of the stepped out H<sub>2</sub>S gas after contacting the mud samples.

For BASE, H<sub>2</sub>S began to breakthrough after 20 minutes and reached saturation concentration after 42 minutes, yielding a scavenging capacity of 84.3 mg H<sub>2</sub>S/l of mud. Using TRZM, the H<sub>2</sub>S breakthrough and saturation periods were pushed up to 42 and 146 minutes, respectively, with a 179% improved scavenging capacity of 235.5 mg/l. IGM, on the other hand, showed H<sub>2</sub>S breakthrough and saturation times of 29.5 and 163 minutes, respectively, resulting in a 131% increase in H<sub>2</sub>S scavenging capacity to 194.8 mg/l. Adding different amounts of steelmaking waste to the base drilling fluid improved the H<sub>2</sub>S scavenging capacity and delayed the breakthrough and saturation periods to varying extents.

The addition of 1 g steelmaking waste (SWM1) raised the scavenging capacity to 172.8 mg/l, which is the double of that obtained using the base mud, with extended breakthrough and saturation periods of 61 and 116 minutes, respectively. When the waste content was increased, the scavenging performance was preferably improved, as in SWM2, the scavenging capability was tripled with 168- and 216-minute breakthrough and saturation durations, while it reached up to a 363-minute saturation period and 508.3 mg/l capacity with SWM3, showing a 503% improvement over the base mud.

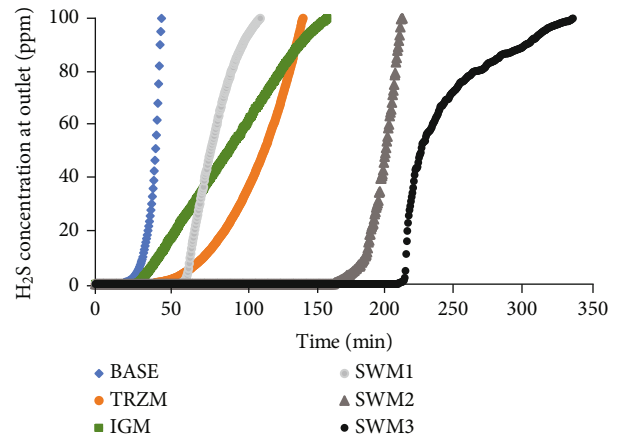


FIGURE 2: The H<sub>2</sub>S concentration in the outlet gas stream as a function of time.

Because both zinc and iron compounds are utilized as H<sub>2</sub>S scavengers in drilling operations with proven efficacy, the extraordinary scavenging performance of the steelmaking waste might be attributed to the presence of zinc and iron components in the steelmaking waste as revealed by the XRD and XRF test analyses.

According to the findings of the H<sub>2</sub>S scavenging experiments, increasing the steelmaking waste content in the water-based drilling fluid significantly boosted the mud ability to adsorb the associated H<sub>2</sub>S by driving the scavenging capacity to substantially higher levels. The effects of adding 1, 2, and 3 g of steelmaking waste on essential mud characteristics (i.e., rheology, alkalinity, and filtration) were studied and discussed hereunder.

**3.2. Rheology Measurements.** The rheological properties including the apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) were calculated using the Bingham plastic rheology model. In which the AV is one-half of the dial reading at 600 rpm, while the PV, which refers to the internal resistance to flow when force is applied, was calculated from the difference between the dial readings at 600 and 300 rpm. The YP is a measurement under flowing conditions of the electrochemical forces in the drilling mud; it was calculated by subtracting the determined PV from the dial reading at 300 rpm.

The rheology measurements (Figure 3) revealed that the base mud had an AV value of 18.7 cP, a PV of 8.8 cP, and a

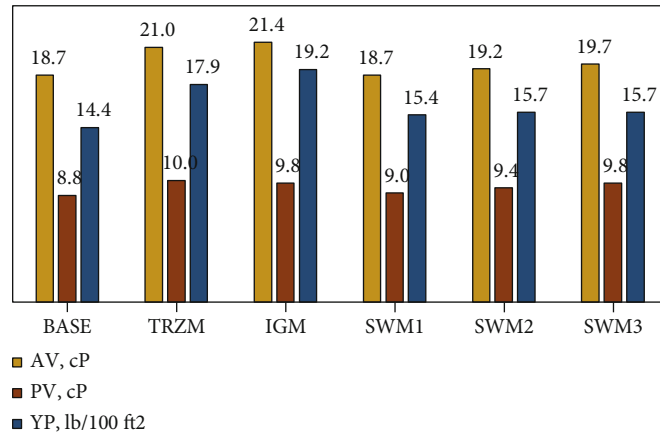


FIGURE 3: The apparent and plastic viscosities and yield points of the formulated water-based muds.

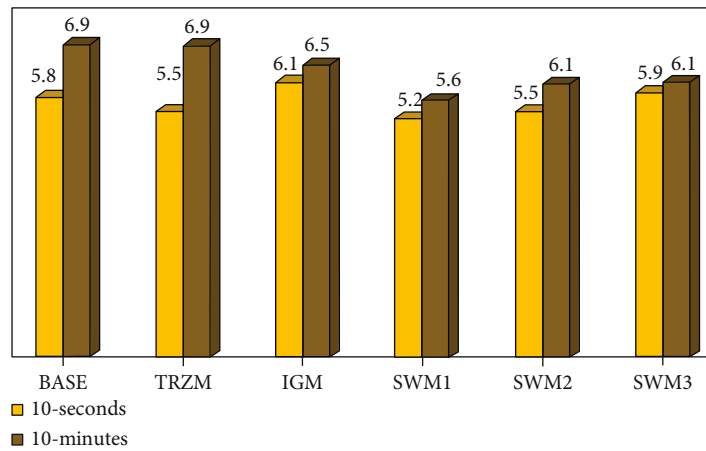


FIGURE 4: Gel strengths of the prepared mud samples.

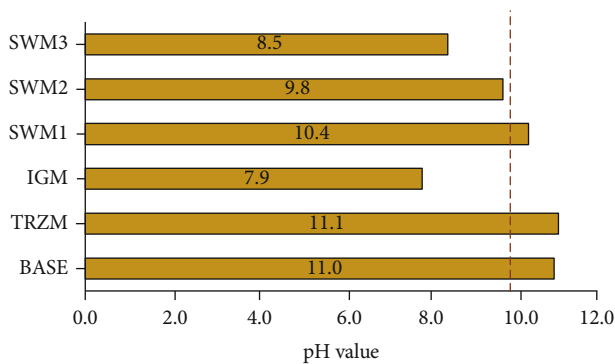


FIGURE 5: pH values of the different muds formulated in this work.

YP of 14.4lb/100 ft<sup>2</sup>. The TRZM exhibited higher AV, PV, and YP values of 21 cP, 10 cP, and 17.9lb/100 ft<sup>2</sup>, respectively. While the IGM had comparable AV and PV values to the TRZM, it had a higher YP of 19.2lb/100 ft<sup>2</sup>. On the other hand, SWM1 raised the YP to 15.4lb/100 ft<sup>2</sup> with a minor PV increase to 9 cP and no effect on AV. When the steelmaking waste content was doubled, the AV began to rise, as the SWM2 yielded 19.2 cP-AV with a PV of 9.4 cP

and a higher YP value of 15.7lb/100 ft<sup>2</sup>. Additionally, the SWM3 increased the AV and PV to 19.7 and 9.8 cP, respectively, with the same YP value as the SWM2. As displayed in Figure 4, there were no significant variations in the 10-second/10-minute gel strengths for the examined mud samples. Nevertheless, the slight reduction in gel strength values caused by the addition of steelmaking waste could be contributed to reducing the equivalent circulation density.

The rheological properties of the water-based drilling fluids have practical prescribed ranges that are: the AV is recommended to be greater than 15 cP and, preferably, in the range of 20–35 cP for better fluid loss behavior [76, 77], and the PV is recommended not to exceed 25 cP [77, 78] to minimize friction and pressure losses, while high YP values, but not exceeding 50 lb/100 ft<sup>2</sup>, are preferred [79] in order to improve the solids carrying capability. In light of the aforementioned ranges, both the TRZM and IGM muds meet the criteria. Also, increasing the steelmaking waste content aids in approaching the recommended AV value while increasing both the PV and YP. The PV increment is related to the increase in solids amount into the drilling mud [80–82]. The composition of steelmaking waste, which is similar to bentonite clay, justifies this elevation in rheological parameters [61]. In terms of the

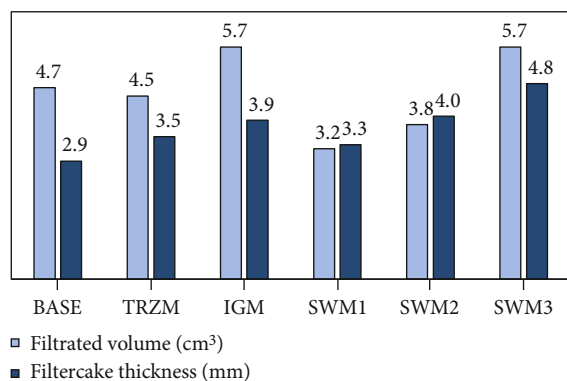


FIGURE 6: The filtration characteristics of the prepared muds.

YP/PV ratio that measures solids' carrying capacity and hole cleaning performance [83], the BASE had a value of 1.64, which was improved to 1.72 by SWM1 and 1.66 by SWM2, but lowered by SWM3 to 1.64. All values, however, satisfy the requirement of being higher than 0.75 [12, 33, 61].

**3.3. pH Measurements.** The pH tests yielded pH values of 11.0, 11.1, and 7.9 for BASE, TRZM, and IGM, respectively (Figure 5). These pH values reveal a significant drop in the mud pH in the presence of iron gluconate and a slight increase in the presence of triazine. On the other hand, the addition of 1, 2, and 3 g steelmaking waste to the base mud reduced its pH to 10.4, 9.8, and 8.5, respectively. In general, the acceptable pH range of water-based drilling fluids is in the range 9.0–11.0; yet, maintaining a pH value greater than 10 is required when drilling H<sub>2</sub>S-bearing formations [84]. As a result, the pH of SWM1 passes the pH criterion, SWM2 is near to the threshold limit of 10, and SWM3 is less than this limit. However, increasing the amount of caustic soda or any pH controller can restore the pH to the accepted level [85].

**3.4. Filtration Test.** According to the filtration experiment, steelmaking waste exhibited superior filtration efficacy in terms of fluid loss, as SWM1 reduced the filtrated liquid volume by 32%, to 3.2 cm<sup>3</sup>, compared to 4.7 cm<sup>3</sup> for the BASE (Figure 6). The improvement of mud rheology and the characteristics of steelmaking waste particles led to a faster plugging process with less filtrated volume and solids invasion, and therefore less formation damage. Similarly, SWM2 showed a 19% decrease in filtrated volume. However, increasing the amount of waste to 3 g increased the filtrated volume to 5.7 cm<sup>3</sup>. Because the thickness of the generated filter-cake is proportional to the solids content, increasing the steelmaking waste content raised the thickness, as the resulting thickness with SWM1, SWM2, and SWM3 was 3.3, 4.0, and 4.8 mm, respectively, as compared to 2.9 mm for the BASE. The TRZM, on the other hand, slightly reduced the filtration volume to 4.5 cm<sup>3</sup> and had a filter-cake thickness of 3.5 mm, while the IGM increased the filtrated liquid to 5.7 cm<sup>3</sup> and the filter-cake thickness to 3.9 mm. Practically, the amount of filtrated liquid in water-based drilling fluids should not exceed 15 cm<sup>3</sup> [86]; therefore, all prepared mud samples meet the standards.

The management of steelmaking waste, which is produced in abundant quantities by many steel manufacturers, presents substantial economic and environmental issues. By utilizing these wastes as an H<sub>2</sub>S scavenger for efficient and safe drilling operations, they are shifted from an economic and ecological burden to a valuable product. This study revealed that increasing the quantity of steelmaking waste improved the H<sub>2</sub>S scavenging capacity of the drilling fluid. Adding 2 g of waste improved mud performance in terms of alkalinity, rheological, and filtration properties. Nevertheless, the waste content can be increased to 3 g to realize the utmost scavenging capacity with practically acceptable mud performance; however, an extra alkalinity controller is necessary to supplement the associated pH drop. Moreover, preparatory testing is essential for practical implementations to account for any changes in mud composition and test parameters.

## 4. Conclusions

Various amounts of steelmaking waste (0–3 g) were employed in this study to improve the H<sub>2</sub>S scavenging ability of water-based drilling fluid. The scavenging capacity and impacts on mud characteristics were evaluated and compared to those of the base, triazine-containing, and iron gluconate-containing muds), yielding the following findings:

- (i) Increasing the amount of steelmaking waste greatly boosted the H<sub>2</sub>S scavenging capacity of the drilling fluid by 105, 399, and up to 503% with SWM1, SWM2, and SWM3, respectively
- (ii) The rheological characteristics, including AV, PV, and YP, increased to varied extents with increasing the steelmaking waste content in the mud, with 2 g providing the best carrying capacity
- (iii) The addition of steelmaking waste reduced mud pH to 10.4, 9.8, and 8.5 with SWM1, SWM2, and SWM3, respectively, compared to 11.0 for the base mud, noting that a 10 pH is recommended for drilling in sour environments and amounts of alkalinity controller could be added to restore the mud pH
- (iv) Using 1 and 2 g of steelmaking waste helped to lower the filtrated volume, unlike the SWM3 that resulted in slightly more filtrated liquid. The filter-cake thickness, on the other hand, increased as solid content increased
- (v) When compared to commercial scavengers, higher quantities of inexpensive steelmaking waste could be employed instead, yielding significantly improved H<sub>2</sub>S scavenging capacity and efficient mud performance, while meeting the practical recommended properties

## Data Availability

All the data are included in the submitted manuscript.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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## References

- [1] F. W. King, "Taking H<sub>2</sub>S from liquid sulphur-why and how," *The Oil and Gas Journal*, vol. 11, pp. 164–175, 1974.
- [2] N. N. Greenwood and A. Earnshaw, "Origin of the elements. Isotopes and atomic weights," in *Chemistry of the Elements*, pp. 1–19, Elsevier, 1997.
- [3] M. Amosa, I. Mohammed, and S. Yaro, "Sulphide scavengers in oil and gas industry – a review," *Nafta*, vol. 61, no. 2, pp. 85–92, 2010.
- [4] A. Aftab, A. Hassanpouryouzband, Q. Xie, L. L. Machuca, and M. Sarmadivaleh, "Toward a fundamental understanding of geological hydrogen storage," *Industrial and Engineering Chemistry Research*, vol. 61, no. 9, pp. 3233–3253, 2022.
- [5] Z. Jiashen and Z. Jingmao, "Control of corrosion by inhibitors in drilling muds containing high concentration of H<sub>2</sub>S," *Corrosion*, vol. 49, no. 2, pp. 170–174, 1993.
- [6] M. A. Sayyadnejad, H. R. Ghaffarian, and M. Saeidi, "Removal of hydrogen sulfide by zinc oxide nanoparticles in drilling fluid," *International Journal of Environmental Science and Technology*, vol. 5, no. 4, pp. 565–569, 2008.
- [7] E. S. Sandnes and H. O. Hundvag, "Removal of H<sub>2</sub>S in drilling mud," U.S. Patent and Trademark Office, Washington, DC, 2002.
- [8] MI-Swaco, "Corrosion," in *Engi Drill. Fluid Man.*, 2001.
- [9] C. H. Chou, J. M. Ogden, H. R. Pohl et al., "Toxicological profile for hydrogen sulfide and carbonyl sulfide," 2016, <https://stacks.cdc.gov/view/cdc/43468>.
- [10] I. M. F. Arnold, R. M. Dufresne, B. C. Alleyne, and P. J. W. Stuart, "Health implication of occupational exposures to hydrogen sulfide," *Journal of Occupational and Environmental Medicine*, vol. 27, no. 5, pp. 373–376, 1985.
- [11] A. Almeida and T. L. Guidotti, "Differential sensitivity of lung and brain to sulfide exposure: a peripheral mechanism for apnea," *Toxicological Sciences*, vol. 50, no. 2, pp. 287–293, 1999.
- [12] A. di Masi and P. Ascenzi, "H<sub>2</sub>S: a "double face" molecule in health and disease," *BioFactors*, vol. 39, no. 2, pp. 186–196, 2013.
- [13] C. Chen and W. Huang, "A study of sulfide scavenger," in *International Meeting on Petroleum Engineering*, Beijing, China, 1986.
- [14] N. P. Tung, P. V. Hung, H. D. Tien, and C. M. Loi, "Study of corrosion control effect of H<sub>2</sub>S scavengers in multiphase systems," in *SPE International Symposium on Oilfield Chemistry*, Houston, Texas, 2001.
- [15] R. D. Kane and J. B. Greer, "Sulfide stress cracking of high-strength steels in laboratory and oilfield environments," *Journal of Petroleum Technology*, vol. 29, no. 11, pp. 1483–1488, 1977.
- [16] G. Y. Grondin and G. L. Kulak, "Fatigue testing of drillpipe," *SPE Drilling and Completion*, vol. 9, no. 2, pp. 95–102, 1994.
- [17] K. T. Kembaiyan and K. Keshavan, "Combating severe fluid erosion and corrosion of drill bits using thermal spray coatings," *Wear*, vol. 186–187, pp. 487–492, 1995.
- [18] R. Stevens, M. Ke, P. H. Javora, and Q. Qi, "Oilfield environment-induced stress corrosion cracking of CRAs in completion brines," in *SPE Annual Technical Conference and Exhibition*, Houston, Texas, 2004.
- [19] W. C. Browning and H. F. Young, "Process for scavenging hydrogen sulfide in aqueous drilling fluids and method of preventing metallic corrosion of subterranean well drilling apparatuses," 1975, U.S. Patent 3,928,211.
- [20] J. Wylde, *Composition and method for scavenging sulfides and mercaptans*, U.S. Patent and Trademark Office, Washington, DC, 2016.
- [21] D. Brondel, R. Edwards, A. Hayman, D. Hill, S. Mehta, and T. Semerad, "Corrosion in the oil industry," *Oilfield Review*, vol. 6, no. 2, pp. 4–18, 1994.
- [22] C. M. Menendez, V. Jovancevic, S. Ramachandran, M. Morton, and D. Stegmann, "Assessment of corrosion under iron sulfide deposits and CO<sub>2</sub>/H<sub>2</sub>S conditions," *Corrosion*, vol. 69, no. 2, pp. 145–156, 2013.
- [23] K. Nalli, *Corrosion and its Mitigation in the Oil & Gas Industry—An Overview*, PetroMini Pipeliner, 2010.
- [24] J. D. Ray, B. V. Randall, and J. C. Parker, "Use of reactive iron oxide to remove H<sub>2</sub>S from drilling fluid," *Journal of Petroleum Technology*, vol. 31, no. 6, pp. 797–801, 1979.
- [25] L. Popoola, A. Grema, G. Latinwo, B. Gutti, and A. Balogun, "Corrosion problems during oil and gas production and its mitigation," *International Journal of Industrial Chemistry*, vol. 4, no. 1, p. 35, 2013.
- [26] G. A. Tarver and P. K. Dasgupta, "Design and development of a system to measure ambient levels of hydrogen sulfide and lower mercaptans from a mobile platform," *Atmospheric Environment*, vol. 29, no. 11, pp. 1291–1298, 1995.
- [27] S. Elkhatny, S. Basfer, R. Shawabkeh, M. Bahgat, and M. Mahmoud, "Assessment of using copper nitrate for scavenging hydrogen sulfide while drilling sour horizontal wells," *Journal of Energy Resources Technology*, vol. 141, no. 12, 2019.
- [28] L. L. Carney and B. Jones, "Practical solutions to combat the detrimental effects of hydrogen sulfide during drilling operations," in *SPE Symposium on Sour Gas and Crude*, Tyler, Texas, 1974.
- [29] O. V. W. Dyke and K. L. Wagner, "Drilling mud composition and process," 1970, 3506572.
- [30] M. Murtaza, S. A. Alarifi, A. Abozuhairah, M. Mahmoud, S. A. Onaizi, and M. Al-Ajmi, "Optimum selection of H<sub>2</sub>S scavenger in light-weight and heavy-weight water-based drilling fluids," *ACS Omega*, vol. 6, no. 38, pp. 24919–24930, 2021.
- [31] Z. B. Huang, B. S. Liu, F. Wang, and R. Amin, "Performance of Zn-Fe-Mn/MCM-48 sorbents for high temperature H<sub>2</sub>S removal and analysis of regeneration process," *Applied Surface Science*, vol. 353, pp. 1–10, 2015.
- [32] J. Wang, B. Liang, and R. Parnas, "Manganese-based regenerable sorbents for high temperature H<sub>2</sub>S removal," *Fuel*, vol. 107, pp. 539–546, 2013.
- [33] S. A. Onaizi, M. A. Gawish, M. Murtaza, I. Gomaa, Z. Tariq, and M. Mahmoud, "H<sub>2</sub>S scavenging capacity and rheological properties of water-based drilling muds," *ACS Omega*, vol. 5, no. 47, pp. 30729–30739, 2020.

- [34] H. Li, S. Su, S. Hu et al., "Effect of preparation conditions on Mn<sub>x</sub>O<sub>y</sub>/Al<sub>2</sub>O<sub>3</sub> sorbent for H<sub>2</sub>S removal from high-temperature synthesis gas," *Fuel*, vol. 223, pp. 115–124, 2018.
- [35] S. D. Matza, E. E. William, and C. Henry, "Fleming, controlling sulfide scavenger content of oil-based drilling fluid," 1989, 4805708.
- [36] T. J. Gilligan III, "Removal of hydrogen sulfide from drilling fluids," 1985, 4548720.
- [37] E. Sunde and H. Olsen, "Removal of H<sub>2</sub>S in drilling mud," 1999, 6365053B1.
- [38] O. W. Agbroko, K. Piler, and T. J. Benson, "A comprehensive review of H<sub>2</sub>S scavenger technologies from oil and gas streams," *ChemBioEng Reviews*, vol. 4, no. 6, pp. 339–359, 2017.
- [39] G. V. Chilingar, R. Mourhatch, and G. D. Al-Qahtani, "Introduction to corrosion," in *The Fundamentals of Corrosion and Scaling for Petroleum & Environmental Engineers*, pp. 1–34, Elsevier, Netherland, 2008.
- [40] R. L. Garrett, R. K. Clark, L. L. Carney, and C. K. Grantham, "Chemical scavengers for sulfides in water-base drilling fluids," *Journal of Petroleum Technology*, vol. 31, no. 6, pp. 787–796, 1979.
- [41] S. Elkatatny, R. Shawabkeh, and M. Mahmoud, "Method for drilling a hydrogen sulfide-containing formation," 2019, 10479919B2.
- [42] J. Sun, S. Modi, K. Liu, R. Lesieur, and John Buglass, "Kinetics of zinc oxide sulfidation for packed-bed desulfurizer modeling," *Energy & Fuels*, vol. 21, no. 4, pp. 1863–1871, 2007.
- [43] A. Aftab, A. R. Ismail, S. Khokhar, and Z. H. Ibupoto, "Novel zinc oxide nanoparticles deposited acrylamide composite used for enhancing the performance of water-based drilling fluids at elevated temperature conditions," *Journal of Petroleum Science and Engineering*, vol. 146, pp. 1142–1157, 2016.
- [44] A. Bagreev, S. Bashkova, D. C. Locke, and T. J. Bandoz, "Sewage sludge-derived materials as efficient adsorbents for removal of hydrogen sulfide," *Environmental Science & Technology*, vol. 35, no. 7, pp. 1537–1543, 2001.
- [45] F. E. Beck, D. E. Boone, R. DesBrandes et al., "Drilling and well completions," in *Standard Handbook of Petroleum and Natural Gas Engineering*, pp. 497–1384, Elsevier, 1996.
- [46] E. Davidson, J. Hall, and C. Temple, "An environmentally friendly, highly effective hydrogen sulphide scavenger for drilling fluids," in *SPE Annual Technical Conference and Exhibition*, Denver, 2003.
- [47] B. R. Palmer, C. Gutierrez, M.-B. Gidas, A. Berrouk, and M. W. H. Gawargy, "Rate phenomena in the reaction of hydrogen sulfide with a zinc oxide-based sorbent," *Energy*, vol. 30, no. 3, pp. 384–391, 2011.
- [48] V. S. Saji, "Research advancements in sulfide scavengers for oil and gas sectors," *Reviews in Chemical Engineering*, vol. 37, no. 6, pp. 663–686, 2021.
- [49] E. Davidson, J. Hall, and C. Temple, "A new iron-based, environmentally friendly hydrogen sulfide scavenger for drilling fluids," *SPE Drilling and Completion*, vol. 19, no. 4, pp. 229–234, 2004.
- [50] F. T. da Silva, "Hydrogen sulphide scavenging by porous magnetite," *Mineral Processing and Extractive Metallurgy*, vol. 114, no. 4, pp. 245–247, 2005.
- [51] J. F. Evers and G. A. Olson, "A comparative analysis of reactivities of commercial iron and zinc compounds used in the removal of H<sub>2</sub>S from drilling fluids," in *SPE Rocky Mountain Regional Meeting*, Salt Lake City, Utah, 1983.
- [52] I. Fox, "Method of using a reactive iron oxide drilling mud additive," 1982, 4324298.
- [53] I. Fox, "Method of using a porous Fe<sub>3</sub>O<sub>4</sub> drilling mud additive," 1977, 4008775.
- [54] H. Lin, A. King, N. Williams, and B. Hu, "Hydrogen sulfide removal via appropriate metal ions dosing in anaerobic digestion," *Energy*, vol. 36, no. 5, pp. 1405–1416, 2017.
- [55] A. Samuels and R. P. Wendt, "Proper fluid pretreatment to minimize hydrogen sulfide dangers," in *Middle East Technical Conference and Exhibition*, Bahrain, 1981.
- [56] M. Amosa, I. Mohammed-dabo, S. A. Yaro, A. O. Arinkoola, and G. O. Azeez, "Comparative analysis of the efficacies of ferrous gluconate and synthetic magnetite as sulphide scavengers in oil and gas drilling operations," *Naft*, vol. 61, no. 3, pp. 117–122, 2010.
- [57] E. Davidson, "Method and composition for scavenging sulphid in drilling fluids," 2002, 6746611B2.
- [58] C. R. Mcdaniel and C. J. Thaemlitz, "Economical method for scavenging hydrogen sulfide in fluids," 2014, 20140251922A1.
- [59] B. Das, S. Prakash, P. S. R. Reddy, and V. N. Misra, "An overview of utilization of slag and sludge from steel industries," *Resources, Conservation and Recycling*, vol. 50, no. 1, pp. 40–57, 2007.
- [60] M. Morone, G. Costa, A. Poletini, R. Pomi, and R. Baciocchi, "Valorization of steel slag by a combined carbonation and granulation treatment," *Minerals Engineering*, vol. 59, pp. 82–90, 2014.
- [61] M. I. Magzoub, M. H. Ibrahim, M. S. Nasser, M. H. El-Naas, and M. Amani, "Utilization of steel-making dust in drilling fluids formulations," *Process*, vol. 8, no. 5, p. 538, 2020.
- [62] M. Yusuf, L. Chuah, M. A. Khan, and T. S. Y. Choong, "Adsorption of nickel on electric arc furnace slag: batch and column studies," *Separation Science and Technology*, vol. 49, no. 3, pp. 388–397, 2014.
- [63] J. Nahm, "Well drilling cuttings disposal," 1994, <https://www.freepatentsonline.com/5277519.html>.
- [64] A. Hale, "Well drilling cuttings disposal," 1994, <https://www.freepatentsonline.com/5341882.html>.
- [65] M. Sayadi and S. Hesami, "Performance evaluation of using electric arc furnace dust in asphalt binder," *Journal of Cleaner Production*, vol. 143, pp. 1260–1267, 2017.
- [66] J. Wang, M. Guo, and Y. Tan, "Study on application of cement substituting mineral fillers in asphalt mixture," *International Journal of Transportation Science and Technology*, vol. 7, no. 3, pp. 189–198, 2018.
- [67] A. Loaiza and H. A. Colorado, "Marshall stability and flow tests for asphalt concrete containing electric arc furnace dust waste with high ZnO contents from the steel making process," *Construction and Building Materials*, vol. 166, pp. 769–778, 2018.
- [68] N. T. Abdel-Ghani, H. A. El-Sayed, and A. A. El-Habak, "Utilization of by-pass cement kiln dust and air-cooled blast-furnace steel slag in the production of some "Green" cement products," *HBRC Journal*, vol. 14, no. 3, pp. 408–414, 2018.
- [69] A. T. Machado, F. R. Valenzuela-Diaz, C. A. C. de Souza, and L. R. P. de Andrade Lima, "Structural ceramics made with clay and steel dust pollutants," *Applied Clay Science*, vol. 51, no. 4, pp. 503–506, 2011.



- [70] H. A. Colorado, E. Garcia, and M. F. Buchely, "White ordinary Portland cement blended with superfine steel dust with high zinc oxide contents," *Construction and Building Materials*, vol. 112, pp. 816–824, 2016.
- [71] Y. Jiang, T.-C. Ling, C. Shi, and S.-Y. Pan, "Characteristics of steel slags and their use in cement and concrete—A review," *Resources, Conservation and Recycling*, vol. 136, pp. 187–197, 2018.
- [72] M. Ahmaruzzaman, "Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals," *Advances in Colloid and Interface Science*, vol. 166, no. 1-2, pp. 36–59, 2011.
- [73] Z. B. Bouabidi, M. H. El-Naas, D. Cortes, and G. McKay, "Steel-making dust as a potential adsorbent for the removal of lead (II) from an aqueous solution," *Chemical Engineering Journal*, vol. 334, pp. 837–844, 2018.
- [74] M. Omran and T. Fabritius, "Utilization of blast furnace sludge for the removal of zinc from steelmaking dusts using microwave heating," *Separation and Purification Technology*, vol. 210, pp. 867–884, 2019.
- [75] Americal Petroleum Institute, *Field Testing Water-Based Drilling Fluids*, American Petroleum Institute, Washington, DC, 5th edition, 2019.
- [76] J. K. Fink, "Fluid loss additives," in *Oil Field Chemicals*, pp. 34–57, Elsevier, Netherlands, 2003.
- [77] S. Perween, N. K. Thakur, M. Beg, S. Sharma, and A. Ranjan, "Enhancing the properties of water based drilling fluid using bismuth ferrite nanoparticles," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 561, pp. 165–177, 2019.
- [78] A. R. Ismail, A. Aftab, Z. H. Ibupoto, and N. Zolkifile, "The novel approach for the enhancement of rheological properties of water-based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads," *Journal of Petroleum Science and Engineering*, vol. 139, pp. 264–275, 2016.
- [79] A. Katende, N. V. Boyou, I. Ismail et al., "Improving the performance of oil based mud and water based mud in a high temperature hole using nanosilica nanoparticles," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 577, pp. 645–673, 2019.
- [80] A. Aftab, M. Ali, M. Arif et al., "Influence of tailor-made TiO<sub>2</sub>/API bentonite nanocomposite on drilling mud performance: towards enhanced drilling operations," *Applied Clay Science*, vol. 199, article 105862, 2020.
- [81] A. Aftab, A. R. Ismail, and Z. H. Ibupoto, "Enhancing the rheological properties and shale inhibition behavior of water-based mud using nanosilica, multi-walled carbon nanotube, and graphene nanoplatelet," *Egyptian Journal of Petroleum*, vol. 26, no. 2, pp. 291–299, 2017.
- [82] A. Aftab, A. R. Ismail, Z. H. Ibupoto, H. Akeiber, and M. G. K. Malghani, "Nanoparticles based drilling muds a solution to drill elevated temperature wells: a review," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 1301–1313, 2017.
- [83] G. V. Chilingarian, E. Alp, R. Caenn et al., "Drilling fluid evaluation using yield point-plastic viscosity correlation," *Energy Sources*, vol. 8, no. 2-3, pp. 233–244, 1986.
- [84] D. R. Carter and N. J. Adams, "Hydrogen sulfide in the drilling industry," in *SPE Deep Drilling and Production Symposium*, Amarillo, Texas, 1979.
- [85] J. Maxey, "Rheological analysis of static and dynamic sag in drilling fluids," *Annual Transactions-Nordic Rheology Society*, vol. 15, no. 181, 2007.
- [86] M. Amanullah, J. Ramasamy, M. K. Al-Arfaj, and S. Aramco, "Application of an indigenous eco-friendly raw material as fluid loss additive," *Journal of Petroleum Science and Engineering*, vol. 139, pp. 191–197, 2016.