Influence of Weighting Materials on the Properties of Oil-Well Cement

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ABSTRACT: The integrity of oil and gas wells is largely dependent on the cement job. Maintaining the properties of the cement layer throughout the life of a well is a difficult task, particularly in high-temperature and pressure conditions such as those in deep wells. Cementing deep wells require slurries with high densities. Heavyweight cement systems are those designed with weighting materials. These materials have a higher specific gravity in comparison to cement. The purpose of this work is to investigate the influence of weighting materials on the properties of Class G oil-well cement and to make necessary recommendations for their use. The rheology, fluid loss, gas migration, and dynamic elastic properties of three cement slurries containing different weighting materials, namely, hematite, barite, and ilmenite, were studied. The results indicate that cement slurry designed with barite exhibits the best rheological behavior that would provide a perfect solution for deep wells where cement placement is a concern. The barite slurry had the lowest plastic viscosity. The plastic viscosity of the hematite and ilmenite-weighted systems was higher by 11.5 and 12.4%, respectively. The barite-based slurry also had the highest yield point of 84.3 lb/100 ft², whereas the yield points of hematite and barite cement were 37.9 and 29.5 lb/100 ft², respectively. Furthermore, the gel strengths of barite cement were the highest, with 10 s and 10 min gel strengths of 11.5 and 39.5 lb/100 ft², respectively. Ilmenite had the most positive impact on fluid loss control, which would be appropriate in high permeable formations. It had a fluid loss of 66 mL/30 min, lower than those of the hematite (80 mL/30 min) and barite (82 mL/30 min) systems. Furthermore, the best dynamic elastic properties were exhibited by the ilmenite system, with the smallest Young’s modulus (27.3 GPa) and the highest Poisson ratio (0.252). This would make the ilmenite to be very useful in developing heavyweight cement composites that could withstand severe external loads imposed on the casing and cement. The hematite cement was the most impermeable to gas migration, with a gas volume of 127.8 cm³, whereas the volume measured in the barite and ilmenite systems were 20.9 and 78% higher, respectively. This makes the hematite to be very useful in deep gas wells where gas migration control is important.

1. INTRODUCTION

During well cementing, the cement slurry is circulated through the casing to a desirable height between the outside of the casing and open hole wall. The cement sheath must carry the casing weight and support any load applied to it, isolate-producing intervals, protect the casing from corrosive fluids, and suppress abnormal pore pressures. Without proper isolation of troublesome zones, the well might never achieve its maximum potential of production. Oil-well cementing is one of the most important drilling operations. The design of cement slurry usually includes several additives that play different roles in achieving a cement layer with high integrity. For instance, high-strength and low-permeability cement can be designed by admixing silica flour. Accelerators may be incorporated to reduce setting time while retarders are used to delay it. Extenders decrease slurry density, dispersants reduce viscosity, and fluid loss agents minimize leakage of the aqueous phase of cement, while defoamers prevent foaming. Due to the high temperature, the cement hydration proceeds very fast, which forces the use of extenders to extend the setting time. However, to decrease the bonding time of cement, the most used accelerator is calcium chloride. It is required to design the cement slurry through many standardized steps to ensure a high-quality cement layer.

In the deep wells, it is a requirement to use high-density cement systems. Cement slurries with a density of 17 ppg and higher may be used in the case of an unstable borehole, zones with high formation pressures, and deformable sections. The cheapest way to increase cement density is by decreasing the

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quantity of water. However, API Spec 10 B2 recommends a water-to-cement ratio of 44% in primary cementing, resulting in slurries with a density of about 16.5 ppg. Heavyweight cement-based systems are very hard to mix and pump without dispersant. An ideal weighting material must be inert and have uniform particle size distribution and greater specific gravity in comparison to the cement. These materials are mostly used in drilling muds to overcome high pore pressure. Since deep oil wells are characterized by high formation pressure, it is essential to use heavyweight materials such as hematite, barite, and ilmenite in oil-well cement.

Hematite (Fe₃O₄) has a specific gravity of about 4.9–5.3. It is a naturally occurring mineral with a brick-red color. Admixing hematite particles can raise the density of the cement to 22 ppg. Hematite was initially introduced due to the challenges faced with barite. However, hematite has an abrasive impact on equipment, but this issue can be avoided using a powder of size less than 45 μm.

Barite (BaSO₄) is a light-gray material. Its specific gravity changes between 4.0 and 4.5 and can increase the slurry density up to 18 ppg. Barite is the most used weighting material for drilling mud; however, it is rarely used in cement slurries due to its high requirement for water, which leads to a reduction in compressive strength. Ilmenite (FeTiO₃) is a naturally occurring mineral with a black to dark color. It has a specific gravity between 4.5 and 5. Even though the specific gravity of ilmenite is slightly less than that of hematite, it does not require extra water and yields a similar density increment as hematite at equivalent concentrations. Ilmenite and hematite have a slight impact on the thickening time and compressive strength. Additionally, ilmenite has a lower percentage of toxic metals and high abrasiveness in comparison to barite due to its coarser particle size. However, this abrasiveness can be reduced using micronized ilmenite.

Weighting materials can influence the rheological properties of the drilling fluid. This effect on the rheological properties is also applicable in cement. In addition, heavyweight materials influence the fluid loss tendencies of cement systems. A high fluid loss reduces the quality of cement-based systems. Extreme filtration quantity can result in clogging the zone near the well and, therefore, increase the time required to induce the production and decrease the efficiency of the well. Controlling fluid loss improves viscosity, reduces formation damage, and decreases annular bridging. Weighting materials have poor gas migration control characteristics because of sedimentation issues. Gas migration is one of the most common problems in drilling operations. It can lead to poor zonal isolation, increased annular pressure at the surface, a decline in production rate, increased gas/water cut, and blowout. Hence, it is very important to test the cement slurry on a gas analyzer to optimize the cement process. Proper cleaning of the annular space before the process of cementation provides the necessary tightness on the contact between the rock formation, the cement sheath, and the casings, which mitigate the gas migration.

Although weighting materials significantly affect the properties of oil-well cement, only a few studies have been performed to examine the influence of some of these materials on some of the cement properties. The objective of this work is to examine the influence of three different weighting materials on several oil-well cement properties such as rheological properties (plastic viscosity, yield point, and gel strength), fluid loss, gas migration, and dynamic elastic properties (Young’s modulus and Poisson’s ratio).

The sequences of the coming sections of the paper are as follows: first, the used weighting materials and the type of cement will be characterized in Section 2.1. Then, the procedure of preparing the cement slurries is explained in Section 2.2. After that, the methodology of measuring each cement property is described in Section 2.3. Then, the results of every cement property is discussed in Section 3. Finally, this research is concluded in Section 4 with the advantages of each weighting material.

2. RESULTS AND DISCUSSIONS

2.1. Rheological Properties. The results show that the weighting materials have different effects on cement rheology. Figure 1 compares the plastic viscosity of the slurries investigated. The ilmenite slurry had the highest plastic viscosity of 388.7 cP, followed by the hematite cement, which had a plastic viscosity of 385.4 cP. The heavyweight system containing barite had the lowest plastic viscosity of 345.7 cP (10.3% less than that of the hematite cement). Low plastic viscosity is preferable, as such a cement system would have a low resistance to flow.

The results of the yield point of the cement slurries are depicted in Figure 2. The results indicated that the ilmenite-based cement had the lowest yield point of 29.6 lb/100 ft². The hematite cement had a yield point of 37.9 lb/100 ft², whereas the yield point of barite-based cement was the highest, with a value of 84.3 lb/100 ft². The high value of yield point in the barite slurry improved the carrying ability of cement slurry

Figure 1. Influence of weighting materials on the plastic viscosity of cement.

Figure 2. Influence of the weighting materials on the yield point of cement.
in the dynamic conditions compared to the other two weighting materials.

The effect of the weighting material on the gel strengths was also investigated in Figures 3 and 4. The gel strengths of the ilmenite cement were the lowest, with a 10 s gel of 10.5 lbf/100 ft² and a 10 min gel of 35 lbf/100 ft². The hematite cement system had 10 s and 10 min gel strengths of 11.2 and 36.4 lbf/100 ft², respectively. The highest gel strengths, the 10 s gel of 11.5 lbf/100 ft² and 10 min gel of 39.5 lbf/100 ft², were recorded with the barite system. These high values of the gel strength in the barite system enhance the carrying ability of cement slurry and help the cement to resist gas invasion in the static conditions.

### 2.2. Fluid Loss

The effect of the weighting materials on fluid loss is presented in Figure 5. The barite slurry had the highest fluid loss (82 mL/30 min), followed by the hematite system (80 mL/30 min). The fluid loss of the ilmenite system (66 mL/30 min) was 17.9% less than that of the hematite slurry. This phenomenon of the low rate of fluid loss observed in the system designed with ilmenite was due to the ability of differential pressure to compress the smaller quantity of particles present in the cement slurry with ilmenite effectively, thus ensuring good hydration of cement. It should be mentioned that all three weighting materials were in the acceptable range of the fluid loss since the range of fluid loss rate for cementing accepted by the industry is 100 cm³/30 min.

### 2.3. Gas Migration

It was observed that weighting materials affect gas migration in heavyweight cement systems (Figure 6). The gas breakthrough in ilmenite started only after 4 min and reached its maximum volume of 227 cm³ in 18 min. Gas migration in the barite slurry began after 8 min and reached its maximum volume of 154 cm³ in 15 min. The lowest volume of migrated gas was recorded in the hematite slurry. Gas invasion in the hematite system was mostly constant at a low volume of 9 cm³ for about 21 min and reached its maximum volume of 128 cm³ in 24 min. Cement systems with low gas volume have better zonal isolation.

It should be mentioned that the three weighting material systems could not prevent gas migration as depicted by their high volume of migrated gas shown in Figure 6. This is because of the low hydrostatic pressure of cement, which was less than the gas pressure after the initial setting time. This low value of cement hydrostatic pressure is due to the reduction of the water volume inside the cement matrix. There are two main phenomena that contribute to this reduction in water volume. The first is the hydration of the cement and the second is the fluid loss to the formation. While it is hard to control the first phenomenon, it is possible to control fluid loss. It is commonly accepted that a cement slurry fluid loss of less than 50 mL/30 min would be enough to mitigate gas migration. However, the fluid loss in the three weighted cement was greater than 65 mL/30 min, as demonstrated in Figure 5. Therefore, to prevent or mitigate this gas migration, it is recommended to reduce the amount of slurry fluid loss by increasing the used fluid loss additive. Another way for mitigating the gas migration is using expansion additives for better bonding of cement in the contact area of cement-casing and cement-formation or using nanoparticles such as nanosilica to prevent gas migration. Also, a combination of hematite and Micromax (manganese tetroxide) with expansion additives and

![Figure 3](https://doi.org/10.1021/acsomega.0c04186) Influence of the weighting materials on the 10 s gel strength of cement.

![Figure 4](https://doi.org/10.1021/acsomega.0c04186) Influence of the weighting materials on the 10 min gel strength of cement.

![Figure 5](https://doi.org/10.1021/acsomega.0c04186) Influence of weighting materials on the fluid loss of cement.

![Figure 6](https://doi.org/10.1021/acsomega.0c04186) Influence of weighting materials on the gas migration of cement.
silica flour could greatly reduce the amount of gas migration as explained by Al-Yami and Al-Humaidi.  

2.4. Dynamic Elastic Properties. Figure 7 compares dynamic Young’s modulus of the hardened pastes of each cement composite. The barite and hematite systems had similar Young’s modulus of approximately 33.4 GPa, whereas the ilmenite system exhibited the lowest Young’s modulus of 27.3 GPa. This value is 18% less than the values measured with barite- and hematite-based systems.

The effect of these materials on dynamic Poisson’s ratio is shown in Figure 8. The hematite cement had the lowest Poisson’s ratio of 0.236. The Poisson ratio of the barite cement was 0.245. The ilmenite cement had the highest Poisson ratio of 0.252. This value was 6.8% greater than that measured on the hematite cement.

The low value of Young’s modulus and high Poisson ratio recorded for the ilmenite cement imply that the system is more flexible, enhancing its resistance against external loads such as those subjected to cement sheath during perforation.

3. CONCLUSIONS

The influence of three weighting materials (hematite, barite, and ilmenite) on the properties of Class G cement was evaluated. The evaluated properties were rheology (plastic viscosity, yield point, and gel strengths), fluid loss, gas migration, and dynamic elastic properties (Young’s modulus and Poisson’s ratio). The following were observed.

- Barite had the most favorable effect on rheology.
- Ilmenite heavywight cement had the lowest fluid loss.
- Ilmenite had the best dynamic elastic properties in terms of Young’s modulus and Poisson’s ratio.
- The hematite system had the lowest gas volume and hence the best control of gas invasion.

The results from this study could serve as a guide in selecting the best weighting material for specific wellbore conditions. For instance, the barite-weighted cement system due to its enhanced rheology would provide an excellent solution for deep wells where cement placement is a concern. The ilmenite on the other hand due to its ability to reduce the volume of fluid loss would be suitable in high permeable intervals. Additionally, because of the high elasticity of the ilmenite-weighted cement, ilmenite would be very useful in developing heavyweight cement composites that could withstand severe external loads imposed on the casing and cement. In deep gas wells, where gas migration control is important, hematite would be useful due to its low permeability to gas.

4. MATERIALS AND METHODOLOGY

4.1. Materials. Three cement slurries were formulated with Class G cement, fluid loss, silica flour, retarder, dispersant, defoamer, water, and weighting materials. The proportion of each composition is listed in Table 1. The three weighting materials were used in various quantities to maintain a constant 18 ppg slurry density. The first cement system is the hematite slurry, which was prepared with 32.9% by weight of hematite (BWOC) of hematite, the second slurry contained 37.6% BWOC of barite, and the third slurry was prepared with 36.3% BWOC of ilmenite.

![Figure 7. Influence of the weighting materials on Young’s modulus of cement.](image1)

![Figure 8. Influence of the weighting materials on Poisson’s ratio of cement.](image2)

Table 1. Cement Slurries Composition

| component   | hematite-weighed slurry | barite-weighed slurry | ilmenite-weighed slurry |
|-------------|-------------------------|-----------------------|-------------------------|
| Class G cement | 100                     | 100                   | 100                     |
| fluid loss  | 0.5                     | 0.5                   | 0.5                     |
| silica flour | 35                      | 35                    | 35                      |
| retarder    | 1.5                     | 1.5                   | 1.5                     |
| dispersant  | 0.25                    | 0.25                  | 0.25                    |
| defoamer    | $4.7 \times 10^{-7}$    | $4.7 \times 10^{-7}$  | $4.7 \times 10^{-7}$    |
| water       | 44                      | 44                    | 44                      |
| hematite    | 32.9                    | 0                     | 0                       |
| barite      | 0                       | 37.6                  | 0                       |
| ilmenite    | 0                       | 0                     | 36.3                    |

Table 2. Specific Gravity of Materials

| materials    | specific gravity (SG) |
|--------------|-----------------------|
| Class G cement | 3.15                   |
| hematite (Fe₂O₃) | 4.95                  |
| barite (BaSO₄)  | 4.20                   |
| ilmenite (FeTiO₃) | 5.10                  |

Table 3. Price of Weighting Materials

| weighting material | cost ($ per pound) |
|--------------------|--------------------|
| hematite           | 0.27               |
| barite             | 0.09               |
| ilmenite           | 0.36               |
Since the objective was to prepare the slurries at the same density, the specific gravities of the cement and heavyweight agents were critical. The specific gravities of the cement and weighting materials are listed in Table 2.

A comparison between the three weighting materials should also consider the cost to study the economic aspects of selecting these materials. According to a service company, the prices vary as shown in Table 3. For instance, the most expensive material is ilmenite, which costs $0.36/lb, followed by hematite, which costs $0.27/lb, whereas barite has the cheapest price of $0.09/lb.

The wet dispersion unit ANALYSETTE 22 Nano Tec plus instrument was used to determine the particle size distribution of hematite, barite, ilmenite, and cement (Figure 9). The median size ($D_{50}$) of Class G cement and barite are 12.15 and 11.65 μm, respectively. The $D_{50}$ (9.41 μm) of hematite falls between those of barite and ilmenite. The smallest material is the ilmenite with a median size of 8 μm.

To compare the elemental composition of the three weighting materials and Class G cement, the X-ray fluorescence (XRF) technique was used. The XRF results indicate that hematite is mainly composed of Fe (95.8%), as shown in Figure 10. The main element in the barite is Ba with 70% concentration, as demonstrated in Figure 11. However, ilmenite is mainly composed of two minerals Fe and Ti with concentrations of 55.9 and 37%, respectively, as displayed in Figure 12. The Class G cement has Ca as the main component in a concentration of 15.5% as depicted in Figure 13.

### 4.2. Slurry Preparation

The three cement slurries were prepared based on the procedure of the American Petroleum Institute.\textsuperscript{13,35} First, Class G cement was dry-mixed with silica flour and the weighting material. Then, the water was placed in

![Figure 9](image-url). Particle size distribution for (a) Saudi Class G cement, (b) barite, (c) hematite, and (d) ilmenite. The blue arrows in this figure indicate the $D_{50}$.

![Figure 10](image-url). Composition of hematite by XRF.
the mixer and the additives were added one by one. Afterward, the dry mix was added to the mixer where the mixing was kept at 12,000 RPM for around 1 min.

After mixing, the slurries were poured into an atmospheric consistometer for conditioning to simulate the bottom hole conditions. The consistometer was run at a speed of 150 RPM and a temperature of 200 °F for 20 min. After conditioning, the slurries were poured into different equipment based on the required test such as the rheology test, filtration test, and gas migration test.

4.3. Properties Measurements. The prepared samples were tested to investigate the influence of each weighting material on the cement properties such as rheology, fluid loss, gas migration, and elastic properties. The procedure for each test is summarized in the following subsections.

4.3.1. Rheology Test. The influence of weighting materials on the cement rheological properties such as yield point (YP), plastic viscosity (PV), 10 s (10 s) gel strength, and 10 min (10 min) gel strength was examined. These properties guide the flow behavior of cement slurries. The rheological properties were measured using the 900 viscometer, and the values of shear stress were recorded at several shear rates including 3, 6, 100, 200, and 300 rpm. The average of the values between the ascending and descending readings was used.

4.3.2. Fluid Loss Test. The fluid loss test is performed to describe the water or fluid content that is separated from the slurry during 30 min of residence time at a pressure of 100 psi and ambient temperature. A substantial volume of fluid loss leads to gas migration and an increase in pumping pressure, which causes more losses and subsequently high slurry viscosity. The HTHP filter press apparatus was used in this study.

After slurry conditioning and heating up the cell of the filter press, the cement sample was carefully transferred into the cell. A 100 psi backpressure was applied to prevent the vaporization...
of the filtrate. The filtration volume was recorded at various periods ranging between 30 s and 30 min.

4.3.3. Gas Migration Test. Gas migration studies were performed at a pressure and temperature of 1000 psi and 250 °F, respectively. The cell has a piston and a mesh screen at the bottom of the piston to simulate the permeable formation on the top of the cement. There is also another mesh screen at the bottom of the cell to simulate the permeable formation below the cement slurry. A pressure of 1000 psi was applied on the piston to simulate the downhole condition during a cementing operation where drilling fluids or spacers apply pressure on top of the cement. Nitrogen gas was injected at 500 psi to simulate high-pressure zones. A backpressure of 300 psi was used to simulate the well pressure formation below. The device records overburden hydrostatic pressure, backpressure, and nitrogen injection pressure. These pressures are constant throughout the test. The device also records variable parameters like pore pressure, temperature, and piston movement.

4.3.4. Dynamic Elastic Properties Test. After conditioning, the slurries were poured into cylindrical metallic molds with a diameter of 1.5” and a length of 4”. Afterward, the slurries were cured at a temperature of 300 °F and pressure of 3000 psi for 24 h using a high-pressure/high-temperature curing chamber. The effect of weighting materials on the elastic properties (Young’s modulus and Poisson ratio) of the hardened cement was studied. The ultrasonic velocities such as P-waves and S-waves were measured using the sonic mode. These ultrasonic velocities provide the dynamic elastic properties at room temperature and atmospheric pressure.

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Notes
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