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ORIGINAL PAPER - PRODUCTION ENGINEERING

Enhancing the cement quality using polypropylene fiber

Salaheldin Elkatatny[1] · Rahul Gajbhiye[1] · Anas Ahmed[1] · Ahmed Abdulhamid Mahmoud[1]

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Abstract

Durability and long-term integrity of oil well cement are the most important parameters to be considered while designing the cement slurry, especially in the high-pressure and high-temperature (HPHT) environments. In this study, the effect of adding the polypropylene fiber (PPF) to Saudi Class G cement is evaluated under HPHT conditions. The effect of the PPF on the cement compressive and tensile strength, thickening time, density, free water, porosity, and permeability was studied. The effect of the PPF particles on the cement sheath microstructure was studied through powder X-ray diffraction (XRD) and scanning electron microscope. The results obtained showed that PPF did not affect the cement rheology, density, and free water. The addition of PPF considerably decreased the thickening time and improved the tensile and compressive strength of the cement. 0.75% by weight of cement (BWOC) of PPF reduced the thickening time by 75%, from 317 to 78 min. The compressive strength of the cement increased by 17.8% after adding 0.5% BWOC of PPF, while the tensile strength increased by 18% when 0.75% of PPF is used which is attributed to the formation of stable forms of calcium silicate hydrates because of the ability of PPF to accelerate cement hydration process as indicated by the XRD results. The ability of the PPF to decrease the cement thickening time along with its ability to improve the cement strength suggests the use of PPF as an alternative for silica floor in shallow wells where a reduction in thickening time will decrease the wait on cement time. Porosity and permeability of the base cement were also decreased by incorporating PPF because of the pores filling effect of PPF particles as indicated by the microstructure analysis.

Keywords Cement · Fiber · Polypropylene fiber · Quality · High-temperature · Compressive strength

Abbreviations

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
Bc	Bearden units of consistency
BWOC	By weight of cement
HPHT	High pressure and high temperature
OWC	Oil well cement
PPF	Polypropylene fiber
ppg	Pounds per gallon
mD	Milli-Darcy

✉ Rahul Gajbhiye
rahulg@kfupm.edu.sa

Salaheldin Elkatatny
elkatatny@kfupm.edu.sa

Anas Ahmed
anaspetrol@hotmail.com

Ahmed Abdulhamid Mahmoud
eng.ahmedmahmoud06@gmail.com

[1] Department of Petroleum Engineering, College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Introduction

After the oil or gas well is drilled, it must be cased and cemented to withstand the formation pressure. The cemented casing in the borehole could add more stability to the wellbore and allows post cementing operations to be performed safely, it could also achieve zonal isolation and prevent fluids communication behind the casing (Parcevaux and Sault 1984; Bourgoyne et al. 1986; Shahriar 2011).

The producing well performance depends largely on the quality of the primary cementing job. Poor quality of cement slurry and solidified cement matrix behind the casing may lead to the need for remedial cementing which will significantly increase the operational cost of the well. Proper laboratory job simulation is needed to select the best composition of the cement slurries to ensure a successful cement job (Calvert and Smith 1990).

Portland cement experiences many structural changes when subjected to high-temperature conditions (i.e., higher than 230 °F), such a phenomenon is known as strength retrogression (Taylor 1997; Luke 2004; Nelson and Guillot 2006). These changes influence the cement matrix compressive strength, promote the evolutions of micro-cracks caused by cement shrinkage under the thermal stresses; therefore, it could increase the cement matrix permeability, and hence, drastically decrease its durability and strength (Shahriar 2011; Ugwu 2008).

Al-Buraik et al. (1998) discussed the challenges associated with a shallow gas zone located at 400–1000 ft below the surface. After setting the casing and cementation, the gas migrated to the surface indicating that the cement did not hold in place. To overcome this issue, it was decided to design a cement to set quickly once it is pumped. This was done by using lightweight latex slurry, and quick-setting cement was designed which reduced fluid loss and shorten thickening time. The limitation was the low compressive strength and the chance of flash setting while pumping. To achieve successful and safe cementing operations, the cement slurry should be designed to withstand the gas flux during and after quick placement in the formation Rogers et al. (2004).

There were several studies conducted on cement to improve its properties and to make it usable at different reservoir conditions in a cost-effective manner. Recently, several new materials were introduced to improve the properties of both the cement slurry and solidified cement sheath such as nanoclay, foam, ash, microsphere, beads, and fibers.

Several previous studies suggested the use of different types of fibers such as the Wollastonite, organic, monofilament, and silicic fibers to improve properties of oil well cement at different conditions, the evaluated fibers were able to improve the strength (Shi et al. 1995; Heinold et al. 2002; Morris et al. 2003; Iremonger et al. 2015) and mitigate the loss circulation (Elmoneim et al. 2000; Ilyas et al. 2012; Al Maskary et al. 2014; Arshad et al. 2014) of the cement.

The synthetic polypropylene fiber (PPF) has been used for soil reinforcement at lab scale where it confirmed high ability to improve the compressive and tensile strengths of the soil (Santoni et al. 2001; Yetimoglu and Salbas 2003; Yetimoglu et al. 2005; Khattak and Alrashidi 2006; Tang et al. 2007; Viswanadham et al. 2009). PPF is also able to reduce the soil shrinkage properties and enabled to mitigate the soil biological and chemical degradation (Musenda 1999; Puppala and Musenda 2000; Vasudev 2007).

The previous studies confirm that fibers could improve the wellbore integrity by enhancing the cement mechanical properties and reducing the loss circulation. Recently, with the need to drill very deep wells as well as the necessity to use thermal techniques to improve oil recovery, the need to have a cement that can withstand into these high-temperature and high-pressure (HPHT) environments increased drastically (Mahmoud et al. 2018; Mahmoud and Elkatatny 2019a; Mahmoud et al. 2019); therefore, there were continuous efforts to investigate the newly developed fibers which can sustain the HPHT condition and improve the cement performance.

This study aims to evaluate the applicability of using the PPF as a complementary additive to improve the properties of the slurry and solidified Saudi Class G oil well cement under the high-pressure and high-temperature (HPHT) conditions usually encountered in oil or gas well.

Experimental procedures

In this study, the cement slurries were prepared and tested according to the American Petroleum Institute standard procedure (API 2013). The materials used in this study, the cement slurry preparation procedures, and the evaluated properties of the cement slurry and cement matrix are discussed in the following sections.

Cement slurry preparation and additives

The cement slurries were prepared in this study as a mixture of Saudi Class G cement, silica flour, extender, retarder, friction reducer, fluid loss control agent, anti-foaming agent, PPF, and water. High sulfate resistance Saudi Class G cement with a specific gravity of 3.14 and the chemical composition as characterized by powder XRD summarized in Table 1 were used in this study. The cement slurries were prepared with silica flour, extender, retarded, friction reducer, fluid loss control agent, and ant anti-foaming additives provided by a service company.

PPF is synthetically prepared polypropylene fiber with the physical properties and specifications summarized in Table 2. PPF particles used in this study have a triangular-shaped structure that provides a higher surface area and

Table 1 Chemical composition of Saudi Class G cement

Phase	wt%
Silica (SiO_2)	21.6
Alumina (Al_2O_3)	3.6
Iron oxide (Fe_2O_3)	4.9
Calcium oxide, total (TCaO)	64.22
Magnesium oxide (MgO)	1.6
Sulfur trioxide (SO_3)	2.5
Loss on ignition	0.6
Insoluble residue	0.5
Equivalent alkali (as Na_2O)	0.48

Table 2 Commercialized PPF specifications (Madhavi et al. 2015; Patel et al. 2015)

Property	Value
Cut length	6–12 mm (high surface area)
Fiber shape (triangular cross section)	Special for aggregated cement holding improvement
Tensile strength	4000–6000 kg/cm^2 (56,000–85,000 psi)
Melting point	Greater than 250 °C (482 °F)

Fig. 1 PPF structure

higher flexural strength than the ordinary rounded shape fibers as shown in Fig. 1 (Park et al. 2003; Liu et al. 2012).

Figure 2 illustrates the main mechanism of the fiber for creating a mesh network which could improve the strength of the cement as well as further control of circulation losses. PPF could also effectively improve the cement resistance to shrinkage cracking, prevent initiation and propagation of the micro-cracks, improve cement matrix flexural strength, reduce the surface water absorption and the cement permeability, and improve the durability of cement.

The previous discussion indicates that PPF may improve the oil-well cement quality and could be considered as a complementary additive for oil well cement. Unlike concrete, oil-well cement preparation, placement, and subsurface environment are completely different. Also, the results of the concrete are not directly applicable to the oil well cement; hence, it is important to examine the use of PPF for enhancing oil-well cement quality.

Table 3 summarizes the concentration of the additives used to prepare the base cement slurry which has 0% BWOC of PPF, to prepare the PPF-based cement slurries 0.25, 0.5, 0.75% BWOC of the PPF were added to the base cement. The cement properties were also tested for a slurry prepared using only Saudi Class G cement and fiber without any other additive to evaluate the effect of including PPF alone.

Evaluated properties

The prepared cement slurries have been tested for the density, thickening time, free water separation and rheological properties, the cement matrix properties of the microstructure, compressive and tensile strengths, porosity, and permeability were also evaluated. Samples preparation and the conditions of every test will be discussed in the next sections; all properties were evaluated according to the API standards (API 2013, 2019).

Cement density

The pressurized fluid density balance was used to measure the cement slurries density. After conditioning the cement slurries at 194 °F, it was directly poured into the measuring cell, the cell was then pressurized until all the trapped air is removed, after that the cement density is measured.

Rheological properties

A high-temperature (HT) variable speed rheometer was used to measure the cement slurry rheological properties of the yield point, plastic viscosity, and gel strength.

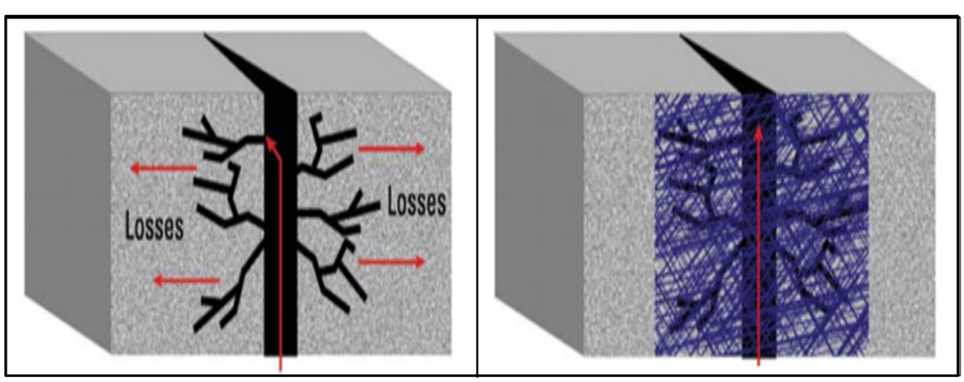

Fig. 2 Fiber mechanism on creating the mesh network to control the loss circulation (Messier et al. 2003)

Table 3 Composition of the base cement slurry used in this study

Additives	Concentration (%BWOC)
Silica flour	35
Extender	1
Retarder	1.5
Friction reducer	0.4
Fluid loss controlling agent	0.7
Anti-foaming agent	0.01
Water	44

Thickening time

The HPHT consistometer was used to evaluate the slurry thickening time. The time needed for all the cement slurries with the concentrations of 0%, 0.25%, 0.5%, and 0.75% BWOC of PPF to reach 100 Bearden units of consistency (Bc) at 9300 psi and 228 °F was recorded as the slurry thickening time.

Free water separation

Free water was measured using a graduated cylinder after slurry conditioning for 20 min at 194 °F. The cement slurry was poured into the graduated cylinder, the top of the cylinder was covered with aluminum foil, then the slurry was kept for 2 h, after that the water volume present on the top of cement which represents the free water content for the specific slurry was measured.

Microstructural analysis

XRD and SEM techniques were used to study the changes in the microstructure of the solidified cement matrix caused by the addition of the PPF. The changes in the cement hydration products were studied by the powder XRD, while the changes in the cement sheath pore structure and topography were investigated by the scanning electron microscope (SEM) technique. All samples studied in this section were cured for 24 h at 292 °F and 3000 psi, after that were removed and the samples studied by XRD were grinded to form a powder.

The main hydration products of the pure Portland cement mixed with water are the portlandite ($Ca(OH)_2$ or CH), different calcium silicate hydrates (C–S–H) such as CSH ($CaSiO_{4.3}H_2O$), C_2SH_2 ($CaSiO_{4.2}H_2O$), and $C_3S_2H_3$ ($Ca_3(HSiO_4)_{2.2}H_2O$) (Brouwers 2004; Bahafid et al. 2017), ettringite ($3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}32H_2O$) (Abid et al. 2015), and unhydrated products of C_2S and C_3S may exist with a very low concentration (Duguid et al. 2011). When silica flour is mixed with the cement, the hydration products and their concentrations will considerably change especially under the HPHT conditions of 292 °F and 3000 psi considered in this study. The addition of silica flour to the cement usually leads to disappearance of the CH peaks while the specific peak of SiO_2 usually appears compared to the products of the neat cement hydration as shown in Fig. 3a for the base cement with 35% of silica; Fig. 3a also indicates that the peaks of the CH and C_2SH were almost disappeared while the C–S–H appeared in the form of $C_5S_6H_5$ (tobermorite) and peaks of SiO_2 still appear in the XRD pattern. $C_5S_6H_5$ is more stable at high-temperature conditions than CH, the needle shape of the $C_5S_6H_5$ enables its particles to combine, and hence, it will form an ideal network structure for the solidified cement sheath as indicated by the SEM image in Fig. 4a.

The addition of the PPF particles leads to disappearance of the CH peaks after 24 h of cement hydration as shown in Fig. 3b–d. This indicates that the PPF can accelerate the cement hydration process, as indicated in Fig. 3b–d that the quartz and C–S–H peaks are increasing with the PPF concentration and they are all greater than the C–S–H peaks for the base cement shown in Fig. 3a. The increase in C–S–H concentration combined with the disappearance of the CH is expected to enhance the cement strength due to the ability of the C–S–H particles to interweave and bond with each other to form a perfect network structure after the cement is solidified as shown in Fig. 4b–d and reported earlier by Mahmoud and Elkatatny (2019b).

Compressive strength

The conditioned cement slurry was used to prepare cubical samples with 2 in. edge using cubical molds. The molds were placed in the HPHT curing vessel at 292 °F and 3000 psi for 24 h. The cured cubes were then used to measure the cement compressive strength through the crushing technique and following the American Society for Testing and Materials standard ASTM C109/C109M (ASTM 2016) and (API 2019). Three samples which represent every specimen were used for compressive strength measurement, and the average compressive strength of the three samples was considered as the specimen compressive strength.

Brazilian tensile strength

To determine the tensile strength, the prepared slurries were poured into cubical metallic molds with 2 in. edge and then cured at 292 °F and 3000 psi for 24 h using the HPHT curing chamber, core plugs of 1 in. in diameter and 0.5 in. in length were cored out of the cubical samples, the core plugs were then loaded diametrically which caused a tensile deformation perpendicular to the loading direction, and this yielded a

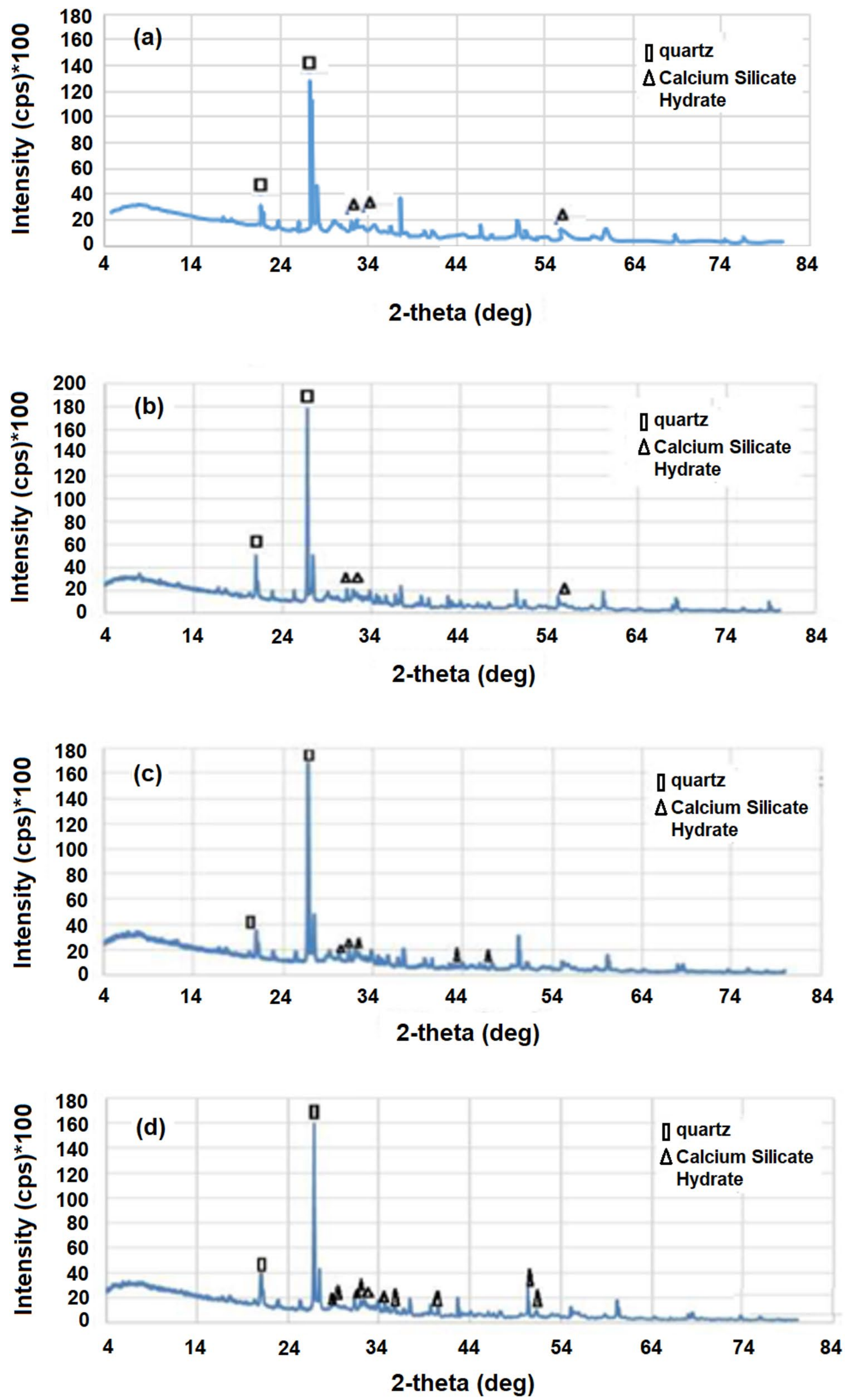

Fig. 3 XRD patterns for the hydrated **a** base cement, **b** 0.25% PPF cement, **c** 0.50% PPF cement, and **d** 0.75% PPF samples, after 24 h of curing at 292 °F and 3000 psi

tensile failure as shown in Fig. 5. The ultimate load the core sample could withstand before failure was recorded; then, the load and the sample dimensions were used to calculate the Brazilian tensile strength of the cement samples. The reported tensile strength in this study is the average strength of three specimens.

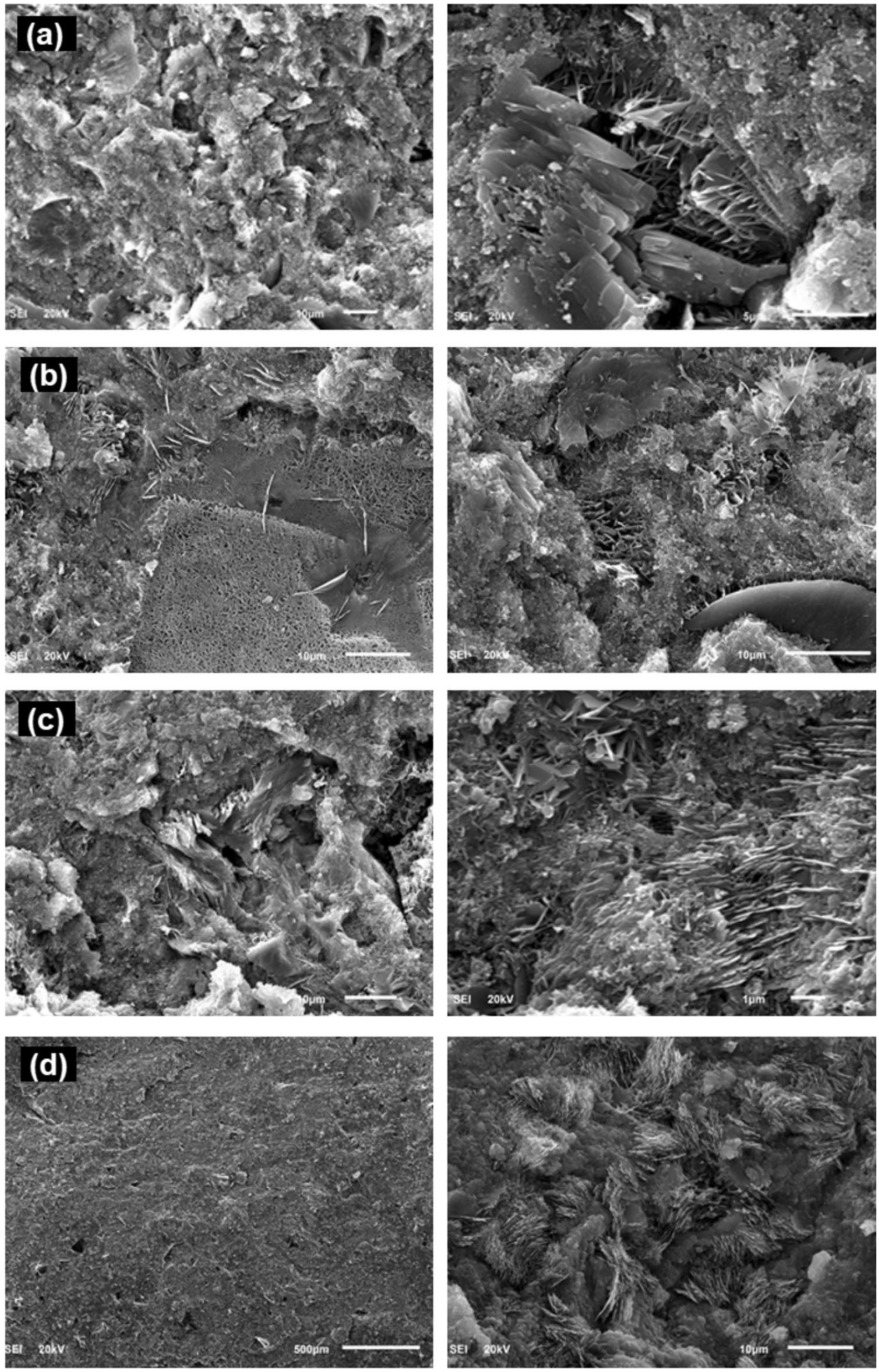

Fig. 4 SEM images for the hydrated **a** base cement, **b** 0.25% PPF cement, **c** 0.50% PPF cement, and **d** 0.75% PPF cement, after 24 h of curing at 292 °F and 3000 psi

Porosity and permeability

Cement cubes with 2 in. edge are prepared following the same procedure used to prepare the samples used for compressive strength testing; then, cement plugs with 1 in. in diameter and 1 in. in length were drilled from the cured cubes. The automated Porosimeter–Permeameter (AP-608) was used to measure the porosity and gas permeability of the cement plugs under a confining pressure of 500 psi.

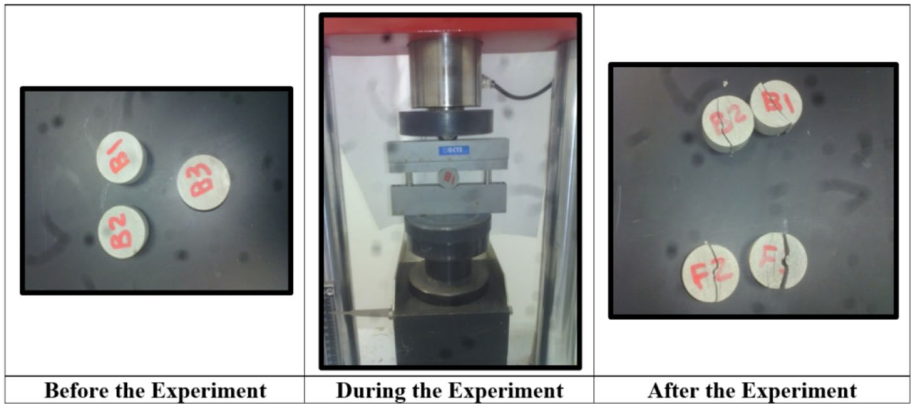

Fig. 5 Left: the disk-shaped specimens cut from the cement plugs. Middle: cement cylindrical sample while subjected to load across its circumference for the tensile strength measurement. Right: cement cylinders after the Brazilian tensile strength testing

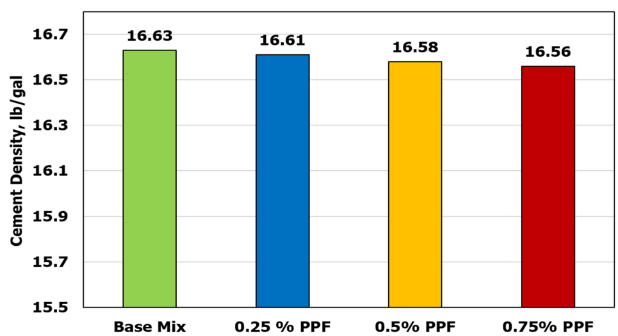

Fig. 6 Effect of adding PPF on the cement density

Results and discussion

Density and rheological properties

Figure 6 summarizes the results of the cement slurry density. The base cement slurry has a density of 16.60 lb per gallon (ppg), the addition of the PPF decreased the cement density linearly with a very small rate as shown in Fig. 6. The PPF-based sample with 0.75% PPF density is 16.56 ppg, which is only 0.4% less than the base sample density. This small decrease in the cement slurry density could help on improving the slurry displacement process; therefore, it enhances zonal isolation before cement solidification.

The base cement has a plastic viscosity and yield point of 263 cP and 6 lb/100 ft^2, respectively, its gel strengths at 10 s and 10 min are 6 and 23 lb/100 ft^2, respectively. Table 4 shows that adding the PPF to the base cement slightly changed the plastic viscosity of the base cement, adding 0.75 BWOC PPF to the base cement reduced the plastic viscosity by 0.4%. In general, reduction in viscosity is better for cement pumpability (Elkatatny 2019; Mahmoud et al. 2019). The same effect was noted for the yield point, adding 0.75 BWOC of the PPF to the base cement increased its yield point from 6 to 7 lb/100 ft^2. PPF has a negligible effect on the gel strength of the base cement as shown in Table 4.

Based on these results, it can be concluded that incorporating the PPF to the base cement has a minor effect on the density and rheology of the cement slurry.

Thickening time

Figure 7 summarizes the thickening time results. The initial consistencies of the cement slurries of 0%, 0.25%, 0.5%, and 0.75% BWOC of PPF are 40, 55, 56, and 65 Bc, respectively. As shown in Fig. 7, a considerable decrease in the cement slurry thickening time was achieved by incorporating the PPF into the base cement slurry. The thickening time for the base slurry was 5 h and 17 min, it reduced to 3 h and 26 min by adding 0.25% BWOC of PPF, and then only slightly decreased to 3 h and 10 min by the 0.5% PPF-based slurry, the 0.75% PPF slurry has the lowest thickening time of 1 h and 18 min which is 75% less than the thickening time of the base slurry. This result is attributed to the ability of the PPF particles to accelerate the cement hydration process (Mahmoud and Elkatatny 2019c) which leads to reduce

Table 4 Rheological properties of cement slurries with different percentages of PPF

Property	0% PPF	0.25% PPF	0.5% PPF	0.75% PPF
Plastic viscosity (cP)	263	261	260	253
Yield point (lb/100 ft^2)	6	6	7	7
10-s gel strength (lb/100 ft^2)	6	6	5	5
10-min gel strength (lb/100 ft^2)	22	23	23	25

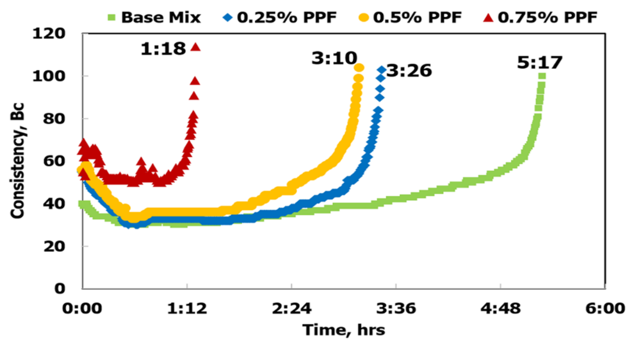

Fig. 7 Thickening time for the cement slurries of 0%, 0.25%, 0.5%, and 0.75% PPF

the time needed for the cement to solidify. Accelerating the cement solidification is one of the biggest concerns when it comes to drilling shallow wells. These results give the PPF a great chance to be used in cementing shallow wells.

The time required for the cement slurries to reach consistencies of 40, 70, 100 Bc is compared in Fig. 8. For all cement slurries, the time difference between the consistencies of 40 Bc and 70 Bc is very long compared to the time difference between the consistencies of 70 Bc and 100 Bc. So, during the cement design process, the 70 Bc should be considered as an indicator that the cement is becoming unpumpable since the time difference required to reach the 100 Bc after reaching the 70 Bc is considerably short.

Free water separation

All the cement slurries considered in this work were tested for the free water separation, the results of these tests showed that addition of the PPF to the base slurry resulted in a free water separation of zero which is the same conclusion when base cement is used. Prevention of free water formation is very important to ensure formation homogeneous cement matrix, which is needed to achieve good zonal isolation.

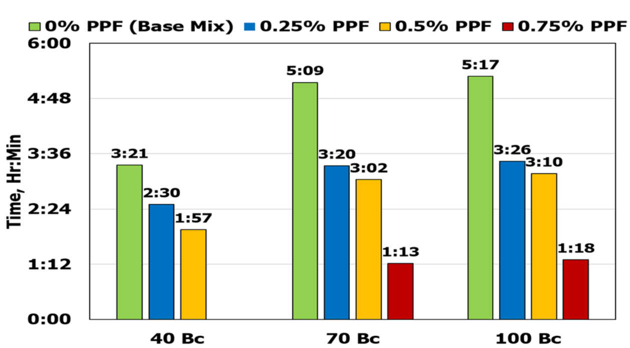

Fig. 8 Time to reach 40 Bc, 70 Bc, and 100 Bc for slurries of 0%, 0.25%, 0.5%, and 0.75% PPF

Compressive strength

Figure 9 compares the compressive strength results. The base cement compressive strength of 6246 psi was increased to 6726 psi by adding 0.25% of the PPF to the base cement, this enhancement in the cement compressive strength is attributed to the high silica content of the PPF which enabled acceleration the pozzolanic reaction and formation more C–S–H products as confirmed by the XRD results. Same results were confirmed by Mahmoud and Elkatatny (2019b). The addition of 0.5% of the PPF increased the base cement strength by 35.03% to reach 8434 psi as shown in Fig. 9.

To assess the impact of PPF on the compressive strength of the cement, another set of experiments was conducted. Three cement samples with Saudi Class G cement only, Saudi Class G with 35% BWOC of the silica flour, and Saudi Class G with 0.5% BWOC of the PPF were prepared. These samples were cured for 1 day at 200 °C and 3000 psi. The samples were then removed kept in water at room condition for 24 h and then crushed to find their compressive strength.

Figure 10 shows that adding 35% silica flour to Saudi Class G cement increased the cement compressive strength from 4198 psi (for the sample with Saudi Class G cement only) to 4461 psi while adding 0.5% BWOC of the PPF to Saudi Class G cement increased the compressive strength from 4198 to 4949 psi. These results confirmed the effect of adding PPF on the compressive strength. These results in addition to the thickening time results suggest the use of the PPF as an alternative material for the silica floor in shallow wells. For shallow wells, using 0.5% BWOC of PPF without the need for any other additives could enhance the compressive strength of the cement and also reduce the thickening time.

Tensile strength

The four cement systems with PPF of 0%, 0.25%, 0.5% and 0.75% BWOC have been subjected to the tensile strength test. It was observed that the addition of the PPF particles

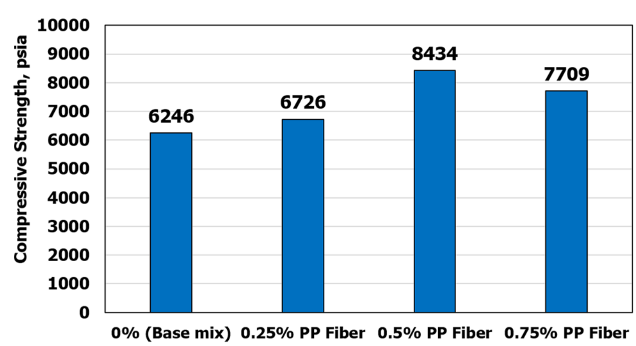

Fig. 9 Cement matrix compressive strength

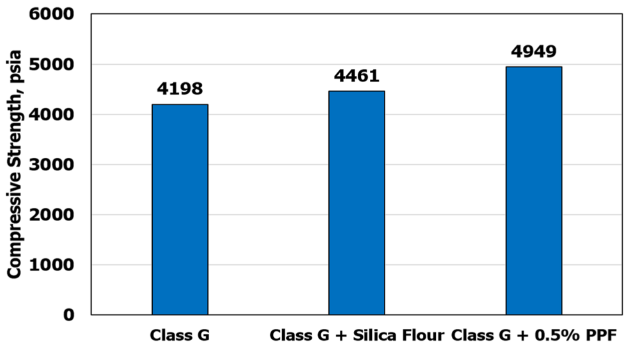

Fig. 10 Effect of adding silica flour and PPF on the compressive strength of Saudi Class G

improved the tensile strength of the base cement (i.e., without PPF). The base cement has a tensile strength of 1333 psi; the tensile strength is increased linearly with the PPF concentration. The 0.75% BWOC of the PPF improved the tensile strength of the base cement by 18% (1574 psi) as shown in Fig. 11.

Porosity and permeability

Table 5 summarizes the porosity and permeability of the cement samples with 0, 0.25, 0.5, and 0.75% BWOC of PPF after 24 h of curing at 292 °F and 3000 psi. It was observed that both porosity and permeability of the cement decreased by adding the PPF. The porosity of base cement was 27.49% which was reduced to 25.09% and 24.56% by adding 0.25% and 0.5% BWOC of PPF, respectively. The addition of 0.75% BWOC of PPF decreased the porosity of the base cement by 16.8% to reach 22.86%.

A considerable decrease in the base cement permeability was observed after incorporating the PPF. The base cement permeability of 0.0023 mD was decreased to 0.0010 mD when 0.75% PPF is added, with a reduction of 56% compared with the base cement sample.

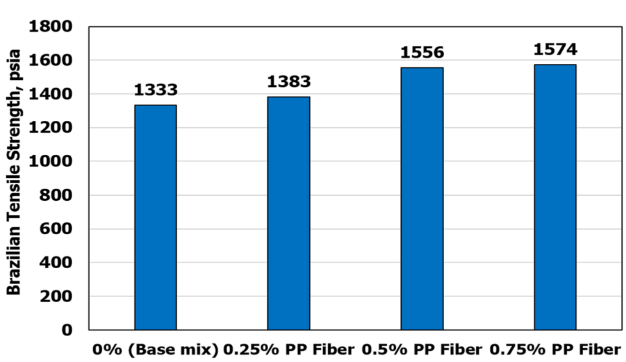

Fig. 11 Brazilian tensile strength for the cement matrices of 0%, 0.25%, 0.5%, and 0.75% PPF

Table 5 Porosity and permeability of cement samples with different percentages of PPF

Property	Base mix	0.25% PPF	0.5% PPF	0.75% PPF
Porosity (%)	27.49	25.09	24.56	22.86
Permeability (mD)	0.0023	0.002	0.0014	0.001

The effect of the PPF on the cement porosity and permeability is attributed to the fact that the PPF particles fill the capillary porous, and hence, decreased the pore spaces present in the solidified cement body as confirmed by the SEM results shown earlier in Fig. 4.

Additional cost to prepare one barrel of the new PPF-based cement

In this section, the additional cost to prepare one barrel of the new PPF-based cement will be discussed. The cost of the PPF is $2.67/kg, if the slurry with the maximum PPF concentration (i.e., 0.75% BWOC of PPF) is considered for cost calculations, to prepare one barrel of the slurry with a density of 16.56 ppg (as shown earlier in Fig. 6) and PPF concentration of 0.75% BWOC; 2.366 kg of the PPF is needed. So, the additional cost of the cement slurry with 0.75% BWOC of PPF is $6.32/barrel of slurry.

Conclusions

Extensive experimental work was conducted to assess the effect of using polypropylene fiber (PPF) with the base cement under high-pressure and high-temperature (HPHT) conditions. Based on the obtained results, the following conclusions can be drawn:

- The microstructural analysis confirmed the ability of the PPF to effectively fill the capillary pores of the cement, so a dense cement structure is formed.
- Adding PPF to the base cement has a negligible effect on cement density, rheological properties, and free water content.
- The PPF contributed to the increase in the resistance to the axial and perpendicular loads which causes improvement in the cement compressive and tensile strengths. 0.5% by weight of cement (BWOC) of the PPF increased the compressive strength of Saudi Class G cement by 17.8%, 0.75% of the PPF increased the cement tensile strength by 18%.
- From the thickening time test, it is observed that PPF acts as an accelerator as it speeds up the hydration reaction which suggests the ability to use the PPF as an alterna-

tive material for silica floor in cementing shallow wells. Adding 0.75% BWOC of PPF to the base cement reduced the thickening time by 75%.

- The addition of the PPF decreased the porosity and permeability of the cement matrix by filling the matrix pores and blocking the interconnection between the pores inside the cement matrix. The base cement porosity and permeability decreased by 16.8% and 56% by adding 0.75% of the PPF.

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