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Original scientific paper

Improving mechanical properties of oil well cement using polypropylene fibers and evaluating a new laboratory method for measuring the casing cement bonding strength

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Abstract

The main objective of this study is to enhance the poor performance of oil well cement in terms of mechanical properties by using pure polypropylene fibers. Polypropylene fibers were added in increasing concentrations from 0 to 0.1%, 0.3%, 0.5%, 0.7%, and 0.9% by weight of cement (BWOC). Rheological parameters, density, fluid loss, permeability, porosity, compressive strength, tensile strength, and flexural strength were all tested. A new method for measuring the tensile strength of cement samples in the presence of a casing is also evaluated in this research. In addition, the interfacial bonding shear strength, which represents the strength of cement adhesion to the casing, was measured using a new laboratory procedure. The influence of adding polypropylene fibers on rheology, density, and fluid loss can be ignored, according to the results of the experiments. The permeability and porosity of cement samples increased as the proportion of polypropylene fibers increased, according to the findings. Further, an increase in polypropylene fibers concentration up to 0.3%BWOC led to improving the mechanical properties at different curing times. The bonding strength of the casing cement interface improved with increasing polypropylene fibers concentration up to 0.5% BWOC.

Keywords:
well cement; rheology; mechanical properties; polypropylene fiber; casing cement bonding strength

1. Introduction

In the oil and gas industry, well integrity is of paramount importance (**Iyer et al., 2022**). The primary cementing process is one of the operations performed during oil and gas drilling and it is integral to the integrity of the well. It is worth noting that the term (cement) means dry cement powder, the mixture of cement, water, and additives is called (cement slurry), and after the cement has hardened is called (cement sheath). In this operation, the cement slurries are pumped into the annulus space between the casing string and the formation (**Lavrov, 2017**). The primary cementing operation provides sufficient protection for the casing from corrosion as well as good zonal isolation for the drilled formations. It also helps to prevent the communication between formations that have different fluids and pressures and prevents the flow of gas through this annulus towards the surface, which has serious environmental impacts. This cement slurry is made of Portland cement and water. Class G Portland cement is the type most used for oil wells around the world (**Barnes and Bensted, 2002**). Portland cement can withstand downhole conditions but not all of them. Generally, the mixture of only Portland cement and water can be applied in wells with downhole circulating temperatures up to 50 – 52°C, depending on the time required to finish the cement job (**Broni-Bediako et al., 2016**), and this calls for using some additives to the cement slurry which help to control the different properties (**Song et al., 2018**). Therefore, extender additives are used to reduce the density of cement slurry like (bentonite, attapulgite, expanded perlite, gilsonite, crushed coal, ground rubber, fly ash, diatomaceous earth, microspheres, microsilica, and sodium silicate) which allow the addition of more water or lightweight materials to the slurry to lighten the mixture and to keep the cement solids from separating, heavy weight agents are used to increase the density of cement slurry which helps to restrain high formation pressures like (hematite, ilmenite, and barite), fluid loss additives are used to reduce fluid loss volume like (cellulose, and polyvinyl alcohol), lost circulation additives are used to avoid lost circulation problem like (ground coal, and ground walnut shell), accelerator additives are used to reduce the thickening time like (calcium chloride, sodium chloride, sodium metasilicate, potassium chloride, gypsum…etc), retarder additives are used to increase the thickening time like (lignosulfonate, and sugars derivatives), expansion additives are used to prevent cement shrinkage like (calcium oxide, and magnesium oxide), antifoam agents are used to prevent foam generation in a cement slurry like (polyethylene glycols), and dispersants are used to decrease the cement slurry viscosity like (sodium salt of polynapthalene sulphonate, etc.) (**Broni-Bediako et al., 2016**). These additives sometimes affect the

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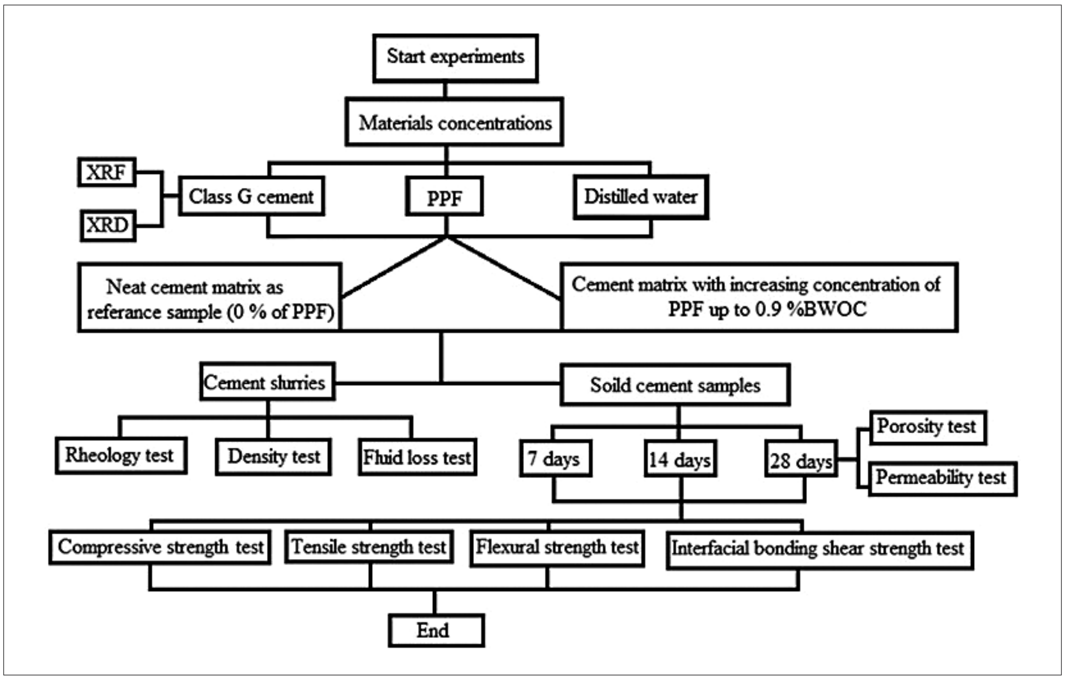

Figure 1: Flowchart of the research methodology.

mechanical properties of well cement by disrupting the production of calcium silicate hydrate (C-S-H) and also the generation of Portlandite in the cement sheath which gives cement its strength (**Heinold et al., 2002; Li et al., 2017**). There are many stresses that well cement may be exposed to during the production period of the well, including tensile stress, compressive stress, and bending stress (**Arjomand et al., 2018**). For this reason, it is important to obtain mechanical properties strong enough to counteract these stresses. Current studies on well cement focus on developing mechanical properties to increase the ability of a cement sheath to resist these stresses by using a wide range of additives (**Adjei and Elkatatny, 2021; Li et al., 2015; Teodoriu et al., 2012**). Microcracks can appear in the well cement sheath during the early life of the oil well and decrease the bonding strength at the interface between the cement and the casing due to the use of high concentration expansion additives (**Al Hammad and Altameimi, 2002**). This increases the cost of maintenance of the well and causes problems, such as gas migration and casing damage (**Zhu et al., 2014**).

Polymers are among the additives that the current studies focus on due to their diversity and distinctive properties. Polypropylene fibers have been industrially developed for use in the construction industry to improve the strength of set cement or concrete. These fibers have unique properties that make them suitable for downhole conditions such as alkali and acid resistance, non-absorptive, and high heat resistance. Polypropylene fibers are generally available in 6mm and 12mm lengths (**Bagherzadeh et al., 2012**). According to a review of the current literature, numerous experiments have been conducted to investigate and use polypropylene fibers on concrete properties (**Al-Tameemi and Mahdi, 2021; Mashrei et al., 2018; Najimi et al., 2009; R. A. S., 2006**). However, there is a limited number of studies that have addressed the use of this kind of manufactured fibers in other practical fields. **Khalaf and Federer (2021)** studied the impact of using polypropylene fibers as an additive to water-based mud. Also, some well cementing studies have been carried out to investigate the effect of polypropylene fibers on well cement under HPHT conditions at a single curing time (**Elkatatny et al., 2019; Ahmed et al., 2018**). These experiments' results showed that using polypropylene fibers does not show any change in the physical properties including (the cement slurry rheology, the cement slurry density, and free water volume), also the porosity values and permeability values of the solid cement samples were decreased but, on another hand, the mechanical properties including (the compressive strength and tensile strength) of solid cement samples were significantly enhanced. Those studies were limited to studying the mechanical properties of samples that had been aged for only 24 hours and did not discuss the effect of these fibers after the completion of cement hardening. It is known that cement needs 28 days to complete solidification. No study has been done before about the impact of adding polypropylene fibers to well cement on the flexural strength and cement casing bonding strength.

This study discusses the possibility of using polypropylene fibers as an additive for well cement in different concentrations through a comprehensive experimental work that includes physical and mechanical properties and studies the effect of this additive at different curing

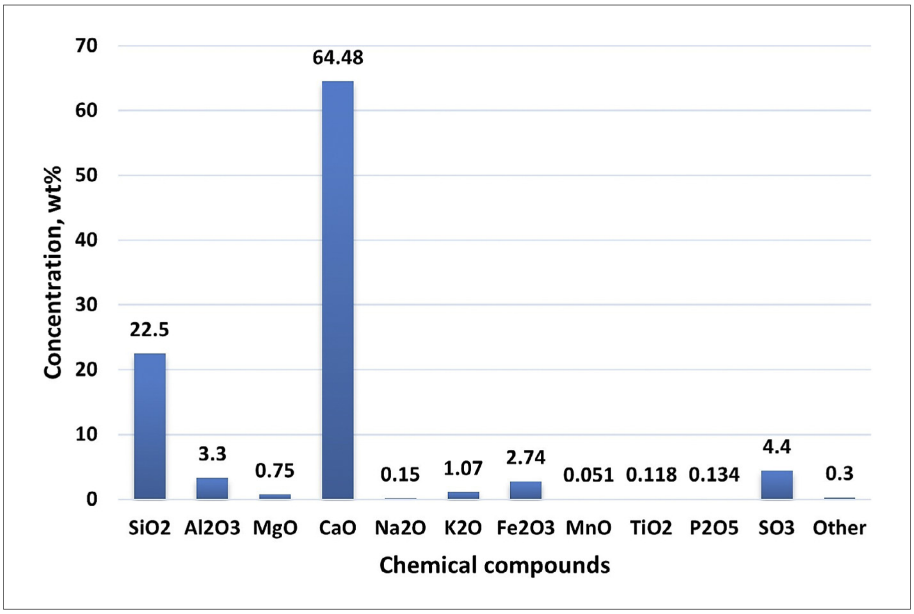

Figure 2: The chemical composition of cement Class G obtained by XRF analysis

times. Also, this study discusses a novel laboratory method to measure the interfacial casing cement bonding strength, which helps to give a clear idea of the possibility of employing polypropylene fibers in oil well cementing. Through this study, an attempt is made to determine the optimal concentration of polypropylene fibers (PPFs) that achieve the best performance of the cement sheath during the life of the well.

2. Experimental work

Figure 1 depicts the methodology of the experimental research.

2.1. Materials

The cement slurries were prepared using Portland cement Class G. This class of Portland cement is typically used in oil and gas well cementing. The chemical composition of the Class G cement employed in this study was determined by X-ray fluorescence (XRF) as shown in **Figure 2**. From the figure it can be seen that Class G cement contains calcium oxide with a high percentage (64.48%) compared to the other oxides involved in the composition of this class. **Figure 3** shows the mineralogy of the neat cement powder which was determined by X-ray powder diffraction (XRD) using Bruker D8 Discover XRD SAXS XRR with long-fine focus tube radiation operating at 50 kV voltage and 50 mA current. Using HighScore software, a crystallographic analysis was performed on the identified minerals in the database PDF. In light of the findings of the analysis, the identified phases are (gypsum, brownmillerite, hatrurite, anhydrite, larnite, quartz, and andradite aluminium) which are the main minerals components of Class G Portland cement. **Figure 4** shows the structure of PPFs that was used as an additive to well cement at increasing dosage (0, 0.1, 0.3, 0.5, 0.7, and 0.9) in percent by weight of cement (%BWOC). These PPFs have important properties such as alkali and acid resistance, non-absorptive, and high heat resistance. **Table 1** displays the technical properties of the PPFs provided by the EAMIC company (manufacturer).

2.2. Preparation of cement slurry

A standard composition of cement slurry was prepared according to API standards as a reference cement sample for this study. **Table 2** summarizes the dosage of the components needed to prepare a cement slurry containing Portland cement Class G, distilled water with water/cement ratio of 0.44, and PPFs. No need to use any other additives to determine the actual effect of adding PPFs on the different properties of well cement. There are no standard procedures for adding PPF during the preparation of cement slurry. Therefore, when preparing the cement slurry for this study, the solid components including cement and the designed concentrations of the PPF were hand-premixed for five minutes to ensure a homogeneous distribution of the PPFs within the cement powder. The mixture was then poured into an OFITE Waring Commercial blender containing distilled water and blended at 4,000 rpm for 15 seconds. Finally, the mixing speed was increased to 12000 rpm for 35 seconds. The cement slurry was prepared at ambient temperature (24°C) and atmospheric pressure conditions.

2.3. Measurement of rheological properties, density, and fluid loss volume

Rheology is the critical parameter that should be determined in order to evaluate the pumpability and estimate the pumping power required during the cement job. The rheological parameters of cement slurries were measured using the Fann Model 35 viscometer, accord-

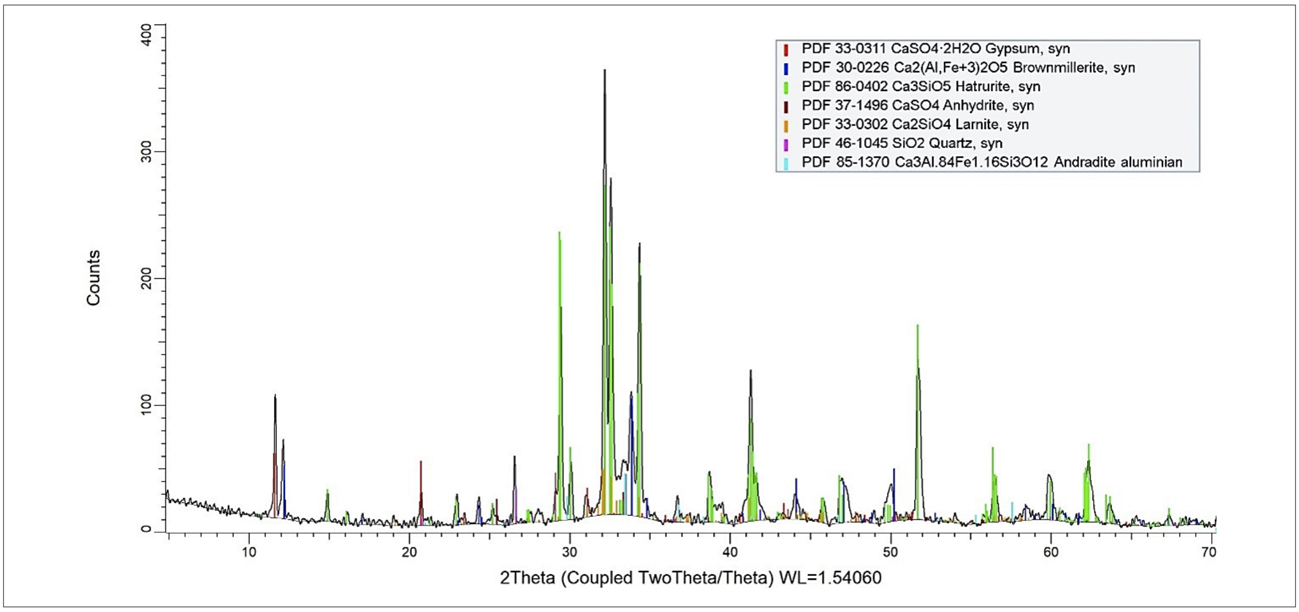

Figure 3: XRD measurement for cement class G

Figure 4: PPFs structure manufactured by the EAMIC company

Table 1: The technical properties of the PPFs manufactured by the EAMIC company

Appearance	White individual fiber
Fiber Length (mm)	12
Thickness (µm)	32
Cross Section	Round
Tensile Strength (N/mm^2)	600 – 700
Young's Modulus (N/mm^2)	3000 – 3500
Elongation (%)	20 – 25
Specific Density, (g/cm^3)	0.91
Water Absorption (%)	Nil
Melting Point (°C)	160 – 170
Alkali Resistance	Strong
Acid Resistance	Strong
Biological Resistance	Stable
Cement Compatibility	Excellent compatibility with all types of Portland cements
Thermal & Electrical Conductivity	Low

Table 2: The cement slurries compositions used in this study

Cement slurry	Concentration of PPFs (%BWOC)	Weight of PPFs (g)	Weight of cement Class G (g)	Distilled water (g)
Slurry I	0	0.00	792	349
Slurry II	0.1	0.792	792	349
Slurry III	0.3	2.376	792	349
Slurry IV	0.5	3.960	792	349
Slurry V	0.7	5.544	792	349
Slurry VI	0.9	7.128	792	349

ing to **API RP 10-B2 recommended practice (2013)**. This device is provided with six different speeds (3 rpm, 6 rpm, 100 rpm, 200 rpm, 300 rpm, and 600 rpm). The dial reading was recorded from the dial of the device at different rotation speeds. The shear stress and shear rate can then be plotted to identify the optimal rheological model. Then the plastic viscosity (PV), yield point (YP), the consistency index (k), and behaviour index (n) can be calculated. The rheological test was carried out at room temperature (24°C) and atmospheric pressure.

The cement slurry density was measured using Fann mud balance Model 140. The device cup was completely filled with cement slurry and the lid was closed. The cup was placed on the fulcrum after it was cleaned of excess cement that seeped from the hole of the lid. An attempt was made to find the balance between the cup and the sliding weight on the arm until the pointer bubble was centred. The density value was then recorded from the ruler on the arm, measured in (lb/gal). The density test was performed at ambient temperature (24°C) and atmospheric pressure conditions.

The problem of fluid loss is the most familiar problem during well drilling and cementing operations. The cement slurry after being pumped into the annulus and due to the pressure difference between the wellbore and the formations, the liquid phase enters the formations. This leads to the loss of the original properties of the cement slurry, as well as accelerating the hardening of the cement. This measurement is performed by using a low pressure/low temperature filter press device. The device cell is filled with the sample and the cover is closed after making sure that the sealing ring and the filter paper are placed in the right place. A 100-psi pressure is then applied to the cell from the nitrogen gas bottle by placing it in reverse position on the device holder. In a small cylinder placed below the cell, the filtrate is collected and measured in millilitres (mL) for 30 minutes.

2.4. Measurement of porosity and permeability

A cement sheath in oil wells should have low permeability and porosity in order to obtain the insulation function with high efficiency. High permeability of the cement sheath allows formation fluids to pass through it and upward to the surface which creates serious environmental problems. The measurements of porosity and permeability were performed using cylindrical cement samples after the samples were cured for 28 days in the water bath at atmospheric pressure and ambient temperature (24°C) conditions. The permeability of cement samples was measured by using the nitrogen gas permeability method, and the absolute permeability of the samples was calculated using the Klinkenberg equation. The porosity of the cement samples was measured by using QUANTACHROME 1200e Helium Pycnometer with a measured volume accuracy of +/- 0.02%. The average time required for measuring the porosity for each sample was 20 minutes. Then, Boyle's ideal gas law at low pressures was used by applying **Equation 1** (**Peters, 2012**).

$$P1 \cdot V1 = P2 \cdot V2 \tag{1}$$

Where:
P1 – the initial pressure of the gas,
V1 – the initial volume of the gas,
P2 – the pressure of the gas after change,
V2 – the volume of the gas after change.

2.5. Measurement of unconfined compressive strength, Tensile strength, and flexural strength

The cement samples for the unconfined compressive strength test were cast in cylindrical plastic molds with an inner diameter of 36 mm and a height of 64 mm. Before the cement slurry was poured into the molds, the clean inner surfaces were lubricated with a non-reactive release agent to facilitate sample extraction after the curing time. The samples were then monitored to be free of air bubbles for a few minutes. In a distilled water bath at ambient temperature (24°C) and atmospheric pressure, all the cement samples were cured for 7, 14, and 28 days. Then, the cement samples were taken out of the water bath and polished after demoulding to reduce the roughness of the top and base surfaces using abrasive papers. The compressive strength test was carried out by a hydraulic press with a capacity of 250 kN with a constant loading rate of 18 kN/min and free of vibration to measure the axial load required to crush the sample. The average test results of three samples of each concentration at different curing times were reported to use in the calculations. In order to calculate the unconfined compressive strength of a sample, the maximum axial load required to crush it is recorded using **Equation 2.**

$$UCS = \frac{4 \cdot Fmax}{\pi \cdot D^2} \tag{2}$$

Where:
UCS – the unconfined compressive strength (MPa),
Fmax – the max axial load recorded during the test (N),
D – the diameter of the cement sample (mm).

In this study, the Brazilian test was used as an indirect method to measure uniaxial tensile strength. The cement sample was poured into plastic molds 50 mm in length and 100 mm in diameter and the samples were monitored to be free of air bubbles for a few minutes. These cement samples were then cured in a distilled water bath for 7, 14, and 28 at atmospheric pressure and ambient temperature (24°C) conditions. After that, samples were taken out from the water bath and demolded. Then, the maximum load required to appear the first crack in the sample across its diameter was recorded as shown in **Figure 5a**. The tensile strength test was carried out by a hydraulic press with a capacity of 250 kN with a constant loading rate of 18 kN/min and free of vibration. The average test results of three samples of each concentration at different curing times were reported to use in the calculations. **Equation 3** was used to calculate the tensile strength (**Heinold et al., 2003; Lavrov and Torsæter, 2016**).

$$TS = \frac{2 \cdot F}{\pi \cdot D \cdot L} \tag{3}$$

Where:
TS – the tensile strength (MPa),
F – the load at cement sample failure (N),
D – the diameter of the cement sample (mm),
L – the length of the cement sample (mm).

In addition, the authors suggested a new method for calculating the tensile strength in the case of a tube centered within the same cement sample used for the Brazilian test. The objective of this measurement is to simulate the conditions of the cement in the well filling the annulus around the casing. The outer diameter, the wall thickness, and the length of the tube are 42.33, 5.93, and 70 mm, respectively. The test is completed after initial cracks appear in the cement sample during the loading step, then the max load applied was recorded as shown in **Figure 5b**. It was found during the measuring process that the applied load did not lead to a single diagonal crack like the Brazilian test, but rather several radial cracks distributed around the tube. The cracks were located mainly at the crown (this is the part of the cement sample on the vertical axis located above the tube) and invert (this is the part of the cement sample on the vertical axis located below the tube) and some secondary cracks. The average test results of three samples of each concentration at different curing times were reported to use in the calculations. **Equation 4** was used to calculate the tensile strength.

$$TS = \frac{2 \cdot F}{\pi \cdot (D - d) \cdot L} \tag{4}$$

Where:

TS – the tensile strength (MPa),
F – the load at cement sample failure (N),
D – the diameter of the cement sample (mm),
L – the length of the cement sample (mm),
d – the outer diameter of the tube (mm).

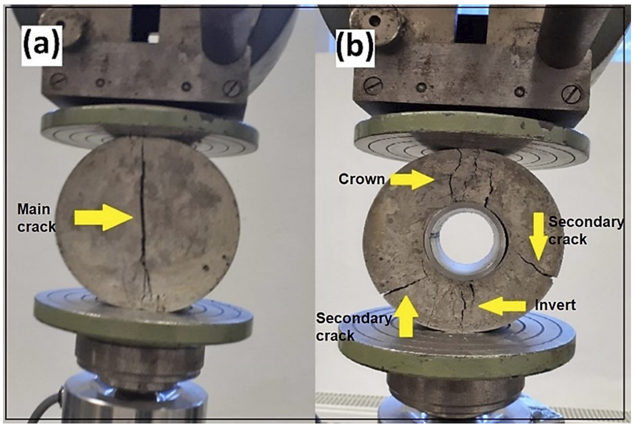

Figure 5: (a) Brazilian test, and (b) Tensile strength test in case of casing inside the cement sample.

A prismatic sample with dimensions of (40 mm×40 mm×160 mm) was used during the measurement process of the flexural strength under three-point loading on a simply supported span of 100 mm. This test was carried out according to European Standard EN 196-1 (**British Standards Institution, 2005**). Typical molds consisting of three horizontal compartments were used to prepare the cement samples for this test. Firstly, the inner face of the compartments was coated with a non-reactive release agent before pouring the cement slurry to facilitate sample extraction after the curing time. These cement samples were then cured in a distilled water bath for 7, 14, and 28 at atmospheric pressure and ambient temperature (24°C) conditions. The flexural strength test was carried out by a hydraulic press with a capacity of 250 kN with a constant loading rate of 18 kN/min and free of vibration. The axial load required to fail the sample was recorded. The average test results of three samples of each concentration at different curing times were reported to use in the calculations. **Equation 5** was used to calculate and determine the flexural strength of samples.

$$R = \frac{3 \cdot F \cdot l}{2 \cdot b \cdot t^2} \tag{5}$$

Where:

R – the flexural strength (MPa),
F – the load at cement sample failure (N),
l – the length of the support span (mm),
b – the width of the cement sample (mm),
t – the thickness of the cement sample (mm).

2.6. Measurement of interfacial bonding shear strength

The adhesion strength that occurs between two different substances, such as casing and cement, is known as interfacial bonding. This interfacial bonding is very important in oil wells because it achieves the required isolation of the annulus. The strong interfacial bonding shear strength prevents many problems in the well such as casing corrosion and gas migration. Measurement of this bonding is limited to geophysical methods (**Saini et al., 2021**). To date, there is no standard method to measure this boding property. Some research has been done on suggesting methods to simulate and measure this bonding in the laboratory (**Kremieniewski, 2020; Lambrescu et al., 2021; Teodoriu et al., 2019**). In this research, two scenarios are presented for a new approach for assessing interfacial bonding shear strength in the laboratory. The first scenario is the case in which cement fills the inner hollow of the casing, simulating the case of placing a cement plug into the well to start drilling the deviating section or abandoning the well. The second scenario is the cement surrounds the casing from the outside, simulating that the cement sheath filling the annulus. Casing samples are prepared in both cases from the same tube to ensure that the same dimensions and roughness are obtained. Casing samples should be clean, dry, and uncoated with any non-reactive materials when the cement slurry is poured in or around the casing for both scenarios. These cement samples were cured in a distilled water bath for 7, 14, and 28 at atmospheric pressure and ambient temperature (24°C) conditions. The dimensions of the casing and cement samples that were used in the test are presented in **Table 3**. The samples were taken out of the water bath after the cured time was passed. This test was carried out by a hydraulic press with a capacity of 250 kN with a constant loading rate of 18 kN/min and free of vibration. The load required to push out 20 mm of the cement plug out the casing for the first scenario was recorded as shown in **Figure 6a, 6b**.

Table 3: Geometrical details of the first and second scenarios of shear strength samples

Scenario number	Casing length (mm)	Casing outer diameter (mm)	Casing inner diameter (mm)	Cement outer diameter (mm)	Cement length (mm)
First scenario	50	114.50	102.00	102.00	50.00
Second scenario	70	42.33	36.40	100.00	50.00

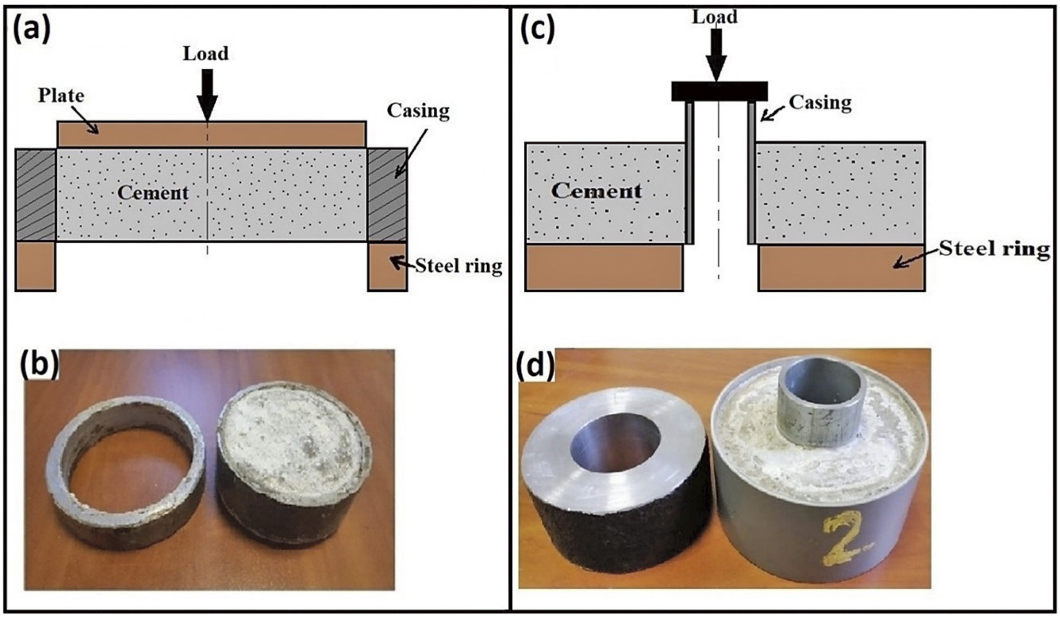

Figure 6: Interfacial bonding shear strength for (a, b) the first scenario and (c, d) for the second scenario

Also, the load required to push out 20 mm of the casing out the cement for the second scenario was recorded as shown in **Figure 6c, 6d**. A steel ring placed under the sample was used for both cases to allow space for the cement or casing to pass through. The average test results of three samples of each concentration at different curing times were reported to use in the calculations. Then, the following **Equation 6** can be used to calculate the interfacial bonding shear strength.

$$\sigma = \frac{Fmax}{\pi \cdot Dio \cdot L} \tag{6}$$

Where:

σ – the interfacial bonding shear strength (MPa),

Fmax – the maximum axial load recorded during the test (N),

Dio – the inner diameter of the casing (first case) (mm) and outer diameter of the casing (second case) (mm),

L – length of the interfacial area between casing and cement (mm).

3. Results and discussions

3.1. Rheological properties results

A cement slurry is a non-Newtonian fluid. There are three models that can describe the non-Newtonian behaviour of a cement slurry (Bingham plastic model, power-law model, and Herschel–Bulkley model). The Bingham plastic model is the dominant model due to its linear form and established applicability. The plastic viscosity (PV) is the slope of the shear stress/shear rate line above the yield point in the Bingham plastic model, while the yield point (YP) is the zero-shear-rate intercept (YP is the yield stress extrapolated to a shear rate of zero). The consistency index (k) and behaviour index (n) in the power-law model indicate the apparent viscosity and degree of non-Newtonian behaviour in the cement slurry, respectively. The effect of adding an increasing concentration of PPFs to the well cement slurry on the rheological parameters is discussed. **Figure 7** illustrates the shear stress versus shear rate of cement slurries including different concentrations of PPFs added (0, 0.1, 0.3, 0.5, 0.7, and 0.9) %BWOC. With an average absolute percentage error (AAPE) of less than 0.05, the power low model was found to be the best fit for describing the rheological behaviour of cement slurries. **Table 4** shows the results of the rheology test. Contrary to the findings in the study by **Ahmed et al. (2018)**, where PPFs additives have been used in well cement, it was found that the plastic viscosity was not significantly affected by the addition of PPFs, but the yield point was decreased. **Elkatatny et al. (2019)** reported that the plastic viscosity and yield point were marginally different from the neat cement sample. Also, it can be noted

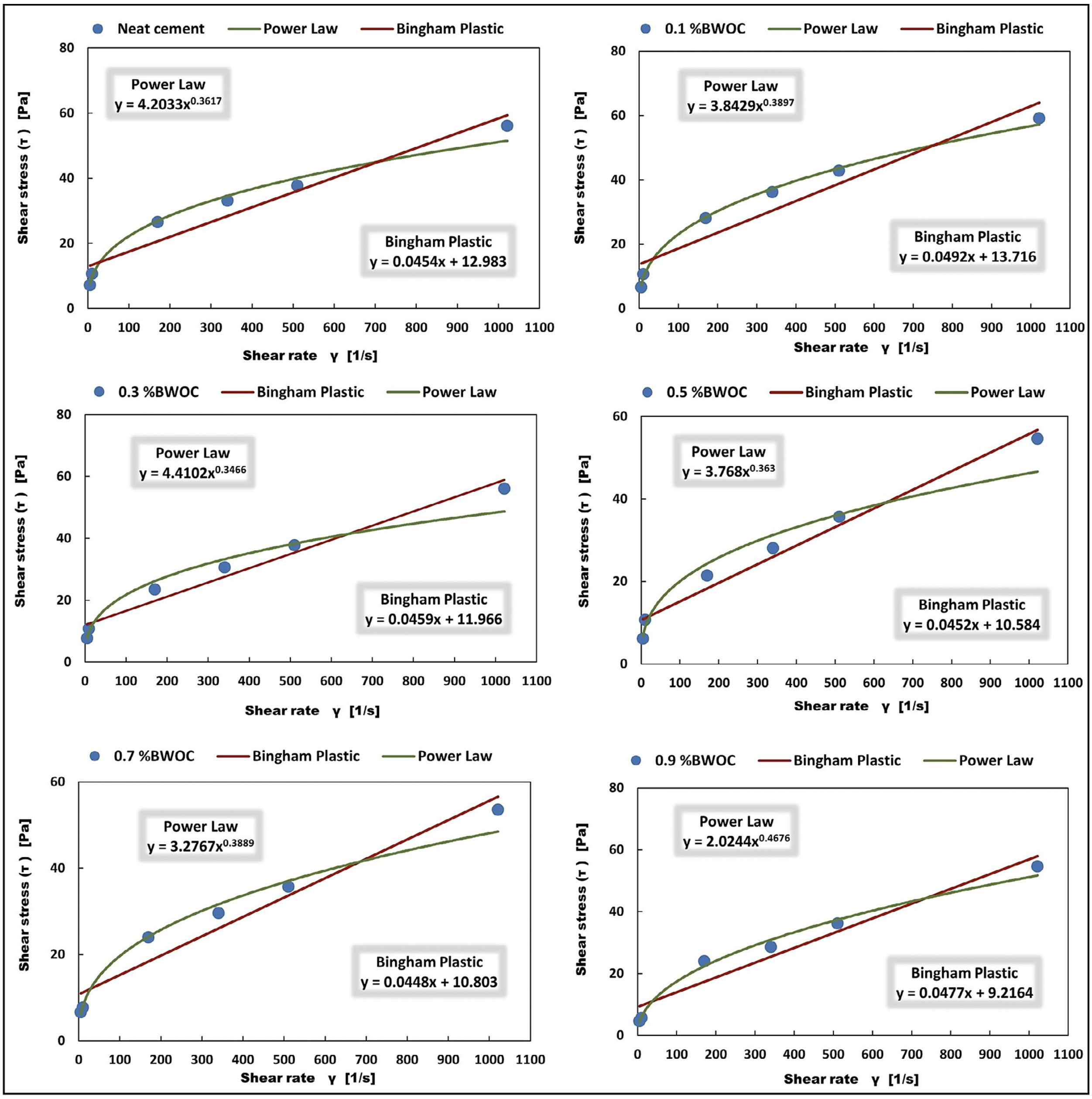

Figure 7: Shear stress against shear rate for the cement slurries

Table 4: Rheological properties of cement samples with increasing concentrations of PPFs

PPFs (%BWOC)	PV (mPa·s)	Yp (Pa)	K (Pa.s^n)	n
0	21.619	12.983	8.7789	0.3617
0.1	23.429	13.716	8.026	0.3897
0.3	21.857	11.966	9.2108	0.3466
0.5	21.524	10.584	7.8696	0.363
0.7	21.333	10.803	6.8435	0.3889
0.9	22.714	9.216	4.2281	0.4676

that the consistency index (k) was decreased, but the behaviour index (n) slightly increased. It can be noted that increasing the PPFs content had no significant effect on the rheological parameters. This may be due to the distribution of PPFs into the slurry without their interaction with the cement slurry components because PPFs are a polymeric material, but it does not dissolve in the cement slurry, keeping the rheological properties of the cement practically constant. Another reason could be that the concentrations of PPFs involved in this investigation are very low.

3.2. Density test results

Figure 8 presents the density test results of a cement slurry containing increased concentrations of PPFs. The density of the reference cement slurry was 1929 (kg/m^3). The influence of PPFs on the density property can be ignored, as shown in the figure, which accords with the

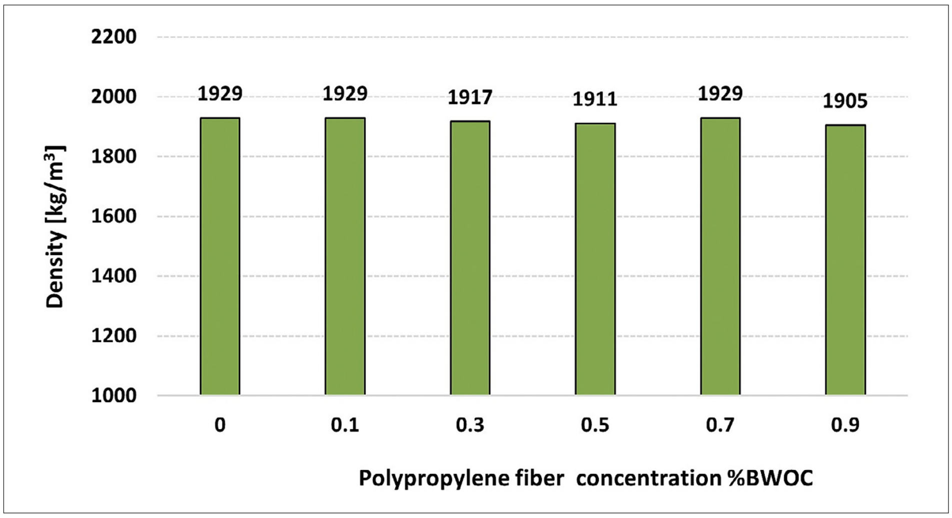

Figure 8: The density of cement slurry at different concentrations of PPFs

findings of **Ahmed et al. (2018)** and **Elkatatny et al. (2019)**, who employed PPFs additives in well cements. The lowest value of the density is 1905 (kg/m^3) which recorded after 0.9%BWOC of PPFs was added, which is 1.24% lower than the original density of the reference cement slurry. The reason for this could be that the PPF concentrations employed in this investigation were extremely low.

3.3. Fluid loss test results

Figure 9 shows the results of measuring the volume of fluid loss after 30 minutes for all cement slurries designed for this study. It is clear to say that the fluid loss volume is not affected by increasing the concentration of PPFs. As a result, the influence of adding this type of fibers on fluid loss volume can be ignored. The volume of fluid loss of the reference cement slurry was 116 mL. The lowest value of the fluid loss volume is 113 mL when 0.9%BWOC of PPFs is added, which is 2.59% lower than the original fluid loss volume of the reference cement slurry. This is not regarded as a significant reduction in fluid loss volume. Attributed to the fact that these PPFs are not water absorbent, confirming that they have no effect on fluid loss.

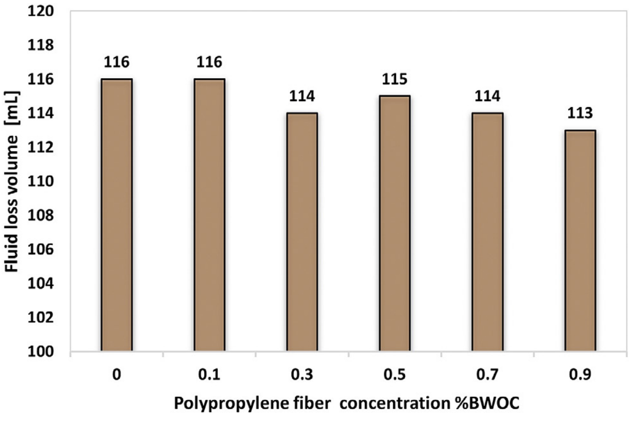

Figure 9: API fluid loss volume of the cement slurry at different concentrations of PPFs

3.4. Porosity and permeability tests results

The primary function of the cement sheath is to achieve zonal insulation and prevent the passage of gases through it. For this purpose, the cement sheath should have low permeability and porosity. **Table 5** depicts the changes that occur in the porosity and permeability due to the addition of increasing concentrations of PPFs in the cement samples. The porosity of the reference cement sample was 31.34%. It was observed from the results that the porosity was 32.08%, 32.89%, 33.7%, and 34.83% when adding the PPFs at a concentration of 0.1%BWOC, 0.3%BWOC, 0.5%BWOC, 0.7%BWOC, and 0.9%BWOC, respectively. **Figure 10** depicts the solid volume (Vs) to void volume (Vp) ratio for cement samples containing different concentration of PPFs. The data show that when PPFs are added in increasing concentrations, there is a modest increase in this ratio. This happens due to cement additives have an unfavourable influence on the homogeneity of the well cement, which leads to an increase in the percentage of porosity (**Ahmed et al., 2019; Elkatatny, 2019**).

Regarding permeability, the permeability of the reference cement sample was 0.08 (10^{-3} µm^2). It was observed from the results that the permeability increased to become 0.16 (10^{-3} µm^2), 0.27 (10^{-3} µm^2), 1.44 (10^{-3} µm^2), 1.06 (10^{-3} µm^2), and 0.58 (10^{-3} µm^2) when adding the PPFs at a concentration of 0.1%BWOC, 0.3%BWOC, 0.5%BWOC, 0.7%BWOC, and 0.9%BWOC, respectively. **Figure 11** depicts the change in permeability as a function of mean pressure for nitrogen. It was found in the study conducted by **Elkatatny et al. (2019)** that porosity and permeability decrease with increasing PPFs concentrations. Generally, the permeability of well cement is considered acceptable if it is less than 0.1 (10^{-3} µm^2). Thus, the addition of PPFs leads to an increase in the permeability of the cement.

Table 5: Results of porosity and permeability measurements of cement samples containing PPFs

PPFs (%BWOC)	Diameter (cm)	Length (cm)	Mass (g)	Porosity (%)	Average solid volume (cm^3)	Permeability (10^{-3} µm^2)
0	3.582	5.431	89.62	31.34	37.58	0.08
0.1	3.595	5.984	97.94	32.08	41.25	0.16
0.3	3.596	5.739	92.83	32.89	39.11	0.27
0.5	3.589	5.921	93.42	34.11	39.47	1.44
0.7	3.592	5.613	89.22	33.7	37.71	1.06
0.9	3.604	5.934	92.94	34.83	39.45	0.58

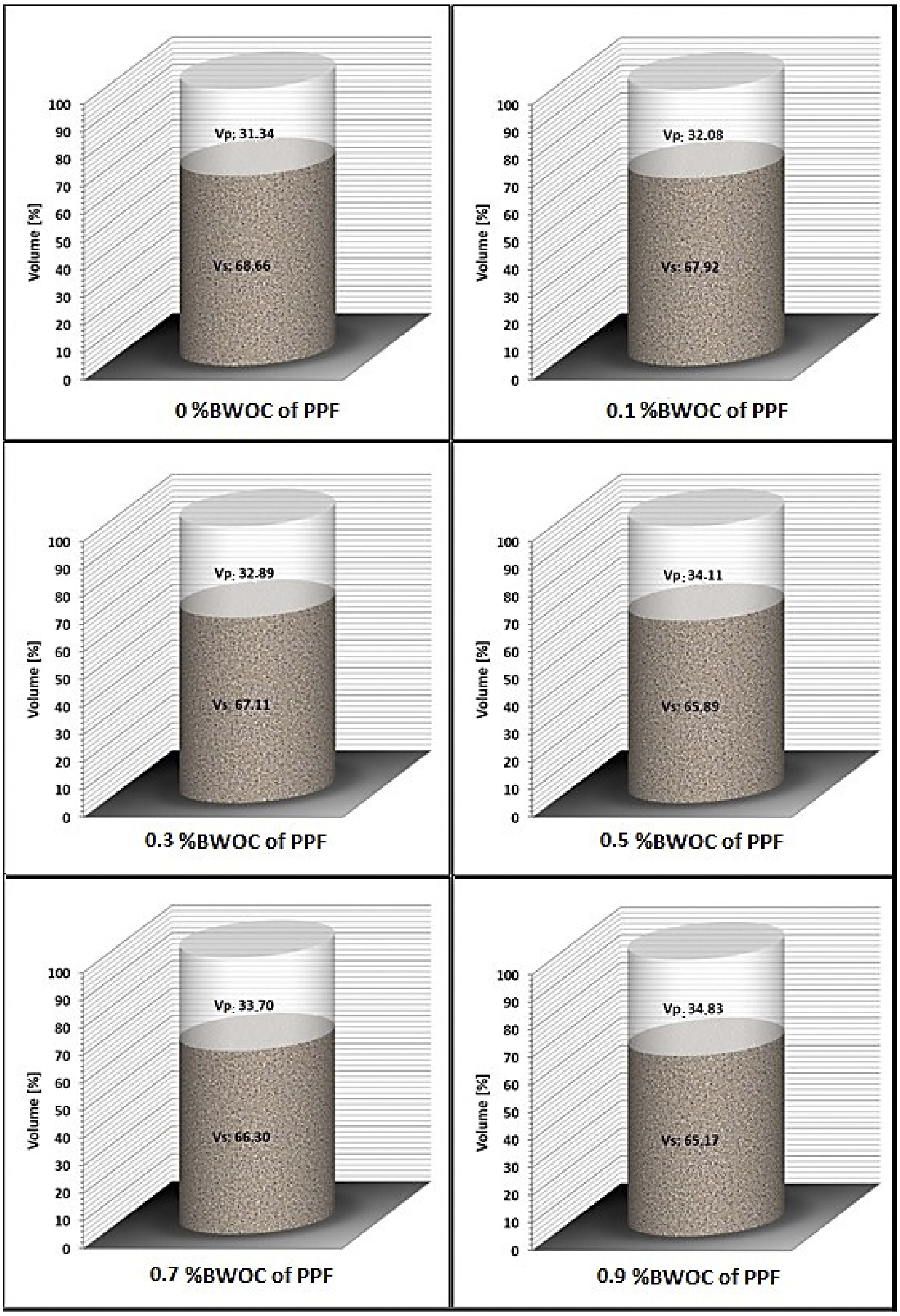

Figure 10: The ratio of solid volume to void volume for cement samples

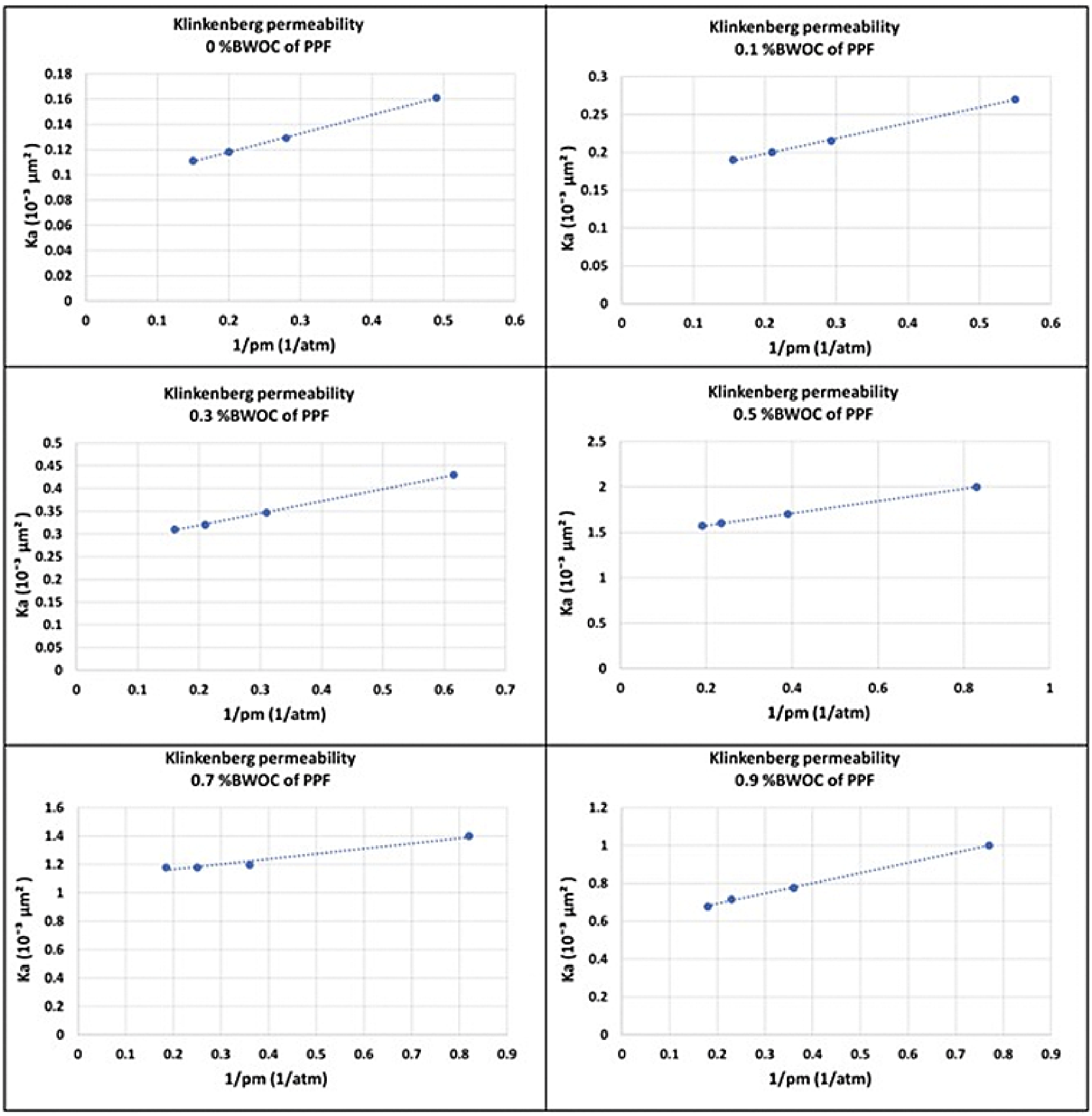

Figure 11: The change in permeability as a function of mean nitrogen pressure

3.5. *Compressive strength test results*

The effect of PPFs on the compressive strength a concentration of PPFs from 0 to 0.1%BWOC, 0.3%BWOC, 0.5%BWOC, 0.7%BWOC and 0.9%BWOC was added. **Figure 12** shows the compressive strength test results of cylindrical cement samples containing increasing concentrations of PPFs at different cured times. From this figure, it is clear to say that adding PPFs to well cement improves compressive strength. The highest increasing rate in compressive strength were 26%, 46% and 24% for the curing time of 7, 14 and 28 days, respectively, when 0.3%BWOC of PPFs was added to the cement slurry. Also, the compressive strength decreases after using concentrations above 0.3%BWOC of PPFs for all cured times. The presence of PPFs within the cement slurry may have generated a connective web, increasing the strength of the internal bond between the portions of

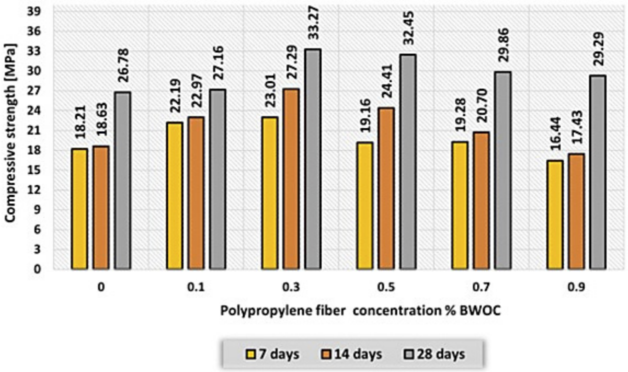

Figure 12: The compressive strength of the cement samples

the cement sample, which could explain the increase in compressive strength. This internal bond helps create effective resistance against micro-cracks spreading in the load direction. This resistance prevents the expansion of micro-cracks that lead to failure. The addition of PPFs above 0.3%BWOC leads to a decrease in the compressive strength, and this could be due to an increase in PPFs concentration leads to a poor homogeneous distribution within the cement slurry. Another reason could be that high PPFs concentrations reduce the amount of C-S-H and also the amount of portlandite in the well cement, as well as impair the interlocking mechanism that gives cement samples their strength. Nevertheless, the value of compressive strength for all used concentrations of PPFs stayed higher than the reference cement sample after 28 days of cured time. In other words, the optimum PPFs concentration is 0.3%BWOC, and this concentration achieved a maximum compressive strength value of 33.27 MPa after 28 days of cured time while in the study of **Ahmed et al (2018)**, it was found that the concentration of 0.5%BWOC is the optimum concentration that gives the highest value of compressive strength. Likewise, in the study by **Elkatatny et al. (2019)** where PPFs were used in well cement under HPHT conditions, it was found that the 0.5%BWOC of PPFs is the optimum concentration to enhance the compressive strength.

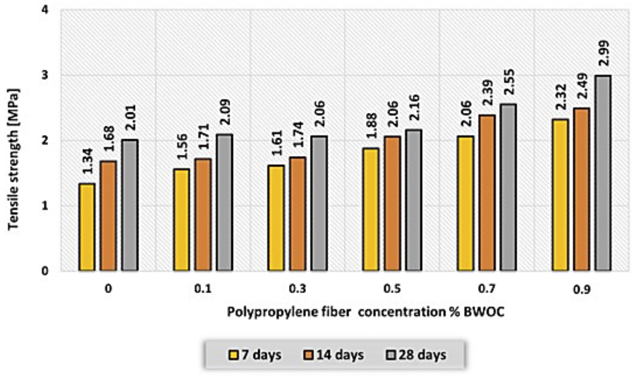

Figure 13: Tensile strength of the cement samples containing different concentrations of PPFs at different curing times resulting by the Brazilian test

3.6. Brazilian tensile strength test results

The tensile strength of the reference cement sample was 1.34 MPa, 1.68 MPa, and 2.01 MPa at 7,14, and 28 days of curing time, respectively. The values of tensile strength for the samples including an increasing concentration of PPFs up to 0.9%BWOC showed higher values than the cement samples free of PPFs for all curing times as shown in **Figure 13**. The experiment results showed that the maximum tensile strength was observed in the samples containing 0.9%BWOC of the PPFs. **Elkatatny et al. (2019)** found that tensile strength increased with increasing PPFs concentration up to 0.75%BWOC. The PPFs mixed with cement create a PPFs network that spreads vertically in the direction of the applied load forming a bridge across the crack which led to reducing the size of the main crack as shown in **Figure 14**. Here, the fibers are responsible for withstanding the tensile stress rather than the cement. PPFs have a considerable influence on enhancing the tensile strength of well cement, according to the findings.

Figure 14: PPFs network distribution inside the main crack of the Brazilian test sample

The Brazilian test has one primary crack spreading in the same direction as the applied load. In the case of the presence of the metal tube centered inside the cement sample, the fine and big cracks will appear and be distributed radially around the casing when the maximum tensile strength is exceeded as shown previously in **Fig-**

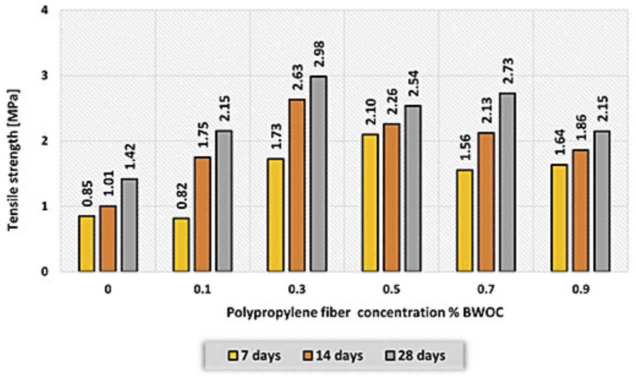

Figure 15: The tensile strength of the cement samples in the presence of the metal tube

ure 5b. Therefore, this paper is the first research to evaluate this new method. Through this method, it is possible to obtain a more precise idea about the effect of tensile strength on a cement sheath surrounding the casing string. The results presented in the **Figure 15** show that the tensile strength increases dramatically with an increase in fiber concentration up to 0.3%BWOC. Increasing PPFs concentration to more than 0.3%BWOC, led to a decrease in the tensile strength, but stayed higher than the reference sample. The maximum tensile strength value was recorded in this case at 0.3%BWOC of PPFs 28 days after the start curing time.

3.7. Flexural strength test results

Figure 16 shows the results of measuring the flexural strength of the studied cement samples containing different concentrations of PPFs. The reference samples showed a flexural strength of 0.71 MPa, 1.57 MPa, and 1.75 MPa after 7, 14, and 28 days of curing times, respectively. The flexural strength was dramatically increased with an increase in the PPFs concentration up to 0.3%BWOC. The maximum value of flexural strength was 3.52 MPa which was obtained at 0.3%BOWC after being cured for 28 days. The flexural strength decreased as the PPFs concentration increased above 0.3%BWOC. The flexural strength increased again at 0.9%BWOC but with a rate less than its increase when using 0.3%BWOC of PPFs. The explanation for this is that the accumulated fibers in the crack area increased their resistance to failure when added with concentrations up to 0.3%BWOC. This resistance helped to delay the failure due to the transfer of the stress from the cement to the fibers. Increasing the concentration above 0.3%BWOC led to a disturbance in the cement hydration process. In addition, the high concentrations of the PPFs lead to a non-homogeneous distribution of the PPFs in the cement slurry. The significant change in flexural strength values at different curing times can also be noted in the same figure. In other words, increasing the curing time resulted in increased flexural strength for all the studied concentrations.

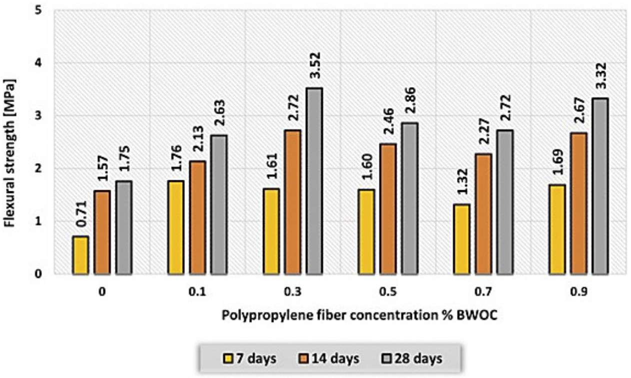

Figure 16: The flexural strength of the cement samples

3.8. Interfacial bonding shear strength test results

The bonding strength of the casing with the cement has an important indication of the effectiveness of the cement insulating property. The weak bond strength leads to many problems due to the entry of formation fluids into the casing-cement bounded zone. These problems include casing corrosion and gas migration. For this purpose, this study suggests a new mechanism for measuring this bonding. **Figure 17** shows the interfacial bonding shear strength test results for the first scenario. The reference samples of first scenario showed a bonding shear strength of 1.38 MPa, 1.66 MPa, and 1.75 MPa after 7, 14, and 28 days of curing times, respectively. The results show that the bonding strength in this case increases with an increase in the concentration of PPFs up to 0.5%BWOC. Subsequent increases in PPFs concentration cause a decrease in bond strength. The maximum value of interfacial bonding shear strength was achieved at 0.5%BWOC of PPFs after 28 days of curing time. Likewise, for the second scenario, the interfacial bonding shear strength increased dramatically with an increase in PPFs concentration up to 0.5%BWOC, as shown in **Figure 18**. The increase in concentration after this concentration shows a decrease in the bonding shear strength. In both scenarios, later ages of curing (28 days)

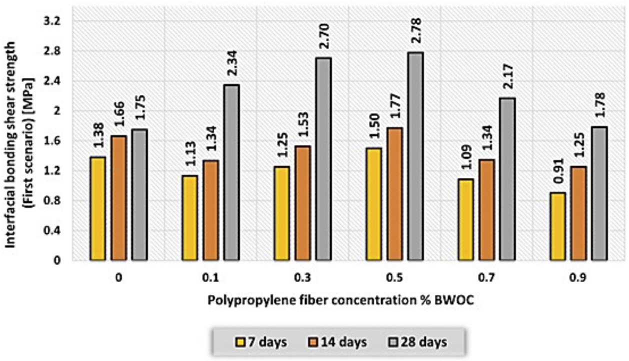

Figure 17: Interfacial bonding shear strength of the cement samples at different concentrations of PPFs for the first scenario

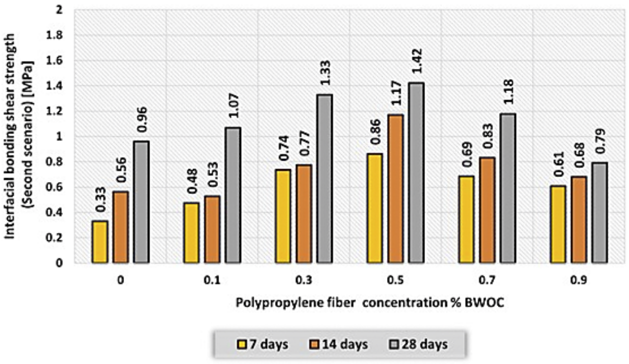

Figure 18: Interfacial bonding shear strength of the cement samples at different concentrations of PPFs for the second scenario

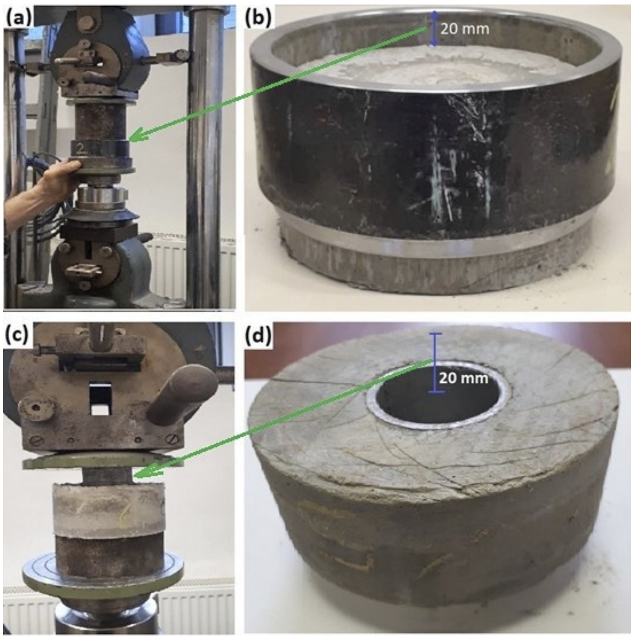

Figure 19: Interfacial bonding shear strength sample for the first scenario (a) during and (b) after testing, and for the second scenario (c) during and (d) after testing

show significantly greater bonding shear strength compared to early ages of curing (7, and 14 days). Thus, the curing time has a significant impact on the bonding shear strength because of the complete hardening of the cement after 28 days of curing. Also, PPFs have contributed to improving the bonding shear strength when added at certain concentrations. This can be explained by the results of the compressive strength test, tensile strength test, and flexural strength test, which improved with the addition of PPFs. The surface roughness of these PPFs can be the main factor in the bonding strength between cement and fibers, which positively affects the mechanical properties as reported by **Liu et al., (2021)**. Also, the roughness of the fibers at the interface between the cement and the casing may have contributed to the improvement of the cement casing bonding strength. **Figure 19** shows the interfacial bonding shear strength test using a hydraulic press and the resulting samples after testing.

4. Conclusions

In the study, PPFs were used to improve the oil well cement mechanical properties with different concentrations at atmospheric pressure and room temperature. Comprehensive laboratory measurements were conducted by studying the rheological parameters, density, fluid loss, permeability, porosity, and mechanical properties including (compressive, tensile, and flexural strength). From the experimental results it was found that adding different concentrations of PPFs does not have any significant impact on the physical parameters of cement slurries. The addition of PPFs led to an increase in the porosity and permeability values. The highest porosity value is 34.83% and was recorded when 0.9%BWOC of PPFs was added while the highest permeability value was 1.44 mD which was recorded when 0.5%BWOC of PPFs was added. The addition of PPFs greatly improved mechanical properties, according to the findings. The addition of PPFs at a concentration of 0.3%BWOC provided maximum values for both compressive strength (33.27 MPa) and flexural strength (3.52 MPa) compared to the other concentrations used and the reference sample after curing the samples for 28 days. The tensile strength of cement samples increased by increasing the concentration of PPFs up to 0.9%BWOC, which reached (2.99 MPa) for the samples that were cured for 28 days. While the addition of 0.5%BWOC showed maximum values for the interfacial bonding shear strength, which reached (2.78 MPa) for the first scenario and (1.42 MPa) for the second scenario for the cement samples that were cured for 28 days. The results also revealed that as the curing period was increased, the strength of the set cement improved. Finally, the efficacy of using polypropylene fibers as an additive to increase the mechanical properties of oil well cement can be announced as a result of this research.

This study was limited to studying the effect of PPFs on well cement at room temperature and atmospheric pressure conditions. Therefore, it is highly recommended to study the effect of these PPFs on the well cement properties under high-pressure/high-temperature conditions in an attempt to simulate the set cement in deep oil wells and geothermal wells.

Note

This study was produced from the first author's PhD thesis prepared under the supervision of the second author.

5. References

Papers:

Adjei, S. and Elkatatny, S. (2021): Overview of the lightweight oil-well cement mechanical properties for shallow wells. Journal of Petroleum Science and Engineering 198, 108201. https://doi.org/10.1016/j.petrol.2020.108201

Ahmed, A., Elkatatny, S., Gajbhiye, R., Rahman, M.K., Sarmah, P. and Yadav, P. (2018): Effect of Polypropylene Fibers on Oil-Well Cement Properties at HPHT Condition, in: All Days. Presented at the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, p. SPE-192187-MS. https://doi.org/10.2118/192187-MS

Ahmed, A., Mahmoud, A.A., Elkatatny, S. and Chen, W. (2019): The Effect of Weighting Materials on Oil-Well Cement Properties While Drilling Deep Wells. Sustainability. 11(23), 6776. https://doi.org/10.3390/su11236776

Al Hammad, M.A. and Altameimi, Y.M. (2002): Cement Matrix Evaluation. In IADC/SPE Drilling Conference. Society of Petroleum Engineers. https://doi.org/10.2118/77213-MS

Al-Tameemi, A.A. and Mahdi, A.K. (2021): Influence of polypropylene fibers reinforcement on the mechanical properties of roller compacted concrete used in airports with partial replacement of cement by cement kiln dust. Journal of Physics: Conference Series. 1973, 012173. https://doi.org/10.1088/1742-6596/1973/1/012173

Arjomand, E., Bennett, T. and Nguyen, G. (2018): Evaluation of cement sheath integrity subject to enhanced pressure. Journal of Petroleum Science and Engineering, 170,1-13. https://doi.org/10.1016/j.petrol.2018.06.013

Bagherzadeh, R., Pakravan, H.R., Sadeghi, A.-H., Latifi, M. and Merati, A.A. (2012): An Investigation on Adding Polypropylene Fibers to Reinforce Lightweight Cement Composites (LWC). Journal of Engineered Fibers and Fabrics, 7, 4. https://doi.org/10.1177/155892501200700410

Broni-Bediako, E., Joel, O. and Ofori-Sarpong, G. (2016): Oil Well Cement Additives: A Review of the Common Types. Oil and Gas Research, 2. https://doi.org/10.4172/ogr.1000112

Elkatatny, S. (2019): Development of a Homogenous Cement Slurry Using Synthetic Modified Phyllosilicate while Cementing HPHT Wells. Sustainability, 11, 7, 1923. https://doi.org/10.3390/su11071923

Elkatatny, S., Gajbhiye, R., Ahmed, A. and Mahmoud, A.A. (2019): Enhancing the cement quality using polypropylene fiber. Journal of Petroleum Exploration and Production Technology, 10, 1097–1107. https://doi.org/10.1007/s13202-019-00804-4

Heinold, T., Dillenbeck, R.L., Bray, W.S. and Rogers, M.J. (2003): Analysis of Tensile Strength Test Methodologies For Evaluating Oil and Gas Well Cement Systems. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/84565-MS

Heinold, T., Dillenbeck, R.L. and Rogers, M.J. (2002): The Effect of Key Cement Additives on the Mechanical Properties of Normal Density Oil and Gas Well Cement Systems. Presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/77867-MS

Iyer, J., Lackey, G., Edvardsen, L., Bean, A., Carroll, S.A., Huerta, N., Smith, M.M., Torsæter, M., Dilmore, R.M. and Cerasi, P. (2022): A Review of Well Integrity Based on Field Experience at Carbon Utilization and Storage Sites. International Journal of Greenhouse Gas Control, 113. https://doi.org/10.1016/j.ijggc.2021.103533

AL Khalaf, H. and Federer, G. (2021): Enhancement of Water-Based Mud Properties using Polypropylene Fibers. Petroleum and Coal, 63, 3, pp. 704-709.

Kremieniewski, M. (2020): Ultra-Lightweight Cement Slurry to Seal Wellbore of Poor Wellbore Stability. Energies, 13, 12. https://doi.org/10.3390/en13123124

Lambrescu, I., Teodoriu, C. and Amani, M. (2021): Experimental and Numerical Investigations of Cement Bonding Properties. Materials, 14, 23. https://doi.org/10.3390/ma14237235

Lavrov, A. (2017): Lost Circulation in Primary Well Cementing. Energy Procedia, 114, 5182–5192. https://doi.org/10.1016/j.egypro.2017.03.1672

Li, L., Perez, C., Lew, R. and Hughes, B. (2017): Evaluation of Testing Environments and Additives on Cement Tensile Strength using HPHT Tensiometer. In the AADE National Technical Conference and Exhibition, American Association of Drilling Engineers, p. 8.

Li, M., Liu, M., Yang, Y., Li, Z. and Guo, X. (2015): Mechanical properties of oil well cement stone reinforced with hybrid fiber of calcium carbonate whisker and carbon fiber. Petroleum Exploration and Development, 42, 1, 104–111. https://doi.org/10.1016/S1876-3804(15)60012-X

Liu, Y., Wang, L., Cao, K. and Sun, L. (2021): Review on the Durability of Polypropylene Fibre-Reinforced Concrete. Advances in Civil Engineering. 2021, 1–13. https://doi.org/10.1155/2021/6652077

Mashrei, M., Sultan, A. and M. Mahdi, A. (2018): Effects of polypropylene fibers on compressive and flexural strength of concrete material. International Journal of Civil Engineering and Technology, 9, 11, 2208–2217.

Najimi, M., Farahani, F.M. and Pourkhorshidi, A. (2009): Effects of polypropylene fibers on physical and mechanical properties of concretes. In the Third International Conference on Concrete and Development, Tehran, Iran.

R. A. S., M. (2006): EFFECT OF POLYPROPYLENE FIBERS ON THE MECHANICAL PROPERTIES OF NORMAL CONCRETE. Journal of Engineering Sciences, 34, 4, 1049–1059. https://doi.org/10.21608/jesaun.2006.110765

Saini, P., Kumar, H. and Gaur, T. (2021): Cement bond evaluation using well logs: A case study in Raniganj Block Durgapur, West Bengal, India. Journal of Petroleum Exploration and Production, 11, 1743–1749. https://doi.org/10.1007/s13202-021-01151-z

Song, J., Xu, M., Liu, W., Wang, X. and Wu, Y. (2018): Synergistic Effect of Latex Powder and Rubber on the Properties of Oil Well Cement-Based Composites. Advances in Materials Science and Engineering, 2018. https://doi.org/10.1155/2018/4843816

Teodoriu, C., Yi, M.C. and Salehi, S. (2019): A Novel Experimental Investigation of Cement Mechanical Properties with Application to Geothermal Wells. Energies, 12, 18. https://doi.org/10.3390/en12183426

Teodoriu, C., Yuan, Z., Schubert, J. and Amani, M. (2012): Experimental Measurements of mechanical parameters of Class G cement, in: All Days. In the SPE/EAGE European Unconventional Resources Conference and Exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/153007-MS

Zhu, H.Y., Deng, J.G., Zhao, J., Zhao, H., Liu, H.L. and Wang, T. (2014): Cementing failure of the casing-cement-rock interfaces during hydraulic fracturing. Computers and Concrete, 14, 1, 91–107. https://doi.org/10.12989/cac.2014.14.1.091

Chapters in books:

Lavrov, A. and Torsæter, M. (2016): Properties of Well Cement, in: Lavrov, A., Torsæter, M. (Eds.), Physics and Mechanics of Primary Well Cementing, SpringerBriefs in Petroleum Geoscience & Engineering. Springer International

Publishing, Cham, pp. 9–23. https://doi.org/10.1007/978-3-319-43165-9_2

Books/thesis:

Barnes, P. and Bensted, J. (2002): Structure and Performance of Cements, Second Edition. CRC Press,584p.

Peters, E.J. (2012): Advanced petrophysics, 1st ed. ed. Live Oak Book Company, Austin, TX.

Reports (Standards):

American Petroleum Institute (API) RP 10B-2, (2013): Recommended practice for testing well cements, 2nd Edition, Washington

British Standards Institution, (2005): Methods of testing cement. Part 1.

SAŽETAK

Poboljšanje mehaničkih svojstava cementnoga kamena u naftnim bušotinama upotrebom polipropilenskih vlakana i ispitivanje nove laboratorijske metode za mjerenje čvrstoće vezanja cementnoga kamena na zaštitne cijevi

Glavni je cilj ovoga istraživanja poboljšati učinkovitost cementnoga kamena u naftnim bušotinama u pogledu mehaničkih svojstava korištenjem čistih polipropilenskih vlakana. U istraživanju su polipropilenska vlakna dodavana u koncentracijama od 0 do 0,1 %, 0,3 %, 0,5 %, 0,7 % i 0,9 % masenoga udjela cementa (engl. *by weight of cement*, BWOC). Ispitana su reološka svojstva, gustoća, gubitak fluida, propusnost, poroznost, tlačna čvrstoća, vlačna čvrstoća i čvrstoća na savijanje. U ovome je istraživanju također ispitivana i nova metoda za mjerenje vlačne čvrstoće uzoraka cementnoga kamena u kombinaciji sa zaštitnim cijevima. Osim toga, novim laboratorijskim postupkom izmjerena je posmična čvrstoća međufaznoga vezanja, koja predstavlja snagu adhezije između cementnoga kamena i zaštitnih cijevi. Na temelju provedenoga istraživanja moguće je zaključiti da je utjecaj polipropilenskih vlakana na reološka svojstva, gustoću i svojstvo gubitak fluida zanemariv. Rezultati upućuju na to da se povećanjem udjela polipropilenskih vlakana povećava propusnost i poroznost uzoraka cementnoga kamena. Nadalje, povećanje koncentracije polipropilenskih vlakana do 0,3 % masenoga udjela cementa dovelo je do poboljšanja mehaničkih svojstava u različitim vremenima očvršćivanja. Čvrstoća vezivanja cementnoga kamena duž zaštitnih cijevi poboljšana je povećanjem koncentracije polipropilenskih vlakana do 0,5 % masenoga udjela cementa.

Ključne riječi:
cementni kamen u bušotini, reološka svojstva, mehanička svojstva, polipropilenska vlakana, čvrstoća vezanja cementnoga kamena na zaštitne cijevi

Author’s contribution

Hani Al Khalaf (PhD student, Petroleum Engineer performed the laboratory test and presented the results. **Gabriella Federer Kovacsne** (Assoc. Prof. Dr., Petroleum Engineer) provided the analyses of the results. **Nagham Al Haj Mohammed** (MSc student, Petroleum Engineer) performed the laboratory test and presented the results, and **Ferenc Remeczki** (PhD student, Petroleum Engineer) performed and analysed the porosity and permeability measurements.