

Research Article

Improving Local Class A Cement to Oil Well Cement Using Polyethylene Terephthalate Plastic Waste

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Abstract

Addition of polyethylene terephthalate (PET) waste plastic in cement mixtures tend to negatively affect cement matrix properties. Mainly, decreasing final compressive strengths and impacting cement slurry properties. However, recent studies on concrete cement mixtures show that through prior pretreatment of plastic waste material, via irradiation technique or using oxidizing solutions, the strength of PET plastic containing cement mixtures is regained. This study focuses on promoting similar sustainable practices by investigating the prospect of using PET plastic waste in cementing of shallow oil and gas wells. PET plastic waste was processed into fiber and powder additives and incorporated into locally manufactured general-purpose Class A cement, which was formulated or enhanced into standard oil well cement through addition of a variety of cement additives. The PET derived additives, namely, untreated PET fibers, irradiated PET fibers, and Bis (2-hydroxyethyl) Terephthalate (BHET) were incorporated at dosages of 0.2, 1.0, and 1.8% by weight of cement (bwoc) to assess their influence on oil well cement slurries and matrices. It is observed that plastic viscosities of prepared slurries increased with increasing incorporation dosages of the PET derived additives. Slip effects frequently occurred due to the addition of PET fibers as additives. The addition of untreated PET fibers, irradiated PET fibers, and BHET additives optimally increased final compressive strengths by 22.05, 19.34 and 81.82%, respectively. Addition of a superplasticizer among the additives is crucial in controlling rheological behavior and most importantly in improving compressive strength of PET plastic incorporated oil well cements. Thus, PET fibers have potential to be used as reinforcements while BHET can be readily used as an oil well cement additive.

Keywords

Oil and Gas Wells, Oil Well Cement, Plastic Waste, Chemical Additives, Accelerators

1. Introduction

The hydration reaction of oil well cement involves multiple physico-chemical mechanisms, namely, diffusion, nucleation, growth, complexation, as well as adsorption mechanisms. A sequence of reactions takes place simultaneously and consecutively between water and cement constituents, with

chemical additives in some cases, thereby leading to the setting and hardening of the oil well cement slurry. Strengths of hardened oil well cement mainly define the reliability and the ability to resist deformation when loads are applied. Deficiency in set cement's compressive strength signal increased

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chances of casing failure accompanied by a decrease in lifespan of a well [1]. On the other hand, increased compressive strengths are associated with decreased porosity in addition to increased durability [2]. Aside from ensuring adequate mechanical properties of the set cement after the oil and gas well cementing operation, oil well cement additives also play a crucial role in controlling slurry properties including rheological behavior, thickening time, and fluid loss.

Reutilization of polymer waste, such as rubbers and plastics, has been of interest lately, with researchers struggling to find widely applicable and sustainable alternative methods to handle this abundant non-biodegradable polymer waste materials [3, 4]. Nonetheless, several studies focusing on utilization of these polymer wastes in cementing research have been carried out. The studies show that polyethylene terephthalate (PET) plastic waste can be incorporated or added into concrete as aggregate, powder, or fibers, and these approaches have been successful to some extent. As fibers and coarse aggregates, PET in concrete has been reported to improve workability of concrete [5]. Furthermore, it improves impact resistance, enhances cracking properties, and leads to increased flexural strength, especially in fiber forms as used in various studies [6-8]. These researchers commonly reported that final compressive strengths of set cement mixtures were reduced with the incorporation of PET plastics. Additional effects are the slight decrease in density and decrease in elastic modulus with the increase in PET fiber incorporation volume [6]. PET plastic's increased sensitivity to alkaline environments is also one of the concerning setbacks. Given the PET plastic's increased sensitivity to alkaline environments, improvements brought about by adding recycled PET fibers can deteriorate after 150 days, accompanied by increasing porosity after about 365 days [7]. Different studies have also emphasized that the use of PET enhanced concrete under aggressive alkaline conditions must be thoroughly evaluated given the increased possibility of degrading durability performance under these conditions [8, 9]. Contrarily, the incorporation of PET waste in concrete as fine powder, after pulverization, yielded varying results [10].

Based on literature, the reductions in compressive strength and workability which occur when different percentages by volume of plastic flakes partially replace sand in concrete are minimal [11]. Furthermore, these reductions can be countered by adding a superplasticizer. In one study, workability of the concrete mixed with waste plastic was reported to have increased by around 10-15%, while the compressive strength increased by approximately 5% following the addition of a superplasticizer to the cement mix [11].

Chemically treating PET plastics, using the strong oxidizing calcium hypochlorite solution ($\text{Ca}(\text{ClO})_2$), before incorporation in concrete as a replacement of coarse aggregate has been reported to yield notable improvements in bond strength between cementitious matrix and the PET plastic aggregates [12]. As a result of such PET plastic pretreatment, the compressive strength of the concrete (containing chemically oxi-

dized PET plastic aggregates) increased, while porosity and permeability decreased. Likewise, major breakthroughs of using PET plastic waste to achieve notable improvements in cement related operations involved pretreatment of plastic before it is applied as a concrete additive, either in the form of aggregate or powder.

Based on several studies, gamma irradiation of PET and its thermal depolymerization through glycolysis have emerged as leading techniques utilized to transform waste PET plastics for beneficial use in cement mixtures. Gamma irradiation effects lead to direct changes in physical properties of PET. PET, like many other polymers, undergoes major crosslinking and minor oxidative degradation after being exposed to gamma radiation. PET's sterilization through gamma radiation readily occurs in both film and fiber forms, withstanding at least 1000 kGy of gamma radiation even though discoloration takes place at lower doses [13]. Either radiation-induced crosslinking or chain scission due to the radiation can result in improved PET plastic strength [9].

Another study reported that high density polyethylene (HDPE) mechanical strength properties improve with increasing gamma irradiation dose [14]. Furthermore, the application of radiation at lower dose rates led to obtaining lower doses that provide a similar change in resistance parameters as high doses. This means that gamma radiation affects HDPE in a more efficient way at lower dose rates. In the case of irradiated PET as sand substitute in concrete, a related study concluded that irradiated PET-enhanced concrete shows greater mechanical strength [15]. It was reported that radiation-induced crosslinking improved the mechanical strength of PET enhanced concrete for doses up to 150 kGy, with greater compression strength exhibited by samples irradiated at a dose of 100 kGy [15].

Effectiveness of gamma irradiated PET plastic when used as an additive in cement paste comprising of supplementary cementitious materials such as silica fume and Class F fly ash has been explored [9]. The study involved irradiation doses of 10 kGy for the low dose plastic additive and 100 kGy for the high dose plastic additive. It was then found that irradiating plastic at a high dose (100 kGy) was the best, recuperating strength lost due to the addition of plastic in cement paste. Furthermore, it was clarified that adding a high dose irradiated PET plastics rather than regular, non-irradiated or low dose irradiated PET plastics in various cement concrete mixtures led to reduced porosity in addition to increased compressive strength [9].

Thermal depolymerization of polyethylene terephthalate through glycolysis to yield Bis(2-hydroxyethyl) Terephthalate (BHET) has been covered in numerous studies over the past decades. The studies include a comprehensive overview of recent advances in PET chemical recycling [16]; simulating the process of BHET production and its recovery using two-stage evaporation systems [17]; and catalyzing PET depolymerization through glycolysis in an environmentally friendly way, using a bio-derived solid heterogeneous orange

peel ash catalyst [18]. Research has proven that the BHET (synthesized through glycolysis from PET plastic waste) has great potential to be applied as a concrete mixture additive, although further research was recommended, particularly on resulting mechanical as well as durability performances [19].

In one remarkable study it was found that cementitious composites of BHET have higher calcium hydroxide content, lower porosity, as well as lower water absorption percentages in comparison to cementitious composites of dioctyl terephthalate [20]. It was reported that hydrogen bonds are formed in BHET cementitious composites, and those hydrogen bonds crucially prevent cement particles from agglomerating because of electrostatic attraction. They further significantly contribute to healing cracks through formation of more hydrated products.

Studies focused on testing different polymers and improving their temperature resistance to enable their usage as oil well cement additives are of interest lately [21]. Thus, this study, unlike the previous studies, focuses on investigating the prospect of using waste PET plastics in cementing shallow oil and gas wells. Effects of the PET derived additives are investigated in significantly dispersed oil well cement slurries following addition of highest superplasticizer amounts, hence its benefits to strength in PET containing concrete mixtures. PET was used in the form of untreated fibers, irradiated fibers, and powdered BHET synthesized through its glycolysis (thermal depolymerization), while shallow oil well conditions were assumed.

2. Materials and Methods

Experimental work carried out for this project involved prior analysis of the local class A cement, preparations of PET/PET plastic based additives, and the base design of the oil well cement. Preparations of oil well cement slurries blended with the prepared PET/PET plastic based additive(s) followed, accompanied by the determination of relative

rheological behaviours and pumpabilities, before curing and testing of final compressive strengths.

2.1. Materials

Local class A cement (42.5R AfriSam high strength cement) for use under normal conditions was sourced from AfriSam South Africa, and its composition was determined through XRF analysis using an X-ray Florescence (XRF) spectroscopy. A polycarboxylate based superplasticizer (PCE) used in this study was provided by Sika South Africa. Oil well cement additives, namely, citric acid as a retarder, calcium oxide (CaO) as an expanding agent, polyvinyl alcohol (PVA) as a fluid loss additive, and polyethylene glycol (PEG) as a defoamer were used in the formulation of slurries. Calcium oxide, polyvinyl alcohol, polyethylene glycol (PEG 6000), and citric acid were sourced from Sigma Aldrich, together with ethylene glycol ($\geq 99.5\%$) and lead acetate used during the PET depolymerisation to yield the BHET additive. PET was obtained from waste PET plastic bottles, which were washed and dried before they were processed accordingly.

2.2. Preparation of PET Additives

Waste PET plastic bottles were washed using tap water, dried, and cut into flakes of about $1\text{cm} \times 1\text{cm}$ dimensions. The flakes were then uniquely prepared or processed as explained and shown below to yield each of the PET plastics derived additive.

1) Additive I - untreated PET fibers

After the cut PET plastic flakes with dimensions of about $1\text{cm} \times 1\text{cm}$ were obtained, they were further cut into short and thin sized PET fibers using a scissor. Final length of the fibers was limited to 1cm while the thickness was limited to less than $1180\mu\text{m}$ with the help of sieve analysis as shown in Figure 1.

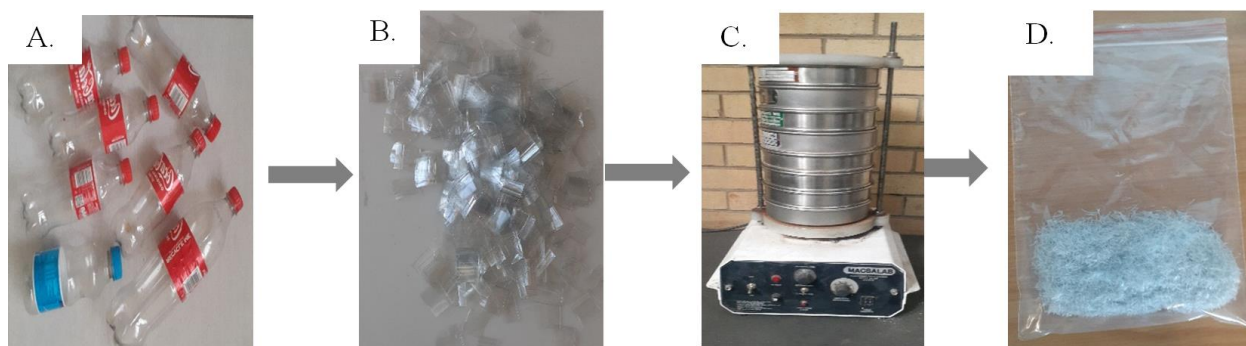


Figure 1. Stepwise preparation of the untreated PET fibers used as additives (A. Waste PET plastic bottles, B. Cut PET plastic flakes, C. Sieve through to eliminate thicker fibers, D. Prepared untreated PET fibers additive).

2) Additive II - irradiated PET fibers

Washed, dried, and cut waste PET plastics with dimensions

of about $1\text{cm} \times 1\text{cm}$ were sent to an irradiation facility where they were irradiated at radiation doses of 5.8 Gy/min up to a

total dose of 10 kGy using a cobalt-60 gamma irradiator.

Irradiated PET plastic flakes were then further cut into short and thin sized PET fibers using a scissor. Final length of the fibers was limited to 1cm while the thickness was limited to less than 1180 μ m with the help of sieve analysis as in part a.

3) Additive III - depolymerized PET plastic powder additive to form BHET

PET plastic was depolymerized through glycolysis to form Bis (2-Hydroxyethyl) terephthalate (BHET) as shown in Figure 2. PET plastic flakes weighing 20.132 grams and 80mL of ethylene glycol (a solvent) were introduced into a 250mL round bottom flask, followed by the addition of 0.406g of lead acetate as a catalyst. The prepared mixture was then refluxed at a temperature of 190 $^{\circ}$ C in a closed system for 90 minutes, using a glass condenser and continuously running tap water for cooling. As the reaction continued under reflux,

the mixture changed from being clear with visible continuously dissolving flakes of PET to being uniform, viscous and grayish liquid, which further turned into an opaque gray coloured semi-solid when cooled to room temperature.

After the mixture was heated under reflux and allowed to cool, unreacted ethylene glycol was dissolved by adding 40mL volume of distilled water into the refluxed mixture and gentle heating the resulting mixture while stirring using a magnetic stirrer hot plate. The mixture was then allowed to cool to room temperature and as it was cooling, development of white crystals, the resulting BHET, could be seen. Vacuum filtration of the mixture using a buchner funnel, vacuum flask, filter paper and a vacuum pump then followed. Thereafter, the recovered crystalline residual BHET was dried in an oven at a temperature of 65 $^{\circ}$ C before being used as the cement additive.

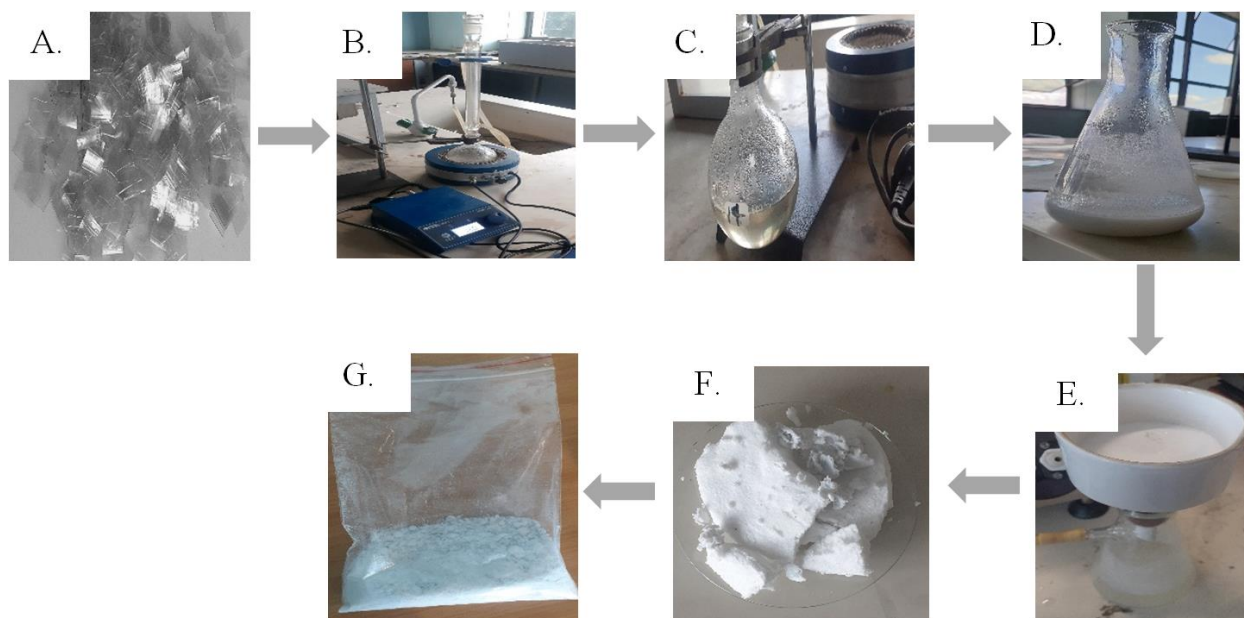


Figure 2. Stepwise depolymerization of PET into BHET (A. PET plastic flakes, B. Mixture under reflux, C. Resulting homogeneous mixture after reflux, D. Mixture after dissolving excess solvent, E. Vacuum filtration of the mixture, F. Resulting residual BHET, G. Dried and packed BHET).

2.3. Slurry Formulation

Oil well cement slurries and specimens were prepared following American Petroleum Institute (API) recommended practices [22]. The cement was sieved to pass through an 850 μ m sieve prior to being utilized, and slurries were puddled in layers as they were being placed in moulds containing a releasing agent and a sealant.

A slurry base design was performed to design a base oil well cement slurry that is suitable for use to assess effects of incorporating the prepared PET based additives. Standard mix water ratio, compatibilities, and influences of the additives were determined during the slurry base design. Based on

literature, incompatibility between citric acid and the PCE superplasticizer results from competitive adsorption of citrate onto the particle surface of cement causing displacement of PCE, thereby workability of resulting oil well cement slurry would be reduced [23]. Furthermore, it was reported that there are different concentration regimes for this competitive additive adsorption [24]. In this study, such incompatibility was avoided by adding limited citric acid amount, as a result there were enough free adsorption sites on cement grains and that prevented the retarder from competing with PCE for adsorption onto the cement surface.

Mixabilities and settling of the base slurries were monitored closely as part of the base design. Precisely 41% bwoc mix water ratios were used to prepare the oil well cement

slurries. The formulated slurries had theoretical slurry densities of 15.8 ± 0.05 ppg (1.89 ± 0.005 g/mL), similar to the ordinarily desired density of class A oil well cement slurries used to cement light formations.

Owing to the slurry base design, a slurry containing 2% bwoc CaO, 0.5% bwoc PVA, 0.1% bwoc citric acid, 0.02% bwoc PEG, and 0.4% bwoc PCE was chosen and used as the

control given its impressive properties, namely, rheology, mixability, settling, and final compressive strength. Effects of the prepared untreated PET fibers, irradiated PET fibers, and BHET additives in cementing of shallow oil and gas wells were investigated by adding these additives in concentrations of 0.2, 1.0, and 1.8% bwoc, as presented in Table 1.

Table 1. Mix designs of oil well cement slurries.

Slurry	Additives (% bwoc)							
	CaO	PVA	Citric acid	PEG	PCE	Untreated PET fibers	Irradiated PET fibers	BHET
Base slurry	2	0.5	0.1	0.02	0.4	–	–	–
+ 0.2% bwoc untreated PET fibers	2	0.5	0.1	0.02	0.4	0.2	–	–
+ 1.0% bwoc untreated PET fibers	2	0.5	0.1	0.02	0.4	1	–	–
+ 1.8% bwoc untreated PET fibers	2	0.5	0.1	0.02	0.4	1.8	–	–
+ 0.2% bwoc irradiated PET fibers	2	0.5	0.1	0.02	0.4	–	0.2	–
+ 1.0% bwoc irradiated PET fibers	2	0.5	0.1	0.02	0.4	–	1	–
+ 1.8% bwoc irradiated PET fibers	2	0.5	0.1	0.02	0.4	–	1.8	–
+ 0.2% bwoc BHET	2	0.5	0.1	0.02	0.4	–	–	0.2
+ 1.0% bwoc BHET	2	0.5	0.1	0.02	0.4	–	–	1
+ 1.8% bwoc BHET	2	0.5	0.1	0.02	0.4	–	–	1.8

2.4. Assessment of PET Additives

To determine the effects of adding the prepared PET plastic derived additives in oil well cements, rheological property tests, slurry pumpability tests, and compressive strength tests were performed.

2.4.1. Rheological Property Tests

An MCR 101 conventional rotational and non-pressurized rheometer equipped with a viscotherm and a computerized software for displaying and analysing results was used to measure rheological properties of the prepared sample oil well cement slurries. Following API recommendations, measurements were started at low speeds of about 3 rpm (shear rates of ~ 5 s⁻¹), and limited to a maximum speed of 300 rpm which was equivalent to the maximum shear rate of ~ 392.7 s⁻¹. Readings obtained at rotational speeds greater than 300 rpm were disqualified [25].

The tests were conducted under atmospheric pressure and at a temperature of 38 °C, simulating the bottom hole circulating conditions of shallow oil and gas wells. Rheolog-

ical properties (plastic viscosities and yield strengths) of the slurries were automatically calculated from flow curves generated by the software using Bingham plastic model and Herschel-Bulkley's model.

2.4.2. Pumpability Tests

A prediction model was developed using Ansys computational fluid dynamics (CFD) software. The model assessed the pumpabilities of the oil-well cement slurries by predicting pump rates and pressures required to pump each slurry and fill a 762 m long casing. The slurry density as well as determined slurry viscosities were used as input parameters to determine pumpability of each slurry. Wellbore configuration, geothermal gradient, ground surface temperature, inlet slurry temperature, slurry flow rate, as well as thermophysical properties of drilling fluid, water, cement slurry, formation, and casing used were taken from a previous research study [26]. A static mesh that do not change as the simulation runs was used. Figure 3 and figure 4 show the model environment and mesh.

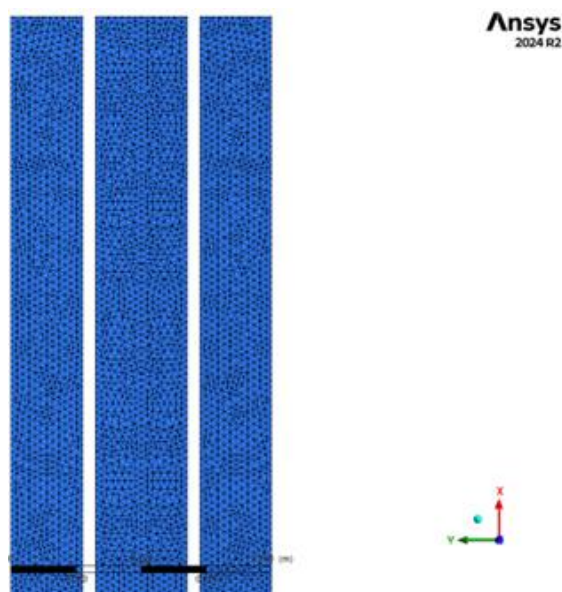


Figure 3. Casing top geometry and mesh.

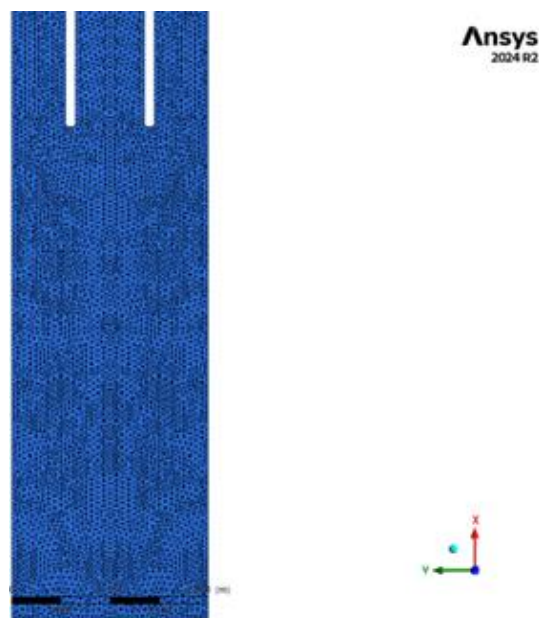


Figure 4. Casing bottom geometry and mesh.

2.4.3. Compressive Strength Tests

Compressive strength tests were performed to determine the ability of each prepared oil well cement sheath to withstand differential oil and gas well pressures. Prepared slurry samples were transferred into 50mm × 50mm cubical steel moulds that were lightly coated with grease as a releasing agent and as a sealant in between the moulds. The top of the moulds was covered with a flat metal sheet as a cover plate, thereafter, the moulds and their contents were completely immersed in a preheated atmospheric curing water bath for a period of 24 hours. This allowed the prepared oil well cement slurries to be cured at 38 °C and atmospheric pressure. These

conditions correspond to bottom-hole circulating temperature and pressures of shallow oil and gas wells according to API recommended practices and ANSI specifications [22, 27]. To further ensure waterproofness, plastic was used to collectively cover the immersed contents. After 24 hours, the cured specimens were removed from the moulds and temporarily submerged in water, then wiped using a paper towel before they were tested. The water temperature was regulated at 27 °C ± 3 °C.

A destructive testing method was employed. The cured oil well cement cubical specimens were crushed using a hydraulic press and a maximum compression load each specimen could withstand was recorded.

3. Results and Discussions

The prospect of using PET waste in cementing atmospheric pressured and elevated temperature oil and gas

wells was investigated following the formulation of local class A cement into oil well cement. Chemical and mineral compositions of the cement determined through XRF analysis are presented in Tables 2 and 3, respectively.

Table 2. Chemical composition of the cement.

Elemental oxides	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Cr ₂ O ₃	LOI
Concentrations (%)	22.11	6.5	2.7	0.09	2.13	57.94	0.02	0.38	0.47	0.12	0.03	4.12

Table 3. Mineral composition of the cement clinker.

Component	3CaO · SiO ₂	2CaO · SiO ₂	3CaO · Al ₂ O ₃	4CaO · Al ₂ O ₃ · Fe ₂ O ₃
Amount (%)	20.24	48.14	12.66	8.21

Composition of the cement exhibits a moderate degree of similarity to that of API certified Class A oil well cements [28-30]. Addition of additives to develop the workable and standard oil well cement slurry from the cement had diverse effects, overall, enhancing mixability/workability. Addition of citric acid as a retarder proved to be extremely effective. Certainly, overcoming the pre-hydration and/or carbonation signaled by the cement's higher loss on ignition. Prolonged retardation of this cement can be attributed to its mineral composition of significantly higher dicalcium silicate with significantly lower tricalcium silicate contents.

3.1. Rheological Properties

Understanding rheological properties of oil well cement slurries is crucial to ensure the integrity of the cementing job as well as structural stability and long-term performance of the well. Oil well cement slurries should behave as a rigid body at low stresses and flow as viscous fluid at high stresses. Such shear thinning behavior ensures proper placement and setting of the cement within wellbores, whereby the slurry remains in place until enough stress is applied to initiate its flow during cementing operations. To illustrate the effects of adding PET derived additives into highly dispersed oil well cement slurries, behaviors of the prepared oil well cement slurries are presented as viscosity-shear rate curves in Figures 5-8.

In these Figures 5-8 it is depicted that the slurries exhibit the shear thinning behavior, shear stresses increase with increasing shear rates. This would ensure that the slurries remain in their fluid state during pumping and only transition to solid state after placement. Similar behaviors are observed in several research studies, except minor slip effects which are occurring at lower shear rates due to presence of the solid PET

fibers as additives [31-33].

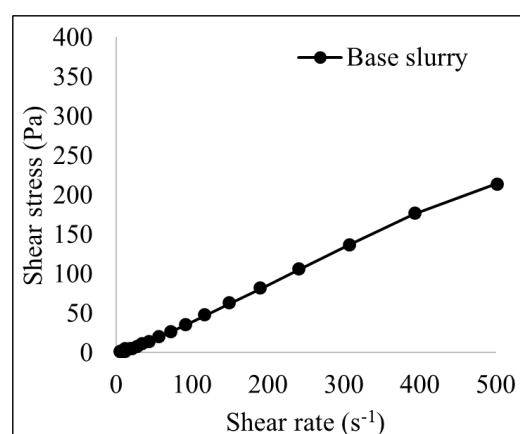


Figure 5. Flow curve of the base slurry.

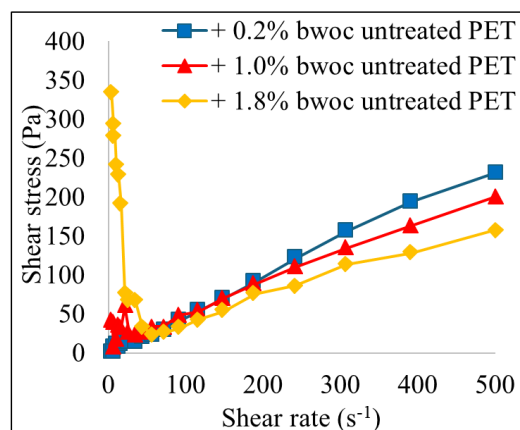


Figure 6. Flow curves of slurries containing untreated PET fibres.

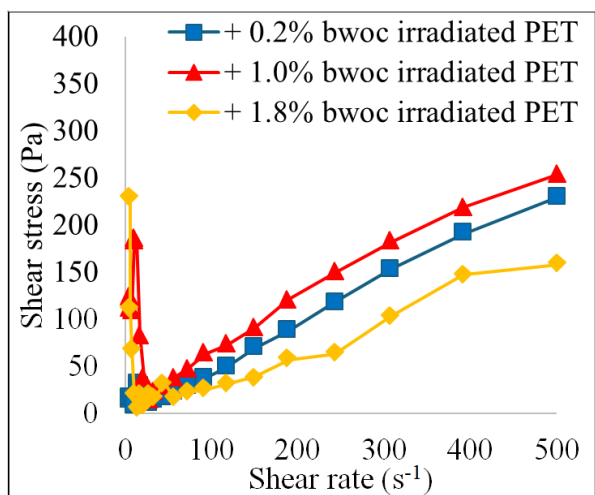


Figure 7. Flow curves of slurries containing irradiated fibres.

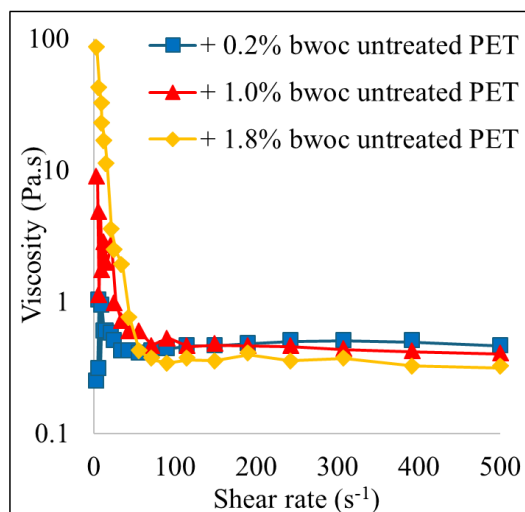


Figure 10. Viscosity-shear rate curves of slurries containing untreated PET fibres.

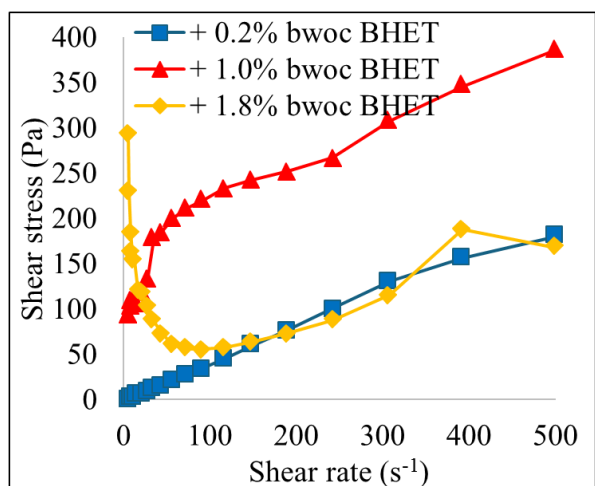


Figure 8. Flow curves of slurries containing BHET.

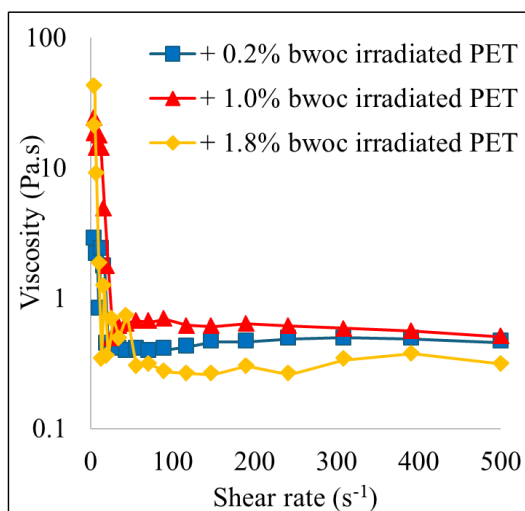


Figure 11. Viscosity-shear rate curves of slurries containing irradiated PET fibres.

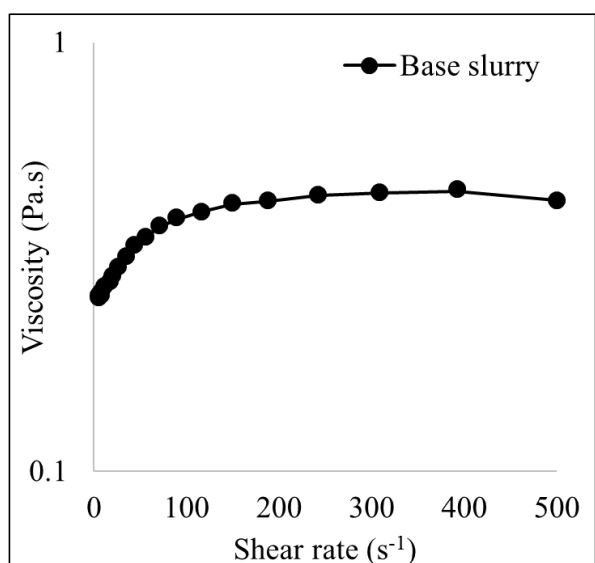


Figure 9. Viscosity-shear rate curve of the base slurry.

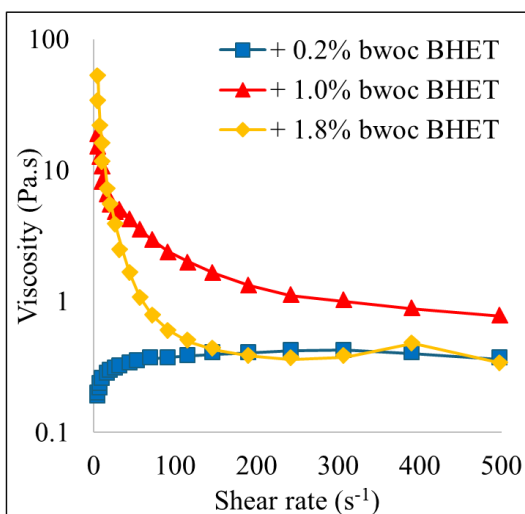


Figure 12. Viscosity-shear rate curves of slurries containing BHET additive.

Addition of BHET at concentrations of 1% bwoc and 1.8% bwoc caused the slurry to thicken more rapidly. The slurry containing 1.8% bwoc BHET additive immediately turned into paste after mixing. Similar plots of shear stress (Figure 8) and viscosity (Figure 12) as functions of shear rate have been observed when analyzing cement pastes [34]. In Figures 6 and 7 it is observed that adding 1.8% bwoc untreated or irradiated PET fibers, respectively, results to slurries exhibiting an uneven linear relationship between shear stress and shear rate even at higher shear rates. This means increased addition of the PET fiber additives would make it hard to reliably predict and control behaviors of the slurries. Excessive surge or swab pressures can occur, leading to wellbore instabilities and more complications during pumping and placement of the slurries.

The formulated base oil well cement slurry (in Figure 9) and the slurry incorporated with 0.2% bwoc BHET additive (in Figure 12) exhibited shear thickening behavior at lower shear rates when apparent viscosity was plotted as a function of shear rate. Shear thickening behavior is disadvantageous and uncommon for oil well cement slurries. In this case, it is

caused by presence of the polycarboxylate-based superplasticizer [32, 35, 36]. It is usually addressed by adjusting formulation, either by reducing contents of solids, adding more dispersant, or by substituting additives that promote shear thickening such as the polycarboxylate based superplasticizer. Nonetheless in this study, after addition or further addition of the PET derived additive (s), the suspension(s) started to exhibit shear thinning behavior, where the viscosity decreased with increasing shear rate.

The incorporation of untreated and irradiated PET fibers resulted to more and more slip effects with increasing incorporation concentrations, making it hard to adequately define and/or measure slurry rheological properties. At assumed shallow well conditions (ambient pressure and 38 °C), the formulated base oil well cement slurry had a plastic viscosity of 381.23 cP after being subjected to shear rates ranging from ~3 rpm up to ~300 rpm. Rheological properties of the slurries were determined using the Bingham plastic model and the Herschel-Bulkley's model from respective flow curves (in Figures 5-12) and are presented in Figure 13 and Table 4.

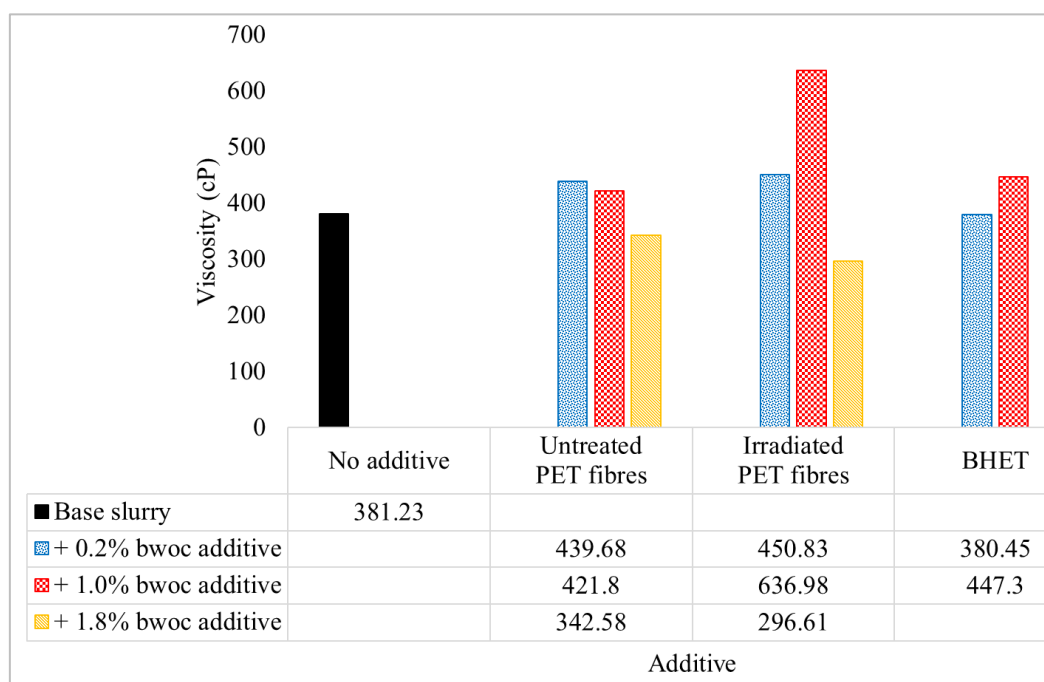


Figure 13. Plastic viscosities of the slurries (determined using Bingham plastic model).

Table 4. Yield strengths determined through the Bingham I and Herschel- Bulkley models.

Slurry	Yield Strength (Pa)	
	Bingham I model	Herschel- Bulkley model
Base slurry	-	0.06
+ 0.2% bwoc untreated PET fibers	1.57	4.93
+ 1.0% bwoc untreated PET fibers	5.53	-

Slurry	Yield Strength (Pa)	
	Bingham I model	Herschel- Bulkley model
+ 1.8% bwoc untreated PET fibers	2.67	3.07
+ 0.2% bwoc irradiated PET fibers	-	3.36
+ 1.0% bwoc irradiated PET fibers	-	-
+ 1.8% bwoc irradiated PET fibers	-	12.06
+ 0.2% bwoc BHET	-	-
+ 1.0% bwoc BHET	170.9	143.35

The incorporation of 0.2% and 1.0% bwoc untreated PET fibers in the oil well cement resulted to 15.33% and 10.64% increases in plastic viscosity, respectively. Lower increase in plastic viscosity after addition of 1.0% bwoc untreated PET fibers is observed. However, due to significantly yield strength (252.59% higher than that of the slurry incorporated with 0.2% bwoc untreated PET fibers), the plastic viscosity of the slurry containing 1.0% bwoc untreated PET fibers is likely to be relatively higher. Such erroneous viscosity measurement could be largely attributed to slip effects. Occurrence of slip effects at lower shear rates, as observed in Figure 10 after incorporation of untreated PET fibers, led to rheological measurements being conducted from significantly higher shear rates ($\sim 72 \text{ s}^{-1}$) for reliable measurements using the models. Pre-irradiation of PET fibers before incorporation had no notable impact in reducing or enhancing the slip effects as shown in Figure 11.

Adding pre-irradiated PET fibers increased the plastic viscosities of the slurries more than adding untreated PET fibers (Figure 13). Addition of irradiated PET fibers at a concentration of 0.2% bwoc increased the slurry's plastic viscosity by 18.26%, while its addition at a concentration of 1.0% bwoc increased the plastic viscosity by 67.09%.

Addition of 0.2% bwoc BHET additive barely affected the rheological characteristics of the slurry. See the resemblance in rheological behaviors of the base slurry and the slurry incorporated with 0.2% bwoc BHET in Figure 9 and Figure 12, respectively. Further, the plastic viscosity of the slurry containing 0.2% BHET differs by only 0.21% from the plastic viscosity of the base slurry (see Figure 13). An increase in BHET incorporation concentration to 1.0% bwoc increased the plastic viscosity by 17.33%. Increases in the viscosities of slurries containing the BHET additive at higher concentra-

tions were observed to be associated with extreme increases in yield strengths. Increases in the viscosities of slurries containing higher concentrations of the BHET additive were found to be linked to significant increases in yield strengths. Addition of the PET fibers as additives at higher concentrations may result in better manageable rheological behavior for oil well cement slurries. Yield strengths for the slurries incorporated with the PET derived fibers as additives were significantly lower compared to yield strengths of the slurries containing BHET (Table 4).

3.2. Pumpabilities

Pumpability of an oil well cement slurry depends on rheological properties, density of the slurry, diameter and length of the casing pipe, as well as friction losses due to contact between the slurry and the wellbore or casing. To effectively displace drilling fluids and ensure the cement slurry completely fills the annular space without damaging the formation or causing incomplete displacement, hydrostatic pressure and friction pressures are necessary to consider along with the pump pressures. Due to the challenges in accurately determining the rheological properties of slurries containing higher dosages of PET-derived additives, the simulated required pump pressures and flow velocities for the slurries containing $\geq 1.0\%$ bwoc of the PET based additives are considered inadequate. Table 5 presents the pump pressures and slurry flow velocities required to pump and fill each slurry containing the PET derived additives within the annular space between the casing and the wellbore wall of a 762m deep well. The findings indicate that the addition of PET-derived additives to the slurry adversely affected its pumpability.

Table 5. Required pump pressures and flow velocities for the slurries.

Slurry	Pressure (psi)	Velocity (m/s)
Base slurry	122.55	29.98

Slurry	Pressure (psi)	Velocity (m/s)
+ 0.2% bwoc untreated PET	139.23	31.96
+ 1% bwoc untreated PET	134.45	31.4
+ 1.8% bwoc untreated PET	111.53	28.59
+ 0.2% bwoc irradiated PET	142.57	32.33
+ 1% bwoc irradiated PET	197.24	38.01
+ 1.8% bwoc irradiated PET	97.75	26.78
+ 0.2% bwoc BHET	95.43	26.46
+ 1% bwoc BHET	141.55	32.22

In Table 5, it is observed that greater force would be required to pump the cement slurries incorporated with PET fibres, particularly irradiated PET fibres, than slurries incorporated with BHET at concentrations $\leq 1.0\%$ bwoc. This is consistent with the rheological properties and behaviors ob-

served in Figure 13 and Table 4. Slurries with higher viscosity and/or yield strength required greater pumping pressures and velocities to be pumped effectively. Figure 14 illustrates pumping of the base slurry through pressure and velocity contours.

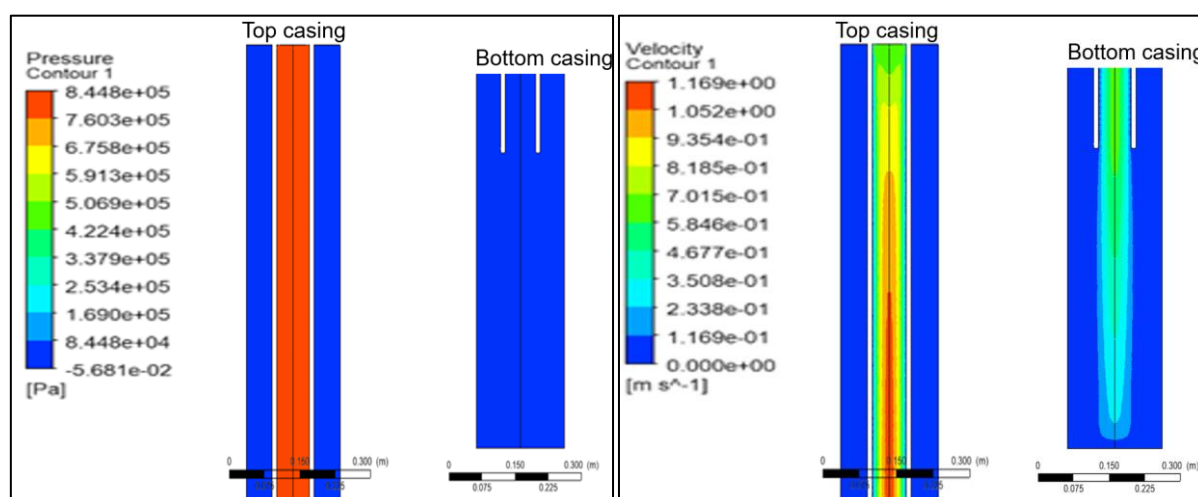


Figure 14. Pressure and velocity contours illustrating variations in pump pressure and flow velocity of the base slurry during placement.

Pump pressures required for placement of the slurry (base slurry) increased by 13.61% and 9.71% after addition of 0.2% and 1.0% bwoc untreated PET fibres, respectively. Increases of 16.34% and 60.95% in pump pressure were observed after the incorporation of 0.2% and 1.0% bwoc irradiated PET fibres, respectively. The incorporation of BHET initially reduced the pump pressure by 22.13% after its addition at 0.2% bwoc, thereafter, the pump pressure increased by 15.50% after BHET's addition at a concentration of 1.0% bwoc. Maximum required pump pressure after addition of the additives at lowest concentrations (0.2% bwoc) was found to be 142.57 psi (after incorporation of irradiated PET fibres), while the minimum required pump pressure was discovered to be 95 psi (after addition of the BHET). The required pump pressures are

comparable to the 100 psi pump pressure that was successfully used to pump a slurry containing 25 wt% elastomeric expandable additive [37]. The required pump pressures for the slurries (Table 5) are significantly lower than the formation fracture pressure limits (2350-2700 psi) discovered during pumping of a heavy slurry into a 3620 m deep well with 9"5/8 casing in Algeria [38]. These pressures are also substantially lower than the average fracture pressure (4585 psi) of carbonates from the Lockhart formation in Pakistan [39]. During a cement job, slurries can even be subjected to total pressures exceeding 30 000 psi [40]. Given the extremely low pump pressures required to pump the slurries containing the PET derived additives, it can be concluded that the addition of untreated PET fibres, irradiated PET fibres, and BHET barely

have adverse effects on pumpabilities of the oil well cement slurries, especially at low concentrations (0.2% bwoc).

3.3. Compressive Strengths

The under investigation local class A cement reached a maximum compressive strength of 27.17 MPa in its pure form, without any additives. This compressive strength significantly exceeds the API specified minimum compressive strength of 12.4 MPa under similar curing conditions and period [27]. As a result, the potential for successful formulation of cement that can withstand harsh conditions such as high pressures, high temperatures, and exposure to aggressive fluids found in oil and gas wells using this cement could be foreseen. Effects of the PET waste derived additives on compressive strength of the prepared oil well cement are presented as Figure 15.

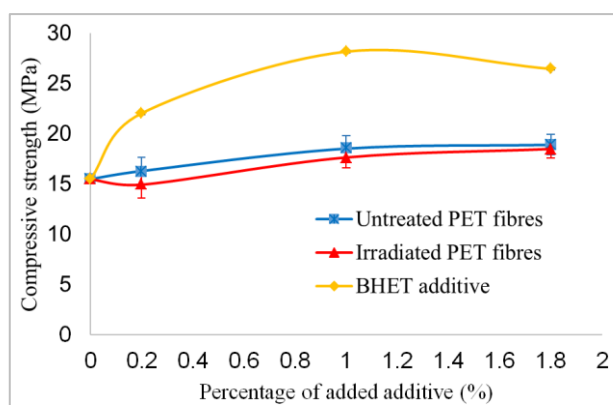


Figure 15. Compressive strengths of the slurries incorporated with PET derived additives.

The base slurry had a compressive strength of 15.51 MPa. Untreated PET fibres increased compressive strength of the oil well cement to 16.32 MPa, 18.55 MPa, and 18.93 MPa after their addition at 0.2%, 1.0%, and 1.8% bwoc dosages, respectively (Figure 15). These are 5.22%, 19.60%, and 22.05% increases in compressive strength, respectively, indicating that the PET fibres as additives played a reinforcing role, thereby, leading to increased strength. The incorporation of irradiated PET fibres at concentrations of 0.2%, 1.0%, and 1.8% bwoc led to 14.96 MPa (3.5% decrease in compressive strength), 17.67 MPa (13.93% increase in compressive strength), and 18.51 MPa (19.34% rise in compressive strength) compressive strengths, respectively. Reinforcing capabilities of the irradiated PET fibres can be observed through the increases in compressive strength with increased incorporation concentration of at most 1.8% bwoc, however, they are relatively lower compared to those brought about by addition of the untreated PET fibres at similar concentrations. The applied irradiation dose (10 kGy) appears to have weakened the strength of PET film flakes, however, not

enough such that the PET becomes brittle and can be easily ground into powder. The increased compressive strengths after the incorporation of 1.0% and 1.8% bwoc irradiated PET fibres could be attributed to formation of C – A – S – H gels together with secondary C – S – H throughout the processes of hydration and/or increased crystallinity of the PET fibres after irradiation [9]. The increases in compressive strength after incorporation of the PET fibres (untreated and irradiated) may be largely attributed to the presence of a PCE superplasticizer as one of the additives. It can stimulate adhesive strength between the incorporated PET fibers and the oil well cement [11]. However, despite these positive effects on compressive strength brought about by these waste PET derived fiber additives, their addition still poses a serious challenge. A challenge of fibers being unevenly distributed as they are excessively light in weight. They tend to occupy the top part/surface of the oil well cement slurries prior and after setting (Figure 16). Such uneven distribution causes set oil well cement to be unevenly reinforced.



Figure 16. Uneven reinforcement in a set oil well cement specimen incorporated PET fibers.

In Figure 16, high standard deviations are observed after compressive strength analyses of oil well cements incorporated with the PET fibres. They range from 0.91 MPa up to 1.36 MPa. This can be a consequence of the inconsistent and uneven reinforcement by the PET fibres. Further, this shows that it will be challenging to ensure that a slurry containing PET fibres as additives remains homogeneous during mixing and placement till setting stages of the cement. Managing the density of such slurries and balancing pumpability with wellbore integrity may be difficult.

Compressive strength of the oil well cement increased by 42.23%, 81.82%, and 70.73% after addition of BHET as an additive at 0.2%, 1.0%, and 1.8% bwoc dosages, respectively. Optimum addition concentration of the BHET additive was observed to be 1.0% bwoc. The significant increase in compressive strength could be attributed to BHET's hydrophilic hydroxyl groups granting increased chances of cement water hydration thus resulting to closely packed oil well cement matrix [20]. It would further be attributed to the fine powdered nature of BHET, which made its incorporation effects outperform the effects brought about by the PET reinforcing fiber additives. An increase in particle size of incorporated

PET leads to a decrease in compressive strength [41]. Similarly, fine powdered nature of the BHET may have also contributed to the higher resulting compressive strengths after its addition.

Standard deviations of ≤ 0.13 MPa were obtained after repeatedly performing compressive strength analysis on cement specimens containing the BHET as an additive. This improved precision signals homogeneous distribution of the additive within the slurry and set cement. Therefore, BHET can be successfully used as an oil well cement additive. Considering the significant early-strength developments of the oil well cement slurries incorporated with BHET, the BHET can be successfully used as an accelerator. The minimal influence of the BHET on plastic viscosity (Figure 13) and rheological behavior (Figures 9 and 12) of the slurry at low concentrations of 0.2% bwoc suggests that it should be added at dosages of about 0.2% bowc.

4. Conclusions

This study was aimed at formulating an oil well cement slurry using local class A cement and investigating the prospect of using untreated PET fibers, irradiated PET fibers, and BHET in cementing of shallow oil and gas wells. The following is concluded:

- 1) The local class A cement was successfully formulated into an oil well cement slurry through the addition of additives.
- 2) Addition of the PET derived additives overcame shear thickening behavior in oil well cement slurries.
- 3) Irradiation of PET to be incorporated in oil well cement slurries resulted to significantly increased plastic viscosities, increasing with an increase in dosage.
- 4) BHET synthesized through glycolysis of PET can be readily used as an accelerator, especially at concentrations of about 0.2% bwoc where it barely affected rheological behavior and pumpability of the slurry while significantly increasing early compressive strength. Nonetheless, its utilization during cementing of HPHT oil and gas wells must be reconsidered given its rapidly decreasing viscosity under high temperatures.
- 5) Presence of the superplasticizer among additives of PET incorporated slurries enabled enhancements in compressive strengths by increasing adhesive strength between PET fibers and cement mixture.
- 6) Oil well cement reinforcements through PET fibers, rarely irradiated and untreated, have a potential to be used in oil well cementing. However, these PET fibers unevenly reinforce different parts of the cement matrix.

Further investigations focusing on the influence of completely powdered and irradiated at varying radiation doses PET plastics are suggested, while more studies on utilization and further influence of BHET in oil well cements are recommended.

Abbreviations

PET	Polyethylene Terephthalate
bwoc	By Weight of Cement
BHET	Bis (2-hydroxyethyl) Terephthalate
XRF	X-ray Florescence Spectroscopy
API	American Petroleum Institute
ANSI	American National Standards Institute
CFD	Computational Fluid Dynamics

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Conflicts of Interest

The authors declare no conflicts of interest.

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