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New HTHP fluid loss control agent for oil-based drilling fluid from pharmaceutical waste

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A B S T R A C T

In Oil-Based drilling fluid systems (OBM, for Oil-Based Mud) the oil phase is the major source of contamination and hydrocarbon pollution is, by far, the main concern. However, the release and accumulation of mud additives in the environment may be deleterious on grounds of volume and/or concentration. This paper describes a waste valorisation study from an antibiotic large-scale manufacturing for the preparation of a new drilling fluid additive (Fluid-Loss-Control agent: FLC) for OBM. This additive is environment-friendly, biomaterial in nature, and totally biodegradable and thus expected to have no detrimental effects on the surrounding environment and ecosystems. After product washing, heating, grinding, and screening, a cationic surfactant was used to improve fluid stability and filtration properties. Our results show that: According to drilling fluid requirements, the treatment of this pharmaceutical reject yields a product with good properties, *i.e.* satisfactory as far as thermal stability, filtration characteristics, and rheology property are concerned, - The pre-treatment of those products (according to their original state and particle size, as well as the type and concentration of added surfactant) enhances additive quality and shows good compatibility in drilling fluid systems, - The substitution of this new product for conventional additives affords good drilling fluid stability and performance under high temperature and high pressure (HTHP) conditions, economic, and environmental solutions to improve the environmental standing of OBMs further.

1. Introduction

Drilling fluids are commonly classified according to their base fluids, which mainly belong to the Water-Based Mud (WBM) or Oil-Based Mud (OBM) types (Caenn et al., 2016). For drilling oil and gas wells, OBM, SOBM (Synthetic Oil-Based Mud) and NADF (Non-Aqueous Drilling Fluid) provide better drilling performance and wellbore stability in comparison with WBM (Davison et al., 2001). Their chemical composition, impact on the environment (Bernier et al., 2004) and safety show a need for a rapid solution in the drilling projects (OGP and IPIECA, 2009), *i.e.* very restrictive regulations on the use of OBM and even WBM, containing numerous contaminants. Some common mud additives are dangerous or hazardous vapours such as polymers, viscosifers, thinners, and corrosion inhibitors and must be handled with caution (ASME, 2005). Perilous effects of the mud additives on human life (Miller and

Pesaran, 1980) and marine life have been reported (Apaleke et al., 2012).

Mud service companies are developing flexible drilling fluid systems (Growcock et al., 2002) that are much more amenable to biotreatment (Amanullah and Long, 2003). Recent research investigated the applicability of food waste products as drilling fluid additives (Al-Hameedi et al., 2019a). Al-Hameedi et al. (2019b) conducted experimental research and concluded that the potato peel powder increased plastic viscosity (PV), decreased yield point (YP) and reduced fluid loss. Iranwan et al. (2009) studied corncob and sugarcane as viscosifying materials. The study showed an improvement in PV but a reduction in the gel strength and YP properties. Abu Taleb et al. (2020) used mandarin peel powder products as drilling fluid additives. The results of this study showed that the product significantly increased YP and PV and reduced fluid loss.

There are some published studies to investigate new the performance

Abbreviations and acronyms nomenclature and symbol		HP/HT	High Temperature/High Pressure
		FAO	Food and Agriculture Organisation
API	American Petroleum Institute	CICAD: Concise International Chemical Assessment Document AV:	
Conv.	Conventional		Apparent Viscosity
FCLS	FeCr–lignosulfonate	PV	Plastic Viscosity
FLC	Fluid loss control	YP	Yield point
HR	Hot Rolling	$G_{0/10}$	Gel after 0 and 10 min
OBM	Oil-Based Mud	R_{600}	dial reading at 600 rpm
WBM	Water-Based Mud	R_{300}	dial reading at 300 rpm
O/W	Oil/Water	d	fluid density
PSD	Particle Size Distribution	K_i	initial Soltrol permeability
RPM	Revolutions per minute	K_f	final Soltrol permeability
SOBM	Synthetic Oil-Based Mud	K_{air}	air permeability
NADF	Non-Aqueous Drilling Fluid	DR	damage ratio, %
CTAB	CetylTrimethyl Ammonium Bromide	ζ	Zeta potential, mV

of new materials to meet functional requirements and enhance the mud properties of WBM (Khodja et al., 2010). These materials are mango leaves and cashew extracts (Omotioma et al., 2014), potato starch extracted from potato tubers (Nyeche et al., 2015), and cellulose from corncob (Nmegbu and Bekee, 2014). Their experiments showed that the potato starch had negative impacts on the rheological and filtration characteristics, while the cashew and mango leaves improved the rheological properties, and the cellulose was efficient in reducing fluid loss of the drilling fluid.

1.1. Drilling fluid

1.1.1. Drilling fluid additives

In OBM, emulsifiers (nonionic and ionic surfactants) are generally multi-functional additives that also serve as wetting agents and improve emulsion stability at high-temperature, high-pressure (HTHP) (Caenn et al., 2016). Herzhaft et al. (2001) reported in their study that the fluid loss control and filter cake quality play an important role in the wellbore construction process and to meet anticipated downhole conditions and reduce the risk of potential drilling problems such as differential sticking (Longeron et al., 1998), loss of circulation and formation damage (Amanullah, 2003).

Wellbore differential pressure provides the driving force for a flow of mud filtrate movement through the borehole wall into the formation (Fink, 2015). The deposition of solids on the face of the porous formation creates a wall cake. The filtration volume and cake thickness are influenced by the equivalent circulation density, which in turn is a function of the fluid composition and formation characteristics (Caenn et al., 2016). In recent times, the oil industry has shown increasing awareness towards maintaining optimum well productivity through better drilling fluid design, since minimising filtration is beneficial to borehole stability (Plank and Gossen, 1989) and production (Audibert et al., 1999). Caenn et al. (2016) investigated the mechanisms of the filter cake properties. They found three main mechanisms for fluid loss control additives in drilling muds (WBM): (1) reducing fluid movement into the formation by viscosifying the base fluid. (2) blocking and plugging of filter cake pores creates low permeability filter cakes, resulting in filtration control. (3) coating mud particulates and creating impermeable layers, preventing the escape of water into the formation.

Most of the fluid loss reducer agents used are amine-treated lignite, or hydrocarbon resin (asphaltite), gilsonite, or natural bitumen (Caenn et al., 2016). Several vitro mutagenicity studies concluded that the asphalt fumes are ambiguous, while carcinogenicity studies found that some asphalt fume condensates can cause tumours when applied dermally to mice. A metaanalysis of 20 epidemiological studies did not find overall evidence for a lung cancer risk among pavers and highway maintenance workers exposed to asphalt (Concise International

Chemical Assessment Document, CICAD, 2004).

Natural and modified natural polymeric thinning agents are used to control fluid loss as coating agent, emulsify oil and water (Rabaioli et al., 1993), and excellent rheological properties stabiliser at elevated temperatures (Tomasz et al., 1984) such as lignitic materials, Cr–lignosulfonate (Wilcox and Jarrett, 1988), FeCr–lignosulfonate, and polyphosphates, to fully synthetic materials, such as maleic anhydride–styrene sulfonate copolymers, and either homo- or copolymers of acrylic acid (Zhang and Yin, 1999). Due to increased restrictions on the use of drilling mud additives based on toxic metals (Kullman et al., 1989) and environmental reasons (Bernier et al., 2004), most of the loss reducers used in OBM formulation belong to two families of products (Bleir et al., 1992). The first group is polymers. The second group is partially soluble or deformable solids, such as treated lignites (e.g. causticized or amine treated) (Kelessidis et al., 2007), organically modified tannin, resin (asphaltic), and gilsonite (IEPCA, 1989).

The main concerns for the conventional mud chemical additives, which are used to formulate the drilling mud, are environmental regulations, health, and safety considerations, and cost. Drilling fluid accounts about one-tenth of the total cost of drilling well operations. Therefore, when using waste products, the drilling mud cost will decrease, and the total drilling cost will be cheaper than applying conventional drilling mud additives.

Food loss and waste products account for about 8.2% (FAO, 2015) and medical waste contributes 9–10% of the greenhouse gas emissions, in particular pharmaceutical waste, since they are consistently calculated to be among the top contributors to healthcare carbon as a result of collection, transporting it to a treatment facility and materials, leading to a significant addition to the environmental footprint in carbon emissions. Carbon reduction, when focused on pharmaceuticals, can cause cleaner, more sustainable healthcare (Richie, 2020). This impacts not only the climate, but also personal and national economics, and it is often utilised for better uses like drilling fluid additives. It's also generally safer to handle waste products compared with drilling mud chemical additives, as some chemical additives have hazards that need proper equipment and safety to be handled. Additionally, when it involves handling conventional drilling fluid additives, it's important to consider the consequences for health, safety, and the environment due to the toxicity of the chemical materials. The oil industry is becoming more aware of the importance of energy transition/net zero. Therefore, the design of the optimum drilling/completion fluid and the selection of drilling fluid additives should be the solution to this problem, not only in application but also from an environmental point of view. Therefore, in this study, a new innovative and alternative waste material of biological origins for HTHP drilling fluid loss control additive has been presented. This material is a biodegradable product that can be used to enhance fluid properties and is available and easily accessible. Thus, it is

expected to be environmentally friendly, have no detrimental effects on the surrounding environment and ecosystems, and is a good candidate for further research investigation. In addition, collecting and preparing prices for waste products (Streptomyces Rimosus) is much cheaper compared with the conventional drilling mud chemical additives. It is well established by previous studies that in nature, cell death of mycelial Streptomyces type strains occurs at the end of their long vegetative phase, which is usually 2–3 days and caused by an absence of nutrients (Yagüe et al., 2013). Additionally, another study that investigated Streptomyces Aureofaciens, a sister strain of Streptomyces rimosus, showed that the degradation products of such bacteria were cytosine, guanosine, and variants of adenosine monophosphate, which are all biological products (Simúth and Zelinka, 1970).

A number of chemical and morphological studies have been carried out on the fate of the streptomycetes bacterial life cycle and its impact on soil organic matter (SOM) formation (Kindler et al., 2006; 2009). They found that the fate and morphology of living and dead bacterial biomass C was analyzed and determined using scanning electron microscopy (SEM). Attachment of soil particles to the intact mycelium as well as decay of dead biomass was observed. Dead bacterial biomass was identified in the form of patchy fragments while the superordinate filamentous structure of the hyphae was still visible and obviously stabilized in soil. This indicates that bacterial cell death results in the release of cytosolic compounds, e.g., intact proteins, as well as the formation of residual cell-envelope fragments, contributing to soil organic matter formation (Fig. 1). Schütze et al. (2013) reported that the heavy metal–sensitive bacterial strain Streptomyces strain (S. lividans TK24) was disintegrated; the necromass fragments would then contribute to soil organic matter formation.

1.1.2. New fluid loss control agent

This study presents a new fluid loss control agent from the pharmaceutical industry. It is a by-product of an industrial antibiotic (Oxytetracycline) fermentation process. Oxytetracycline is derived from *Streptomyces Rimosus* and is one of the most widely used tetracyclines (Kucers and Bennett, 1987). Oxytetracycline is a 'bacteriostatic', used

extensively both for the treatment of infectious diseases, in promoting plant growth and as an additive to animal feeds to facilitate growth (Rajesh et al., 1998).

An ecologically-friendly OBM fluid loss additive was developed from the study of the behaviour of *Streptomyces Rimosus* (hereafter abbreviated as *S. Rimosus*) biomass in such dispersions. This biomass is a heterogeneous material. The cell walls (membranes) of this Gram-positive bacterium mainly consist of two linked heteropolymers (Gimel and Brown, 1996): peptidoglycan and teichoic acids, containing anionic or electron-donor groups such as carboxyl, amino, amide, and hydroxyl (Selatnia et al., 2004), conferring high adsorbent ability towards mud additives (Valstar et al., 2000): cationic and nonionic emulsifiers, organoclays, salts, and mineral compounds, thus giving rise to important aggregation phenomena (Jones et al., 1995). The binding of surfactants, namely SDS (Mosquera et al., 1996), other n-alkylsulfates (Vasilescu et al., 1999), and n-alkyltrimethylammonium salts (Rafati et al., 2004), to the ionic sites of proteins has been extensively studied (Mondal et al., 2006).

Many industrial, pharmaceutical, biological, and cosmetic products contain proteins (Gelamo et al., 2002) and surfactants (Sabate and Estelrich, 2001). Further binding occurs through hydrophobic cooperative interactions (Bordbar et al., 1997). Hence, ionic surfactants interact with proteins (Dickinson, 1993) through a combination of electrostatic and hydrophobic forces (Omidyan et al., 2011). Several other studies used *S. Rimosus* biomass for simultaneous biosorption of various metal ions (Scott and Palmer, 1988). Specifically, (Mameri et al., 1999), as well as (Adour et al., 2003) research investigated the efficiency of this biomass as free cell suspensions and in a packed column, respectively, to bind Zn(II) ions from industrial wastewater. The first authors regenerated the saturated biomass with HCl as the eluate. However, HCl has a deleterious effect on the biomaterial. In the whole range of HCl concentrations tested (0.1–1 mol.L), the biomass loss after regeneration was close to 20%. McCarthy et al. (1999) used filtration to recover biomass for re-use. Basically, peptidoglycan consists of chains of alternating residues of β-1-4-linked N-acetylglucosamine (NAG) and N-acetylmuramic acid (NAM). This biomass is characterised by
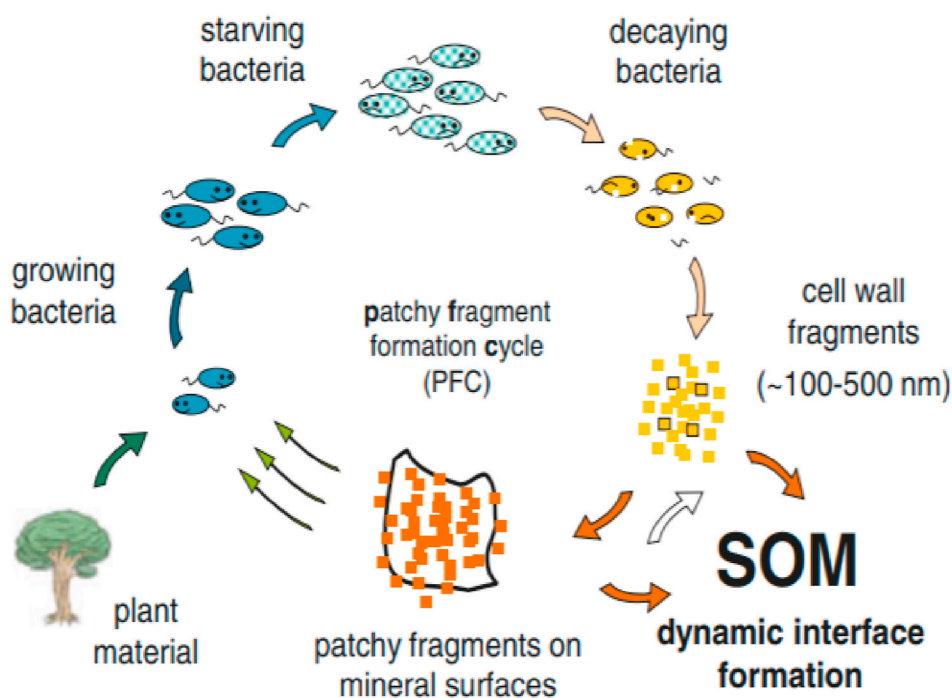

Fig. 1. Patchy fragment formation cycle fragments (visible on SEM micrographs) and the contribution to soil organic matter (SOM) as proposed by Miltner et al. (2012). It is shown that plant material is turned over by microorganisms which die after prolonged starvation. Their cell envelope fragments can be attached to soil minerals and are stabilized in non-living SOM (Coban, 2015).

phosphate-containing repeated structures that carry a strong negative charge (Selatnia et al., 2004). The negative charge of teichoic acid also contributes to the negatively charged *S. Rimosus* cell envelope (Selatnia et al., 2004). Due to the high peptidoglycan and teichoic acid content of the cell walls, the *S. Rimosus* biomass possesses a high adsorption capacity (Sahmoune et al., 2009).

Several chemical modification methods have been applied to enhance the commercial application of biomass-based adsorbents, such as cross-linking, and insertion of new functional groups by enzymatic and chemical grafting, to improve performance and selectivity (Wong et al., 2000). Recently, surfactant impregnation has been applied for modification of various adsorbents such as clay, biomass, activated carbon, and waste pits with excellent results (Anjali et al., 2013). Chatterjee et al. (2009) showed that the adsorption of Congo Red dye by Chitosan beads could be enhanced by surfactant impregnation at a very small dosage, even with an anionic surfactant. Treatments using NaOH (Brierley, 1991) give a high degree of deprotonation of binding groups (Chatterjee et al., 2009), and subsequent alkalinisation of the environment (Fourest and Roux, 1992). After testing some chemicals (NaCl, NH_3, KOH, NaOH, and anionic surfactants), Adour et al. (1999 and 2003) observed that the surfactant provided the best performance. Sodium hydroxide gave similar results, but produced considerable destruction of the biomaterial.

The NaOH (0.1 M) treatment of the biomass was found to significantly increase the adsorption capacity. This was mainly due to the surface groups (—COOH, –NH_2, —PO_4^{3-}). On the other hand, the granules pretreated with anionic surfactant were more rigid than those obtained by NaOH pretreatment. Due to biomass degradation and deprotonation, treatment by NaOH was eliminated (Adour et al., 2003).

The purpose of this innovative research was to test untreated dead *S. Rimosus* biomass and biomass treated with a cationic surfactant for its ability to exhibit HTHP filtration loss control. The fluid thermal stability, filtration and rheological properties, and effect of the drilling fluid filtrate on formation damage were also analyzed. The use of low-cost and biological waste material as a filtration loss control agent has been shown to provide effective technical performance, economic, and environmental solutions to improve the environmental standing of OBMs further.

2. Materials and methods

2.1. Materials

The physicochemical characteristics of the crude biomaterial are presented in Table 1. Scanning Electronic Microscopy (SEM) micrographs allow to visualize morphological aspects of crude biomass (Fig. 2), letting structures with spores and fibres appear, thus making the porous structure with a large surface/volume ratio. *S. Rimosus* is a filamentous bacterium, whose structure resembles that of fungi. Biomass elemental analysis (Phywee instrument) gave: 28.47% C, 3.71% N, 2.26% S, and 3.99% H.

FTIR spectrometry was used for the determine organic functions, and the main absorption bands were 3430 cm^{-1} (V_{OH}), 2913 cm^{-1} (V_{XH}) and 1623 cm^{-1} ($V_{X=O(O)}$). The presence of hydroxyl groups imparts

Table 1
Physical and chemical characteristics of the biomass.

Parameter	Untreated biomass	Treated biomass (10–40 μm)	Treated biomass (40–75 μm)
Color	Brown	Brown	Brown
Density (g/cm^3)	0.48	0.51	0.50
Moisture (%)	5	8	7
Specific area (m^2/g)	1.8	2.1	2.3
ζ potential at pH 8 (mV)	Not determined	−2.7	−1.9
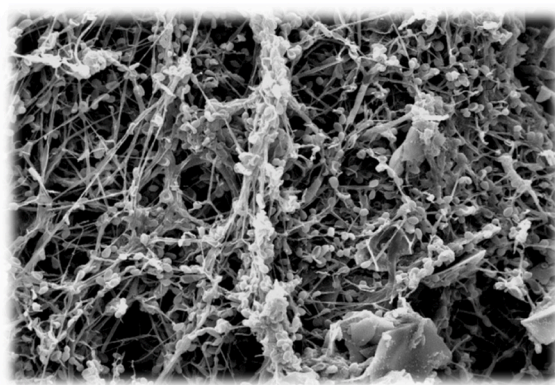
Fig. 2. SEM micrograph of crude biomass Streptomyces Rimosus (X 710).

hydrophilic properties to the biomass (easier dispersion in water). The biomass underwent a pre-treatment: repeated washing with distilled water until the water was clear, then drying at 70 °C for 24 h. It was then crushed and sieved in order to yield fractions with particle diameters of 10–40 μm and 40–75 μm. Apparent density was determined with a pycnometer. Moisture content was measured by drying at 105 °C to a constant weight. The specific area was determined by nitrogen injection in a Syntachrom instrument (NOVA 2000) according to the BET method. ζ Potential was determined by using a Zeta Sizer 3000 HSa (Malvern Instruments).

2.2. Additive preparation

A cationic surfactant: S1 (CetylTrimethylAmmonium Bromide, CTAB, 98%, Aldrich Chemical Co.) or S2 (Alkyl Dimethyl Benzyl Ammonium Chloride, ADBAC, 95%), was added in batch mode at concentrations ranging from 0.01 to 0.05 M to 10 g of biomass for 30 min, and the mixture was maintained in suspension by agitation at ambient temperature (22 °C). The biomass treated was then filtered, dried and sieved in the 10–40 μm and 40–75 μm ranges. The adsorption of surfactant onto biomass was confirmed by analyzing the nitrogen amount of treated biomass, which was always found to be higher than in crude biomass.

Several OBM samples were designed using two sizes (10–40 μm and 40–75 μm) of biomass particles, with different biomass amounts treated with surfactants (0.05 M CTAB). An OBM system was prepared using a silverson mixer with crude biomass for comparison of mud density, HPHT fluid loss characteristics, and rheological characteristics including apparent viscosity, plastic viscosity, yield point, and gel strength. API Standard procedures for field testing of drilling fluids (API, 2005) before and after hot rolling were applied for mud preparation, performance, and characterization, including density, filtration, rheology, and hot roll tests to evaluate the thermal effect on the fluid loss agent performance. During mixing, the biomass was slowly added to the agitated base fluid. The alkalinity of the mud was adjusted with lime. The composition of the Algerian gas oil (diesel oil) used to formulate conventional OBM was (wt.%): saturated (65.40), aromatics (32.84), resins (1.76), no asphaltenes. Organophilic clay was added as a viscosifier and a gelling agent, particularly effective in high-temperature applications.

2.3. Drilling fluid formulation and characterization

For the mud formulation and characterization, the mud weight was determined using mud balance and filtration were obtained using an HPHT filter press at ml/30 min at 250 °F and 500 psi differential pressure. The stability of water in oil emulsion was tested with an electric stability emulsion tester. Voltage was imposed on the OBM using two electrodes and then gradually increased until the initiation of current

flow. The static and dynamic sag at high temperature were measured using a sag tester. The rheological properties at 250 °F and 14.7 psi were conducted using a Fann 35 rheometer at two rotating rates of 600 rpm and 300 rpm dial readings (R600, R300) and the initial gel strength after 10 s and final gel strength after 10 min of setting. Then the rheological properties such as apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) were determined as follows:

$$AV = reading_{600} / 2 \qquad (1)$$

$$PV = reading_{600} - reading_{300} \qquad (2)$$

$$YP = 2(AV - PV) \qquad (3)$$

Gels 0/10, checking mud thixotropy, are 3 rpm readings on 6-Speed Fann Viscometer just after mixing and after 10 min.

Fluid displacement was determined with a Corelab filtration system equipment. Core samples were saturated with synthetic formation brine during 24 h, placed in a Hassler cell under 14 kgf/cm^2 of overbalance pressure at 80 °C. Soltrol 130 was used for filtration tests in a Hassler cell to evaluate initial (K_i) and final (K_f: after fluid injection) permeabilities. In the stable state, the damage ratio (DR) was determined as:

$$DR = (100 (K_i - K_f)/K_i) \qquad (4)$$

3. Results and discussions

3.1. Performance of the new HPHT fluid loss control agent

In order to confirm the suitability of the new fluid loss control agent for HPHT drilling well applications, we performed a series of HPHT tests. This includes compatibility test, oil/water ratio test, anti-high temperature ability test, sag and electrical stability tests, anti-contamination test, rheological property test, filtration characteristics test and formation damage control ability test.

3.1.1. Compatibility test - effect of treatment and biomass size

Eight samples of OBM containing biomass or biomass and cationic surfactant (S1 or S2) were prepared. Their common composition is the following: Diesel oil, 570 mL; primary and secondary emulsifiers, 12 and 8 mL, respectively; lime, 30 g; organoclay, 5 g; saturated brine (340 g/L NaCl), 290 mL. Since surfactant excess is needed to fully saturate anionic or proton-acceptor exchange sites (carboxyl, amino, phosphate, amide, and hydroxyl) and increase mud stability, its concentration was fixed at the low concentration of 0.05 M, used in the present study for S1 and S2. From the data shown in Table 1, the zeta potential of the biomass is known to be slightly negative (−2.7 and −1.9 mV), confirming that for treated products there are negatively charged surfaces due to surfactant-biomass interaction. The amount of biomass, the nature of the other additives, and mud properties of the formulations are reported in Table 2.

Biomass shows good compatibility and stability in all HPHT drilling

fluid systems. The rheological characteristics can be accepted, however, for A, B, and C formulations, the filtrate volumes are too high. Those results reveal that crude (untreated) biomass is not able to replace conventional filtration control additives. For other systems (D, E, and F) using biomass treated with S1, the HPHT filtrate volumes are acceptable for sample D and similar or better for samples E and F and filter cake thickness was enhanced as well when compared to the conventional mud to avoid the frictional resistance of the pipe movements and mechanical pipe stuck during drilling of HPHT wells. On the contrary, for system G, the filtrate is total. Thus, biomass (10–40 μm) treated with S2 does not exhibit good properties in OBM. We can conclude that the mud systems using biomass treated with SI have a good and acceptable compatibility test.

3.1.2. Impact of oil/water ratio test

The aim of the second step is to confirm the performance of S1 in OBM with a high dispersed phase volume ratio (Oil/Water: ~50/50), the amounts of emulsifiers and lime remaining the same as above. A reference OBM system of 75/25 was selected. Formulations and characteristics are presented in Table 3.

In OBM, cationic and nonionic emulsifiers, organoclays, salts, and mineral compounds tend to aggregate.

Here, the interactions between CTAB and the anionic groups of the cell walls of *S. Rimosus* explain the satisfactory properties of the new filtration loss control additive. We can safely confirm that there is no impact of the oil/water ratio on new agent performance.

3.1.3. Anti-high temperature ability test

OBM is generally used as a drilling fluid to drill surface and intermediate sections and as a drill-in fluid (RDF) to drill HPHT reservoir sections. Thus, the thermal stability of a mud containing biomaterial was also tested at a high temperature (120 °C) after hot rolling treatment (16 h at 250 °F and 300 psi). The rheological and filtration properties are measured and compared to the same properties before ageing. Table 4 indicates stable drilling fluid properties, compatibility, and good results.

Table 3

Oil-based mud composition and characteristics with S1 treated biomass: rheological properties at 250 °F and 14.7 psi and filtration properties at 250 °F and 500 psi differential pressure.

Formulation or property	O/W: 75/25	O/W:51/49
Diesel oil (mL)	583	444
Organoclay (g)	5	–
Treated Biomass (g/L)	30	40
Saturated brine 340 g/L NaCl (mL)	276	452
Density (g/cm^3)	0.98	1.02
Apparent Viscosity, AV, (cP)	23	52
Plastic Viscosity, PV, (cP)	21	44
Yield Point, YP, (lb/100 ft^2)	4	16
Gels 0/10 (lb/100 ft^2)	0/1	1/2
HP/HT Filtrate (mL/30min)	10	7
Filter cake thickness, mm	2.6	2.4

Table 2

Oil-based muds: additional ingredients and rheological properties at 250 °F and 14.7 psi and filtration properties at 250 °F and 500 psi differential pressure.

Characteristic	A	B	C	D	E	F	G	Conv.
Biomass (+surfactant)	15[a]	30[a]	30**	30+S1	40+S1	40+S1+barite	25+S2	30
Density (g/cm^3)	0.98	0.95	0.94	0.94	0.99	1.22	0.99	1.03
Apparent Viscosity, AV, (cP)	19.5	22	12.5	12.5	26.5	44	22	57.5
Plastic Viscosity, PV, (cP)	19.5	21	11	11	24	40	20	51
Yield Point, YP, (lb/100 ft^2)	0	2	3	3	5	8	4	13
Gels 0/10 (lb/100 ft^2)	0/1	0/1	0/1	0/1	–	1.5/2	0.5/1	4/5
Oil/Water	79/21	68/32	79/21	82/18	76/24	65/35	68/32	66/34
HP/HT Filtrate, (mL/30min)	29	24	21	13	8	7	Total	9
Filter cake thickness, mm	3	3	2.8	2.6	2.4	2.4	–	2.6

[a] Untreated biomass size 40–75 μm/**: Untreated biomass size 10–40 μm.

Table 4

Oil-based mud formulation and characteristics (Oil/Water, v/v:80/20); H.R: Hot-Rolling at 250 °F and 300 psi.

Formulation O/W 80/20	Composition	Parameter	80 °C	After H.R
Diesel oil (mL)	620	Density	0.95	0.95
Principal Emulsifier (mL)	15	AV (cP)	40	45
Secondary Emulsifier (mL)	12	PV (cP)	35	37
Organoclay (g)	5	YP (lb/100 ft2)	10	16
Lime (g)	30	Gel (lb/100 ft2)	4/5	3/5
Biomass with S1 (g)	30	Filtrate (mL/30min)	7	7
Saturated brine 340 g NaCl (mL)	190	Oil/Water	79/21	80/20
Electric stability (volts)			850	900
Static sag factor			0.51	0.51
Dynamic sag factor			0.52	0.52

This confirmed that the new drilling fluid formulation with the new fluid loss agent can counter high temperature effectively.

3.1.4. Electrical stability and sag tests

The high temperature stability of water in oil emulsion was tested with an electric stability emulsion tester. The static and dynamic sag tests at high temperature were measured using a sag tester. Electric stability and sag tests are compared to the same properties before ageing. The experimental results in Table 4 show that biomass had no impact on electric stability, mud weight, static and dynamic sag. The static sag factor is 0.51 and the dynamic sag factor is 0.52. In general, the closer the sag factor is to 0.50, the better the result. These results confirmed that biomass had improved the HPHT drilling fluid stability and maintained weighting materials in suspension while drilling mud pumps stopped. The stability of water in oil emulsion of 850 V was tested. According to oil industry practice, an OBM with good emulsification will have an electrical stability of 400–500 V. API recommendations, all drilling fluid systems exhibiting good electrical stability, HPHT filtrate and rheology values confirm mud stability under downhole conditions of HPHT drilling operations.

3.1.5. Anti-contamination test

The mud sample was mixed with 5 g of organophilic clay, and heated at 120 °C for 16 h after hot rolling treatment (16 h at 250 °F and 300 psi). Then, rheological properties are measured and compared before aging. The results obtained in Table 4 show optimum fluid thermal stability due to HPHT filtration characteristics and rheology being achieved. The new mud formulation has very good antipollution ability and improved fluid resistance to drill solids contamination under high temperature application.

3.1.6. Rheological properties test

The test results of the rheological properties before and after hot rolling are shown in Table 4. Biomass generated thermal stability under high temperature with optimum apparent viscosity, plastic viscosity relates to the portion of flow resistance caused by mechanical friction and yield point, which is usually good on equivalent circulating density and supports hole stability and cutting transport during drilling of HPHT wells. Excellent behaviour for the gel strength was observed since the difference between the initial and final gel strength did not exceed 5 (Ib/100 ft^2), which will be reflected positively in static equivalent circulating density, particularly during pump-off conditions (tripping) based on Sonatrach oilfield operations to ensure that the mud gel easily breaks when circulation is restarted. Thus, extra drilling mud pump pressure will be required to break the circulation (fluid gel structure) during tripping operations, switching from pump-off to pump-on conditions, which in turn may cause losses of the drilling fluid as a result of induced fractures in weak formations (Caenn et al., 2016).

3.1.7. Filtration characteristics test

Tables 2–4 show the filtration characteristics after hot rolling for biomass were determined with the HPHT filter press at 30 min, with excellent fluid loss and thin filter cake observed as well when compared to the conventional mud to avoid the frictional resistance of the pipe movements and mechanical pipe sticking. In the new OBM formulation, interactions between biomass anionic groups and mud additives (emulsifier micelles, organoclay, salt, and minerals) can increase stability, giving stable aggregates to adsorb oil and/or aqueous phase. The liquid–liquid (organic-aqueous: diesel oil-water) phase equilibrium is governed by the activities of all the components in the organic and aqueous phases. The activity coefficient is a function of solution composition, temperature, and pressure. It appears that H-bonding plays an important role in the phase behaviour of treated biomass, due to high peptidogly can and teichoic acid contents and surfactant composition (Rajesh et al., 1998). Thus, hydrophilic and hydrophobic interactions are likely to govern the behaviour of S. Rimosus cell walls with mud additives (organic and aqueous compounds). The HPHT filtrate volume depends on the filter cake permeability variation. In OBM systems, colloidal control of filter cake permeability is achieved with water droplets stabilized by colloidal particles (e.g. organophilic clays) and surfactants (Jiao and Sharma, 1993). In our case, organic particles formed between biomass and surfactants govern filtration mechanisms. Fig. 3a and b shows proposed treated biomass, water, and diesel interaction mechanisms.

3.1.8. Formation damage control ability test

To demonstrate the performance of treated biomass, studies on formation damage were conducted on core samples. The damage ratios for five core samples (2 with conventional mud systems and 3 using biomaterial) are similar (ca. 63%) (Table 5). For rock sample no.5, with *S1-treated biomass* (40–75 μm), the damage ratio is 54%, which is slightly less than with *S1-treated biomass* (10–40 μm). This is due to the high adsorption and accumulation of fine particles of additives on rock surfaces. Rock 5 shows the best results, probably due to the influence of biomass amount on filtration mechanisms.

With 40 g of treated biomass, a lower fluid volume reduces filtrate invasion. A high-quality filter cake is an effective means of preventing filtrate and solids migration into the formation and, as a result, reducing drilling fluid-related formation damage. Filter cake thickness under downhole conditions is directly related to the filtration rate and depends upon the pore entry size distribution of the porous medium, particle size distribution of the mud, solids concentration, and the amount of water retained in the filter cake.

Filtration rate decreases with increasing solids concentration, but cake thickness increases. Permeability is almost entirely dependent on the proportion and properties of the colloidal fraction. Permeability decreases with an increasing fraction of colloids and is strongly affected by particle size and shape. A broad distribution of particle sizes is important to attain low permeability.

The damage ratios observed for core samples are similar (between 62 and 64%) to those of fine size (10–40 μm). For rock sample no.5, with coarse size (40–75) μm S1-treated biomass, the damage ratio is 53%, slightly less than conventional fluid loss additive. This mud formulation can be used for non-reservoir applications (i.e., surface and intermediate sections). Filter cake thickness under downhole conditions is directly related to the filtration rate and depends upon the pore entry size distribution of the porous medium, particle size distribution of the mud in relation to the size of biomass and solids concentration, and the amount of water retained in the filter cake. Particle sizing is extremely important when considering the bridging mechanisms. It is noted that particles smaller than the pore size of a porous formation bridge rock pores throughout drilling fluid circulation. This leads to reduced fluid loss and protects the formation from damage. In general, with the increasing concentration of bridging particles as a mixture of coarse and fine sizes, bridging occurs faster and spurt loss is reduced (Caenn et al., 2016). The
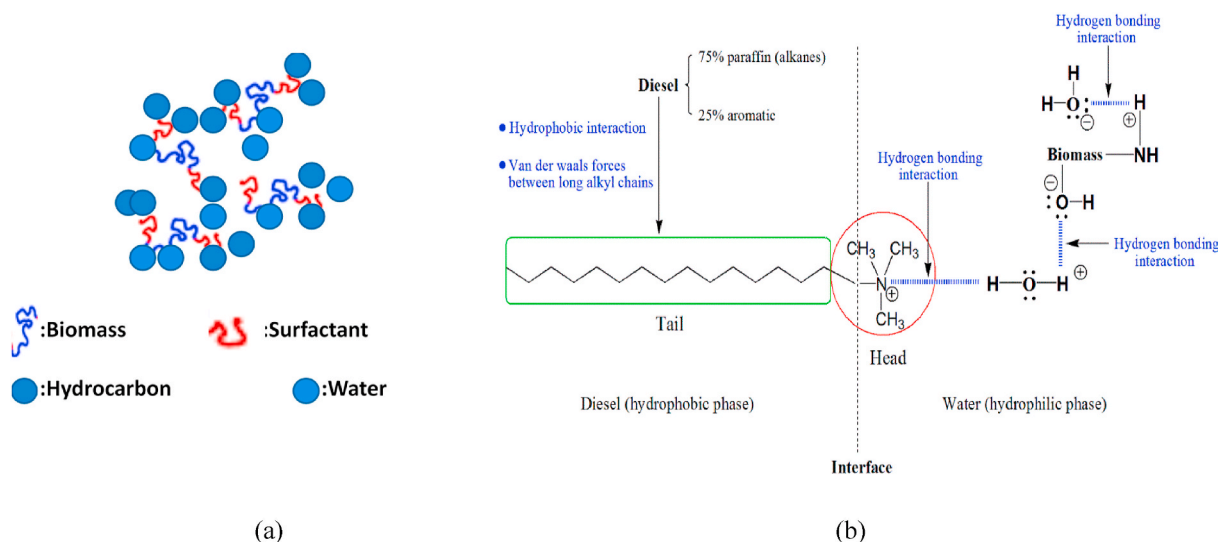
(a)   (b)

Fig. 3. Treated biomass, water and hydrocarbon interactions (a) and Schematic mechanism of interactions between biomass, water, surfactant, and diesel (b).

Table 5
Rock reservoir properties and damage ratio (OBM, Oil/Water, v/v: 80/20).

System	Rock sample	K_{air} (mD)	Porosity (%)	K_i (mD)	K_f (mD)	D (%)
Conventional	1	120	13	42	16	62
Conventional	2	95	15	31	11	64
Substituted[a]	3	112	09	39	14	64
Substituted[a]	4	98	12	33	12	63
Substituted**	5	103	11	37	13	54

[a] Formulation with 40 g of S1 treated biomass, 10–40 μm; ** id., 40–75 μm.

permeability of the filter cake depends on the particle size distribution, as increasing particle size decreases the permeability since colloidal particles get packed very tightly.

It is crucial to highlight that a simple machine has been used to grind the dried biomass. The biomass was not as fine as conventional fluid loss additives. As known, finer particles help to reduce filtration characteristics efficiently and reduce formation damage. Hence, using an excellent grinder to grind the biomass into very fine particles would provide better performance in controlling the filtration characteristics. Therefore, it's desirable to use a more powerful grinder to grind biomass to 5–20 μm which is considered very fine and close to the size of conventional additives for the purpose of better future formation damage analysis.

HPHT wells are commonly characterized by a narrow window between the formation pore and fracture gradients. The drilling operation should be monitored within the formation pressure window boundaries. The combination of high pressure and high temperature can cause degradation of the drilling mud additives and solids settlement, which leads to drilling mud instability, decreased rheological properties, and increased fluid loss. This requires proper mud selection and formulation to avoid variations in mud density, that might result in downhole mud losses or induce drilling problems such as well integrity, differential pipe sticking, formation damage, and wellbore instability. All test results showed that values obtained with biomass treated material are acceptable and similar to those obtained with conventional mud systems. The compatibility test, oil/water ratio test, anti-high temperature ability test, sag and electrical stability tests, anti-contamination test, rheological property test, and filtration characteristics test make the new material (biomass) to meet the functional requirements of HPHT drilling conditions. The test results confirmed that biomass prevented weighting materials sagging, preventing high temperature gelling, and enhanced HPHT filtration characteristics (filtrate and filter cake) and rheological

properties (yield point, plastic viscosity, and gel strength) of the OBM, which increased the mud stability and hole cleaning during drilling of HPHT wells. This means that the OBM formulation with biomass sustained the increase in pressure and temperature to meet downhole operational conditions of HPHT wells. The formulation was able to minimize equivalent circulating density, reduce the risk of differential pipe sticking, minimize barite sag, and reduce the overall well cost for HPHT applications. This will help drilling engineers safely drill deep wells and maintain well integrity during the HPHT drilling operation.

4. Conclusions

A new class of loss reducers for OBM could be prepared by the treatment of dead Streptomyces Rimosus biomass with a cationic surfactant. In order to optimize its preparation and application as a drilling mud additive, several modes of pre-treatment and surfactant reaction conditions have been investigated with regard to the effects of type and concentration of surfactant on filtration and rheological properties. A pre-treatment with a cationic surfactant successfully increased the performance of the biomaterial. Cationic surfactants interact with biomass through a combination of electrostatic and hydrophobic forces. One of the basic mechanisms used in fluid loss prevention consists of the motion of suspended particles through the borehole wall into the formation. The deposition of particles on the face of the formation creates a wall cake. It has been found that the adsorption and filtration reduction abilities of the prepared biomaterial can be enhanced and then show a decrease with particle size and surfactant amount introduced into the biomass. On the basis of the results obtained, and with the size used, a 0.05 M concentration of S1 surfactant (CTAB) was preferred. Numerous benefits were obtained from the use of a new loss control biological fluid when compared with other products. The biomaterial has similar or better rheology and fluid loss control properties, which is cost-effective on a drilling efficiency basis compared to the currently used conventional agents. Rheology and filtration characteristics obtained are similar to or better than for all the oil/water ratios studied (80/20, 75/25, and 70/30). The combination of the new material with classical drilling fluid additives shows good compatibility and thermal stability and gives appropriate mud properties after hot-rolling (16 h at 250 °F and 300 psi). The drilling fluid formulation using developed biomaterial has good HPHT fluid loss control and the rheological properties required for optimum performance. Biomass sustained the increase in the pressure and temperature, which met the downhole operational conditions of HPHT wells. This will help drilling engineers drill HPHT oil and gas

wells safely and efficiently.

This biomass is environmentally friendly, biomaterial in nature, and totally biodegradable, and thus expected to have no detrimental effects on the surrounding environment and ecosystems. Decreasing the quantity of drilling fluid discarded and increasing the biodegradability of used additives will decrease the cost of rig-site cleanup. Furthermore, additional experimental work is required concerning the availability and search of other sources of biomass and the pre-treatment mode effect. These extensions are under investigation.

This study proves the importance of expanding biological and pharmaceutical waste products to participate in the industry's energy transition/net zero and leads to cleaner and more sustainable healthcare. It can provide fluid, compatibility, effective technical performance, reducing the total cost of drilling operations and waste handling, personal health and safety, as well as environmental solutions to improve the environmental standing of drilling fluids further.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

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