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Invasion of $CaCO_3$ particles and polymers into porous formations in presence of fibres

Karl Ronny Klungtvedt[a,b,*], Arild Saasen[b]

[a] EMC AS, NO-4033, Stavanger, Norway
[b] University of Stavanger, NO-4036, Stavanger, Norway

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ABSTRACT

Formation damage can occur through migration of drilling fluid particles and polymers into porous formations. A methodology for assessing formation damage was applied to measure invasion of $CaCO_3$ and polymers into porous formations, where the $CaCO_3$ particles size had been selected using established particle size selection methods. Tests were conducted with and without the presence of a cellulose-based additive, to study if the fibres could reduce the fluid loss and limit the formation damage.

Input factors such as applied differential pressures, ranging from 6.9 to 34.9 MPa (1000-5000psi), and median pore-throat openings of discs were also varied to investigate which parameters affected the significance of the formation damage.

The results showed invasion of $CaCO_3$/ground marble into the formation and that particle size selection methods used to reduce fluid loss also led to formation damage. Further it was discovered that the presence of fibres limited the invasion of both $CaCO_3$ and polymers into the porous formations when the D90 of the fibres were $\geq 3/2$ times the pore-throat size, and that higher applied pressures led to larger formation damage. The fluid loss tests also showed both lower total fluid losses and lower fluid loss rates over time with the fibres added to the fluids, indicating that the filter-cake permeability was reduced with the addition of the fibre particles.

1. Introduction

A simplified method for assessing formation damage experimentally was introduced by Klungtvedt et al. (2021, 2022) for the study of formation damage when drilling either oil-, gas- or geothermal wells. In this method, formation damage was studied by measuring changes in the mass of a porous formation as well as changes in the formation's permeability to a fluid. They concluded that it was possible to measure the increases in disc mass accurately and that for certain tests there were inverse relationships between fluid losses and disc mass increases. Further, in the second study, it was concluded that the high correlations obtained between the changes in disc mass and changes in permeabilities indicate that the different indicators of formation damage yield consistent results.

$CaCO_3$ is used worldwide as a fluid loss additive and weighting agent in reservoir drilling fluids due to factors such as low cost, a density of around 2.7 sg and acid solubility. Numerous studies have been conducted on selection of sealing materials (Alsaba et al., 2014; Jennakorn et al., 2019) and particle size distribution (PSD) for sealing of pore-throats and fine fractures (Whitfill, 2008; Alsaba et al., 2015; 2017) leading to particle size selection methods typically selecting a D50 or D90 value relative to a given median pore-throat size. As an example, both the D90 Rule (Smith et al., 1996) and the Vickers Method (Vickers et al., 2006) suggest selecting a D90 value which is equal to the pore throat size, whilst Abrams Rule suggest selecting particles with a D50 $\geq$ 1/3 of the formation average pore size (Abrams, 1977). The selection methods do, however, not consider compressible or elastically deformable particles like fibres as part of their models to limit fluid loss and prevent formation damage. However, it has also been shown that $CaCO_3$ and graphite particles degrade readily when exposed to fluid shear (Hoxha et al., 2016). It can therefore be questioned how accurate the particle size selection methods are from a field perspective, as the particle size distribution of the particles in the drilling fluid will change during circulation.

Alternative materials such as cellulose-based additives have been proven to seal permeable discs without the presence of solids in the form of weighting agents or drill solids (Klungtvedt et al., 2021b). Other studies have shown that the solids composition of fluids play a role in

* Corresponding author. EMC AS, NO-4033, Stavanger, Norway.
E-mail addresses: krk@emcas.no (K.R. Klungtvedt), arild.saasen@uis.no (A. Saasen).

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reducing the formation permeability, and that increasing the PSD may yield higher return permeability (Pitoni et al., 1999).

When studying the roles of specific materials, it has been shown that polymers such as xanthan gum may significantly reduce formation permeability (Khan et al., 2003, 2007), whilst the presence of cuttings may yield a lower return permeability than a fluid without cuttings (Cobianco et al., 2001).

The scope of the present tests is to apply the method of selecting $CaCO_3$ particles with D90 values equal to the pore-throat size to evaluate the impact on formation damage. Considering that $CaCO_3$ particles added to the fluid will be grinded down in size during circulation, it may be argued that the particles will eventually be reduced to a size smaller than the pore-throat size of the formation. To prevent them from migrating into the formation, $CaCO_3$ particles need to be combined with more shear resistant particles where the D90 value is more stable. A second objective was to see if the fibres also could enable an effective fluid loss control and prevent polymers from damaging the formation permeability, with no $CaCO_3$ present in the fluid. For convenience, the specified median pore-throat size of the ceramic discs will be treated as the relevant pore-throat size. Therefore, two test series were set up to apply the methodology to separately assess the impact of $CaCO_3$ invasion and polymer invasion on permeability and disc mass. These tests were conducted with and without fibres present in the fluid.

The primary objectives of the present tests can be summarised as follows:

- Verify if the recognised particle selection methods are optimal for reducing formation damage
- To identify the formation damage caused by a solids-free polymer fluid or a polymer fluid containing $CaCO_3$ particles.
- To identify if higher applied differential pressures are likely to increase the formation damage
- To identify if application of cellulose fibres may reduce any formation damage caused by either polymers or $CaCO_3$ particles.

2. Methods, results and discussions

The experiments were set up to measure changes in the mass and permeability of porous ceramic discs to provide potential evidence of formation damage caused by $CaCO_3$ and polymers. The methodology used for the testing is presented in detail in the Appendix and in Klungtvedt and Saasen (2022). The key elements of the process are to measure changes in the discs before and after HTHP filtration tests with regards to disc mass and permeability, either after reverse flow with water to remove the filter-cake or after an application of a chemical breaker fluid. The first test series uses a drilling fluid with presence of both polymers and $CaCO_3$, whereas the second test series uses a KCl polymer fluid with no solids present.

Studies have been conducted in the past on application of various breaker fluids for removing polymers such as starch from core samples (AlKhalid et al., 2011). Since the objective of this study partially is to investigate the potential formation damage of polymers, a combination of xanthan gum and low viscosity poly-anionic cellulose was selected for viscosity and fluid loss and a benign oxidizing breaker fluid was selected for light cleaning of the ceramic discs only. It was therefore expected that the application of the breaker would mainly function to disperse the external filter-cake, without removing internal polymer residue or alternatively deposited carbonate or fiber particles.

2.1. $CaCO_3$ invasion into porous discs under high-pressure conditions

Tests were set up to measure the effect of $CaCO_3$ invasion into ceramic discs of mean pore-throat size of 50 μm under different differential pressures and with/without the presence of an Ultra-Fine cellulose-based fibre product which has a specified D90 value of 75 μm (AURACOAT UF, provided by European Mud Company AS). The $CaCO_3$ used was a ground marble and had been sieved to ensure a maximum particle size of 53 μm and an even distribution of particles above and below 23 μm to reflect the guidance of particle selection methods like the D90 Rule, Vickers Method, and the Abrams Rule. In this article, the terms $CaCO_3$, carbonate and ground marble are used interchangeably. The recipe and mixing sequence of the two fluids used is shown in Table 1. The fluids were KCl polymer-based drilling fluids with a concentration of around 56–57 kg/m^3 of $CaCO_3$, with the differences between the fluids being the inclusion of a fibre at a concentration of 13.9 kg/m^3 in Fluid 2, whereas Fluids 1 contained no fibres. The concentration of KCl was kept low, to reflect a drilling composition which may be relevant both for hydrocarbon and geothermal wells. KCl was selected due to its inhibitive effect on reactive clays. The concentration of xanthan gum was around 3.4 g/100 ml to provide sufficient viscosity for barite suspension and suspension of drill solids in wells with low angles of deviation. The fluids were designed with low solids contents and low salinity to be representative of fluids using for drilling of geothermal wells in addition to drilling of a permeable section of an oil- or gas well.

The rheological flow curves of Fluids 1 and 2 at 49 °C are presented in Fig. 1. The inclusion of cellulose fibre increases the concentration of particles in the fluid and increases the measure shear stress slightly at higher shear rates. Shear rates in the annulus will typically be less than 200 reciprocal seconds, and in this region the differences between the

Table 1
Recipe of test Fluids 1-2.

Component and Mixing sequence	Fluid 1	Fluid 2
Water	961g	948g
Soda ash	0.06g	0.06g
Caustic soda	0.71g	0.70g
Xanthan gum	3.39g	3.35g
Low viscosity poly-anionic cellulose	14.1g	13.9g
MgO	2.83g	2.80g
KCl	49.5g	48.8g
$CaCO_3$ (<53 μm)	56.6g	55.8g
Cellulose fibre with D90 of 75 μm		13.9g

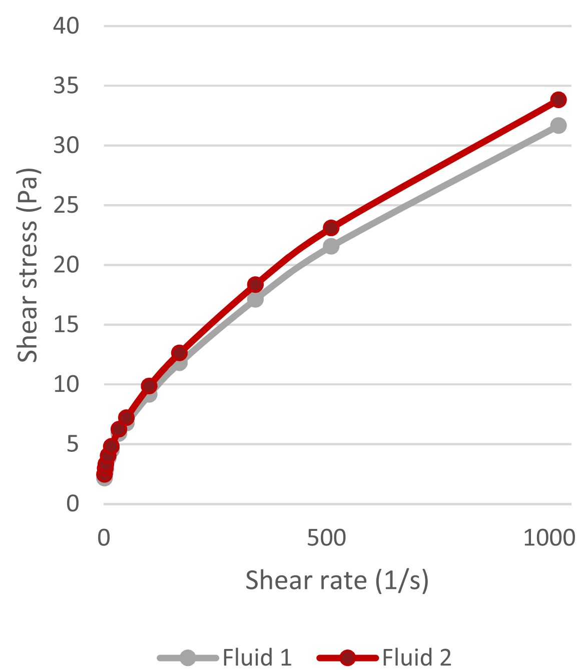


Fig. 1. Flow curves of Fluids 1-2.

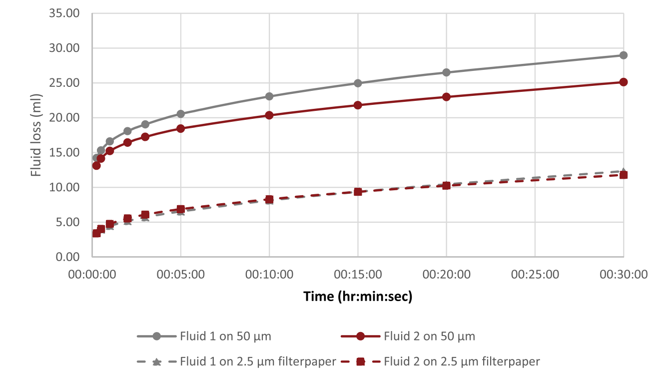


Fig. 2. Fluid loss for Fluids 1 and 2 on filter paper and 50 µm ceramic disc.

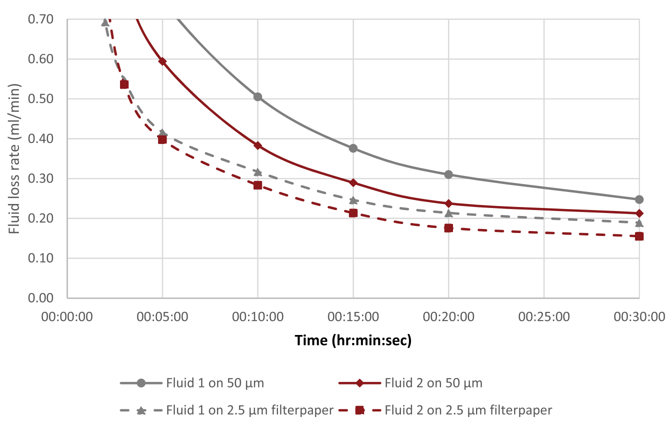


Fig. 3. Fluid loss rate development for Fluid 1 and 2.

measured shear stresses between the two fluids are small.

Fluid loss test were conducted using a conventional HTHP cell at 90 °C with applied differential pressures of 3.49 MPa (500 psi) for the tests on 2.5 µm filterpaper and 6.9 MPa (1000 psi) for the tests on 50 µm ceramic discs, as presented in Fig. 2. Higher pressures were applied for the tests on ceramic discs to reflect that drilling of depleted reservoirs often occur at higher differential pressures than the 500 psi recommended for API HTHP testing. The measured total fluid loss for the tests on filterpaper were relatively similar for Fluid 1 and 2, with 4% lower fluid loss for Fluid 2, indicating that the filter-cakes exhibit similar permeability at 3.49 MPa or that the permeability of the filterpaper is very low and hence does not adequately differentiate the filter-cake permeabilities. In contrast, the test on 50 µm ceramic discs showed a 13% reduction in fluid loss after the addition of Ultra-Fine cellulose fibre to the fluid. The differences in spurt-loss were not large and hence the difference in fluid loss over time may indicate that the filter-cakes exhibit different permeabilities with higher differential pressures applied. A reason for this may be compression of the fibres under higher applied differential pressure, and consequently a tighter packing of the filter-cake. The slight increases in shear stress and reduction in fluid loss for Fluid 2 relative to Fluid 1 may indicate some affinity between the cellulose fibres and the polymers of the base fluid.

To understand the development of the filter-cake permeability and the fluid loss over time, the fluid loss data were converted to a fluid loss rate for any given period of the HTHP test. This is presented in Fig. 3. Here it can be seen that the tests with Fluid 2, with fibre products and ground marble, have a lower fluid loss rate than Fluid 1, with ground marble, at any given point in time, given the same test medium. After 30 min, the recorded loss-rates were 0.25 ml/min and 0.21 ml/min respectively. This is evidence that the inclusion of the cellulose fibres reduced the permeability of the filter-cakes.

Subsequently, Fluids 1 and 2 were tested in a permeability plugging apparatus up to a maximum pressure of circa 34.9 MPa (5000psi) using 50 µm ceramic discs. After the target peak pressure had been achieved, no further fluid was pumped into the cell, and hence the pressure was allowed to fall gradually in line with fluid filtrate passing through the

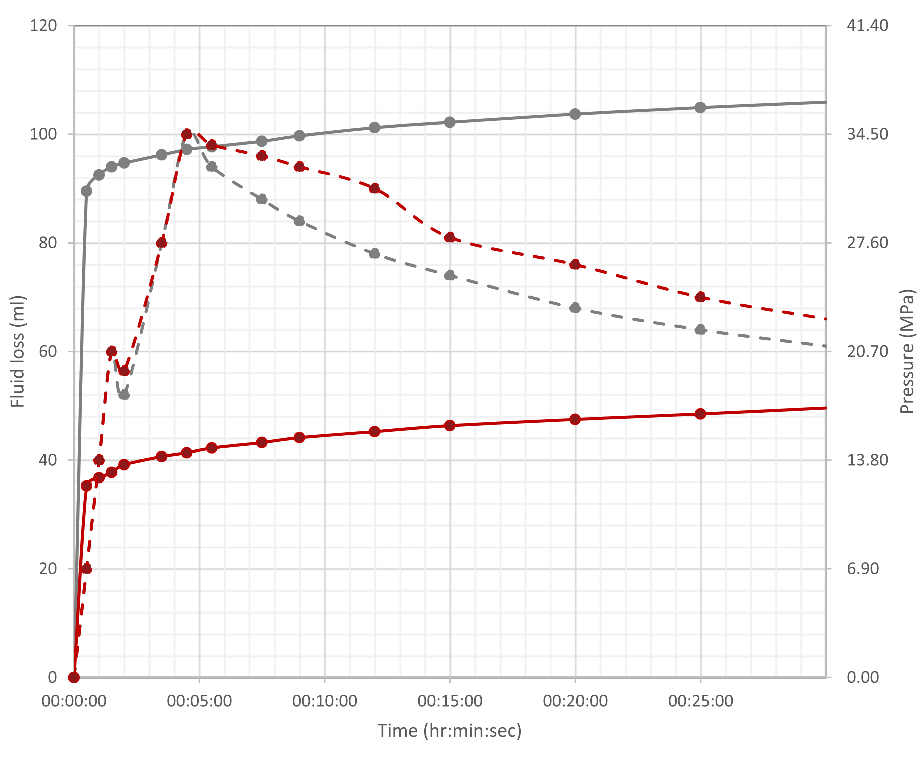
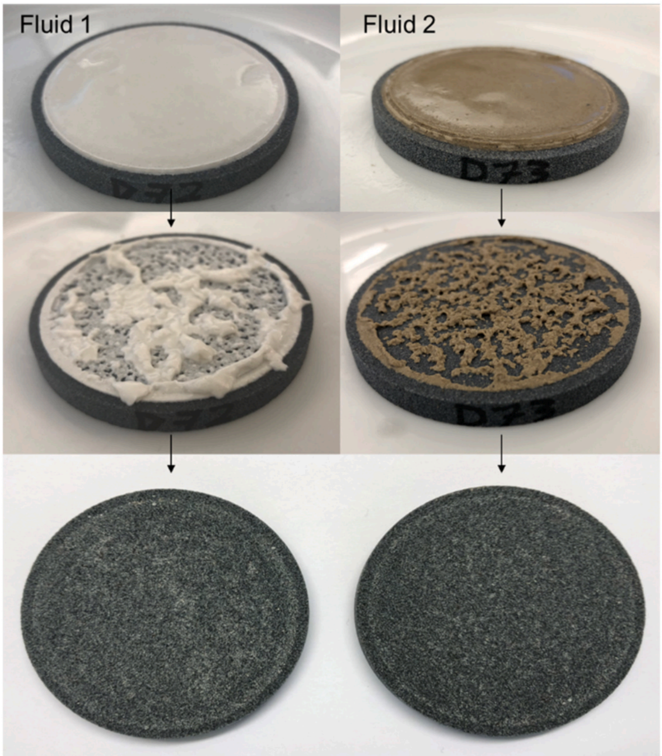


Fig. 4. Fluid loss and pressure development using tests on 50 µm ceramic discs for Fluid 1 with $CaCO_3$/ground marble and Fluid 2 with fibres.



Figs. 5. 50 μm discs used for testing of Fluid 1 and 2.

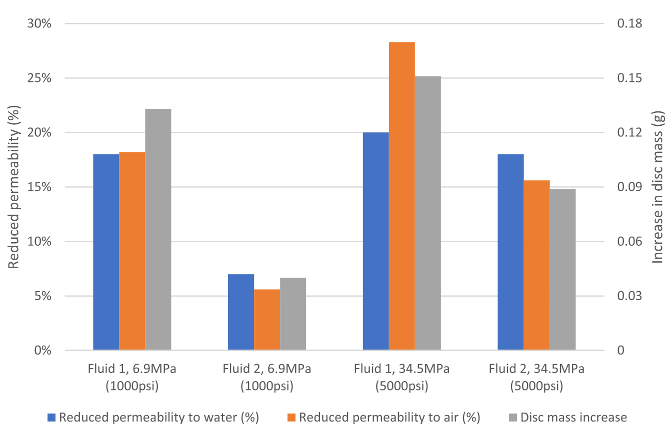


Fig. 6. Indicators of formation damage for Fluid 1 and 2 at different pressures.

ceramic disc and the corresponding de-compression of the fluid in the test cell. The pressure and fluid loss curves are presented in Fig. 4. Relative to the test conducted at 6.9 MPa, the differences in fluid loss between Fluid 1 and 2 increased considerably, with a 53% lower fluid loss with Fluid 1 containing $CaCO_3$ than with Fluid 2 containing fibres and $CaCO_3$.

After the HTHP fluid loss tests, the respective discs were analysed for changes in permeability and disc mass. The tested discs are presented in Fig. 5 at different stages through the process. First, with the discs of Fluid 1 and Fluid 2 after the 6.9 MPa (1000 psi) HTHP test, and in the middle with the filter-cakes partially removed by reverse flow, and then finally after applying an oxidizing breaker for 4 h at 90 °C and drying. During the reverse flow with brine, the filter cakes started disintegrating before a pressure of 0.05 MPa (7 psi) had been reached, but due to the high disc permeability, flow of brine rapidly builds at certain points of the disc and the filter-cakes were washed off in fragments. More of the filter-cake appeared to be lifted off the disc with Fluid 2, relative to the disc with Fluid 1, potentially due to the filter-cake being more cohesive with bonding between the cellulose fibres and the polymers. After the breaker application and drying, there was a visible difference, with less filter-cake residue remaining on the surface of the disc where Fluid 2 has been applied.

Changes in permeability and mass were measured. The results of these measurements are shown in Fig. 6. The three indicators of formation damage yield consistent results between the respective tests. For the 6.9 MPa tests, exposure to Fluid 1 reduced both the permeability to air and water by 18% and the increase in disc mass was 133 mg. After the test with Fluid 2, the permeability to water and air was reduced by 7% and 6%, respectively, whereas the increase in disc mass was only 4 mg, clearly indicating that the presence of cellulose fibre reduced the formation damage to a very low level. The significantly lower mass increase of the disc indicate that the fibres prevented $CaCO_3$ or polymers from migrating into the disc. Also, the tests confirmed the expectation that the oxidizing breaker did not dissolve or otherwise remove all polymers or deposited particles from the ceramic discs, whereas the external filter-cakes were successfully dissolved.

When the applied pressure increased to 34.9 MPa, the fluid loss increased relative to the 6.9 MPa test fluid loss values. This also corresponded with greater signs of formations damage. For Fluid 1 with carbonate particles, the reduction in permeability to water and air increased from 18% to 20% and 28%, respectively, whereas the disc mass increased from 133 mg to 151 mg. For Fluid 2 with cellulosic fibres, the reduction in permeability to water increased from 7% to 18% and the reduction in permeability to air increased from 6% to 16%. The increase in disc mass was more considerable as it increased from 4 mg to 89 mg.

It should, however, be noted that the data on formation damage was better for Fluid 2 at 34.9 MPa, than for Fluid 1 at 6.9 MPa, despite a higher fluid loss. This may indicate that the higher applied pressure for the test with Fluid 2 caused a higher filtrate volume, but that the presence of the fibres still reduced the invasion of solids or polymers into the disc. This observation is also consistent with Green et al. (2017), who concluded that lower fluid loss did not always correspond with lower formation damage.

The overall results of tests indicate that presence of $CaCO_3$, in a concentration of 5.6% by mass, facilitates a sealing of permeable formations up to median pore-throat sizes of 50 μm when the $CaCO_3$ particles were sieved to a size less than 53 μm, supporting the D90 Rule and the Vickers Method. However, the indicators of formation damage show that with presence of polymers and $CaCO_3$, the formation's permeability is significantly reduced. Further, with the addition of cellulose fibre in a concentration of 1.4% by mass, both fluid loss and indicators of formation damage are considerably improved. This indicates that presence of fibre particles with D90 $\geq$ 3/2 times the median pore-throat size may reduce invasion of solids and polymers and thereby reduce formation damage. For both the tests with Fluid 1 on ceramic discs, the disc mass increase was significantly larger than that for the tests with Fluid 2. This indicates that Fluid 1 led to more solids-invasion and hence more particles were forming an internal filter-cake with Fluid 1 than with Fluid 2. Comparing the fluid loss after the first 15 s of the tests conducted at 1000 psi, the fluid loss with Fluid 2 was 20% lower than that of Fluid 1. This is also consistent with the lower fluid loss rate of Fluid 2 than Fluid 1 after 30 min, Shown in Fig. 3. The fact that Fluid 1 likely had formed more of an internal filter-cake and that the fluid loss rate was lower for Fluid 2 after the initial spurt loss, indicates that the filter-cake also has a lower permeability.

2.2. *Limitation of polymer invasion in a solids-free fluid by introducing cellulose-based fibre particles*

To study the potential formation damage of polymers alone and the combination of polymers and fibres, a second series of tests were setup. An Ultra-Fine fibre product proved to limit formation damage in the first

Table 2
recipe of fluids 3-5.

Component and Mixing sequence	Fluid 3	Fluid 4	Fluid 5
Water	971g	961g	961g
Soda Ash	0.06g	0.06g	0.06g
Caustic Soda	0.71g	0.71g	0.71g
Xanthan gum	3.43g	3.39g	3.39g
Low viscosity poly-anionic cellulose	14.3g	14.1g	14.1g
MgO	2.86g	2.82g	2.82g
KCl	50.0g	49.5g	49.5g
Cellulose fibre Fine, D90 of 125 μm		11.3g	
Cellulose fibre Ultra-Fine, D90 of 75 μm			11.3g

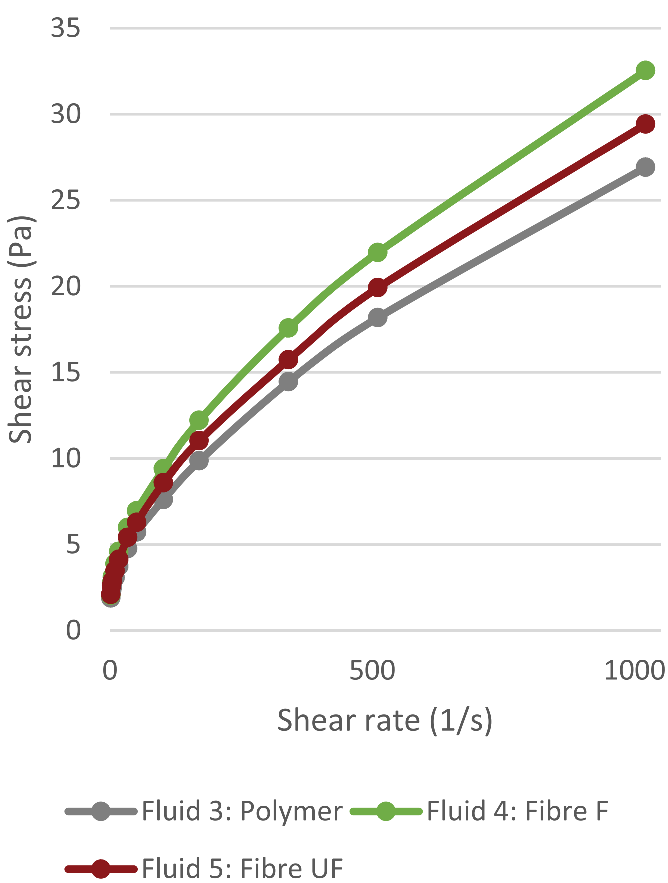


Fig. 7. Flow curves of Fluid 3–5, full viscometer share rate range.

test series when added to a fluid containing both polymers and $CaCO_3$. In addition to the Ultra-Fine fibre used in section 2.1, another Fine cellulose-based fibre product with D90 of 125 μm was selected for testing (AURACOAT F, provided by European Mud Company AS) in a drilling fluid free of solids in the form of drilled solids and weighting agents. The underlying objective was to assess if the fibre products could limit fluid loss and prevent formation damage when drilling with a solids-free drilling fluid. Tests were conducted on discs with a specified mean pore-throat size of 10 μm and 20 μm, with and without the presence of fibres. The recipe and mixing sequence of the three fluids used are presented in Table 2. Fluid 3 is the base fluid, composed as a KCl polymer drilling fluid where the polymers used are xanthan gum and low viscosity poly-anionic cellulose. The Fine fibre product was added in concentration of 11.3 kg/m^3 in Fluid 4 and the Ultra-Fine fibre product was added in a concentration of 11.3 kg/m^3 in Fluid 5.

The rheological flow curves of Fluids 3–5 at 49 °C are presented in Fig. 7. The inclusion of the fibres introduces particles in the fluid and increased the measured shear stress for a given shear rate. The increase

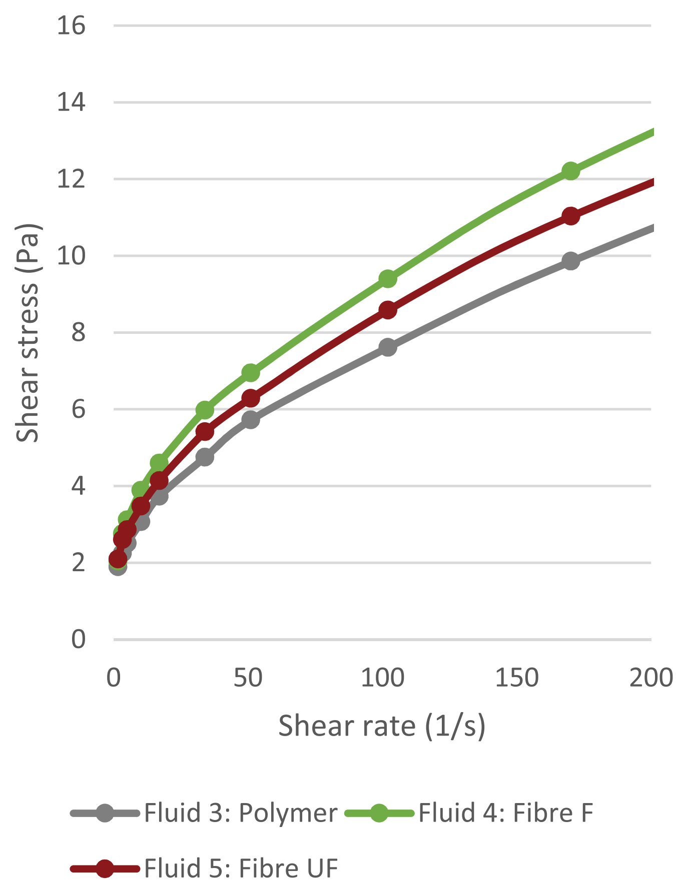


Fig. 8. Flow curves of Fluid 3–5, annulus flow share rate range.

in shear stress is slightly larger for the Fine fibre than for the Ultra-Fine fibre, likely due to the larger particle size, particularly when seen relative to the shear gap of the Ofite 900 viscometer that was used. With a viscometer shear gap of 1.17 mm and D90 particle size of 125 μm for the Fine fibre, the largest particles will be more than 1/10th of the shear gap, which may lead to incorrect readings on the viscometer. In Fig. 8, the lower share rate readings are presented. Here it can be seen that the differences in measured shear-stress between the three fluids reduce with lower shear-rates.

The plots for the fluid loss of Fluids 3–5 are represented in Fig. 9. For Fluid 3, a total loss was recorded on the 20 μm ceramic disc, whereas it managed to seal the 10 μm ceramic disc with a total fluid loss of 48 ml. In the solids-free fluid, the inclusion of the Fine fibre in Fluid 4 enabled effective sealing of the 10 μm disc with a fluid loss of 26 ml and the 20 μm ceramic disc with a fluid loss of 29 ml. With Fluid 5, the inclusion of the Ultra-Fine fibre effectively sealed the 10 μm ceramic disc with a total fluid loss of 19 ml and the 20 μm disc with a fluid loss of 32 ml. Fluids 4 and 5 have the same total concentration of fibre particles. However, due to the smaller particle size of the fibres in Fluid 5, naturally the concentration of particles below 75 μm will be higher than that of Fluid 4. This difference in particle size distribution may explain why the fluid loss is lower for Fluid 5 on the 10 μm ceramic disc. Another factor may be polar forces between the fibres and the polymers. With smaller fibre particles, the surface area will be larger for the same concentration of the Ultra-Fine fibres than for Fine fibres, and hence any polar interaction may be increased. In total, these factors may explain why the fluid loss was particularly low for Fluid 5 when tested on the 10 μm disc.

The fluid loss rate development is presented in Fig. 10. It excludes the test with Fluid 3 on the 20 μm ceramic disc as this yielded a total loss. The fluid loss rates appear very similar for the two fluids with fibres (Fluid 4 and Fluid 5), already after 2 min into the test. During the testing period, the fluid loss rates gradually fall towards a loss rate of 0.2–0.24

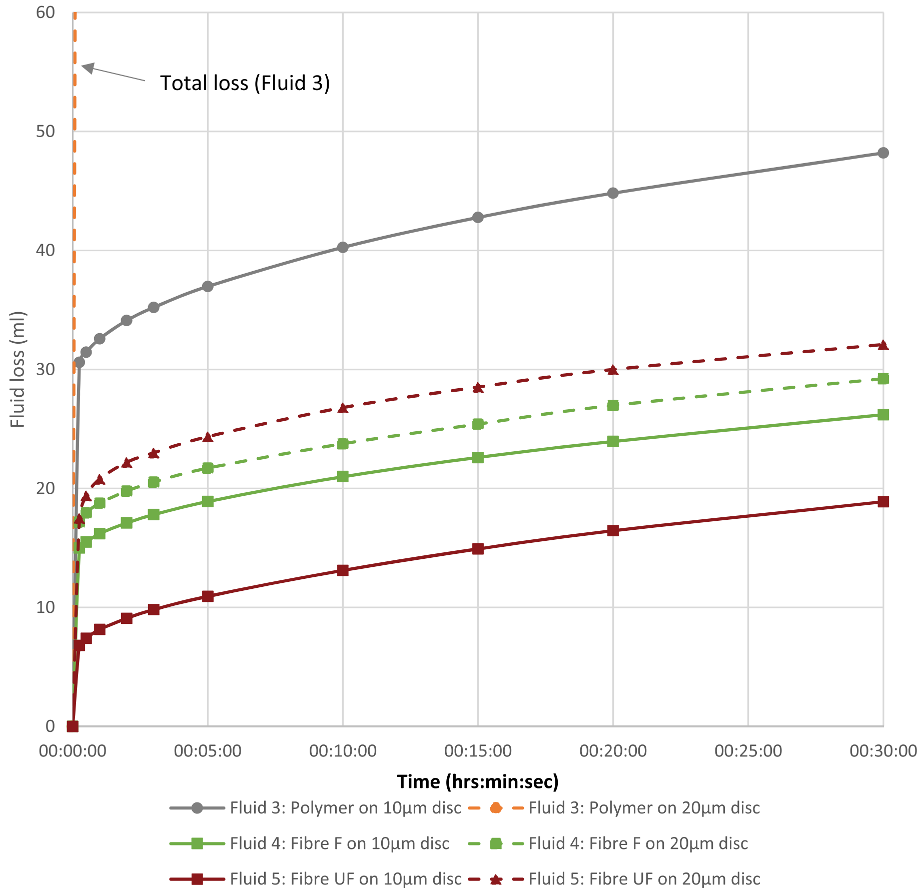


Fig. 9. Fluid loss at 6.9 MPa (1000 psi) for Fluid 3-5.

ml/min, when calculating as the average over the final 10 min of the tests. The main differences between the tests for Fluid 4 and 5 were during the first 15 s, when the internal and initial external filter-cakes were established. It appears that as time progressed, the fluid loss rate was more dependent on the permeability of the filter-cake being developed and less on the original disc permeability. In contrast, the fluid loss rate for Fluid 3 was consistently higher and fell to a rate of 0.34 ml/min during the final period of the test.

The measurements of air permeability and disc mass after reverse flow, and treatment with an oxidizing breaker, are presented in Fig. 11. The two discs that had been tested with Fluid 3 showed signs on considerable formation damage, with 53% and 66% reduction in permeability to air and 146 mg and 262 mg increases in the disc mass. Given that no solids nor fibres were present in Fluid 3, it may be concluded that the damage is due to polymer invasion.

In contrast, the results from the discs tested with Fluid 4 and 5 showed very low signs of formation damage. The recorded reduction in air permeability was 0.9% (10 μm disc) and 32% (20 μm disc) and disc mass increases of 27 mg (10 μm disc) and 21 mg (20 μm disc), where Fluid 4 had been applied. The corresponding numbers were 4.3% (10 μm disc) and 1.0% (20 μm disc) for reduction in air permeability and 0 mg (10 μm disc) and 32 mg (20 μm disc) increases in disc mass where Fluid 5 has been applied. The overall results indicate that the fibres were able to limit the fluid loss and reduce formation damage considerably when a breaker fluid was used to remove the external filter-cake residues. For the tests with Fluids 4 and 5, the D90 values of the fibre particle size distribution were larger than the specified pore sizes. Also, the D90 values of the fibres were higher than the ratio of 3/2 times the median pore-throat size. For Fluid 4, the D90 value was 12.5 times the rated pore size and 6.25 times the pore size, for the 10 μm and 20 μm discs. For Fluid 5, the D90 value was 7.5 and 3.75 times the median pore size. Comparing the formation damage indicators with the tests with Fluid 2, from the first test series, it is not clear if a further increase in the ratio of D90 value of the fibres to the median pore-throat size increases beyond the ration of 3/2 would yield any further reduction of formation damage.

It was observed a significant reduction in permeability to air for Fluid 4 after the test on the 20 μm disc. This is in slight contrast to the measurement of changes in disc mass, which was very low. The observation is also in contrast with the other tests with fluids containing fibres. No clear evidence was found of this deviating data, but a cause may be large differences in initial disc permeabilities and hence pore-sizes The 20 μm disc used for testing Fluid 5 has a low initial permeability to air of 646 mD and a disc mass of 41.768g. In contrast, the initial permeability of the 20 μm disc used for testing Fluid 4 was 8.36 D and the disc mass was 41.461g. Given that the differences in mass was relatively low at only 0.74% it is likely that the large difference in permeability is related to larger pore-sizes on the disc used for Fluid 4. Any surface plugging of some large pore openings may lead to significant reduction in permeability, but with little measured disc mass increase. The specified permeability to air is 2 D, so it is clear that the supplied discs varied greatly from the specification. Other potential causes may be the functioning of the breaker fluid or that the polymers and/or fibres may have combined in a certain way during the drying process.

The overall test results of test series 2 clearly indicates that the cellulose fibres enable HTHP sealing of permeable formations without the presence of solids in the form of drill solids or weighting agents, even in concentrations as low as 11.3 kg/m^3. Also, a fluid with polymers, but without fibres or solids present a great risk of formation damage if used in a reservoir section. Further, the inclusion of cellulose fibres show that formation damage may be substantially limited even with a 6.9 MPa (1000 psi) differential pressure applied and given that the particles have

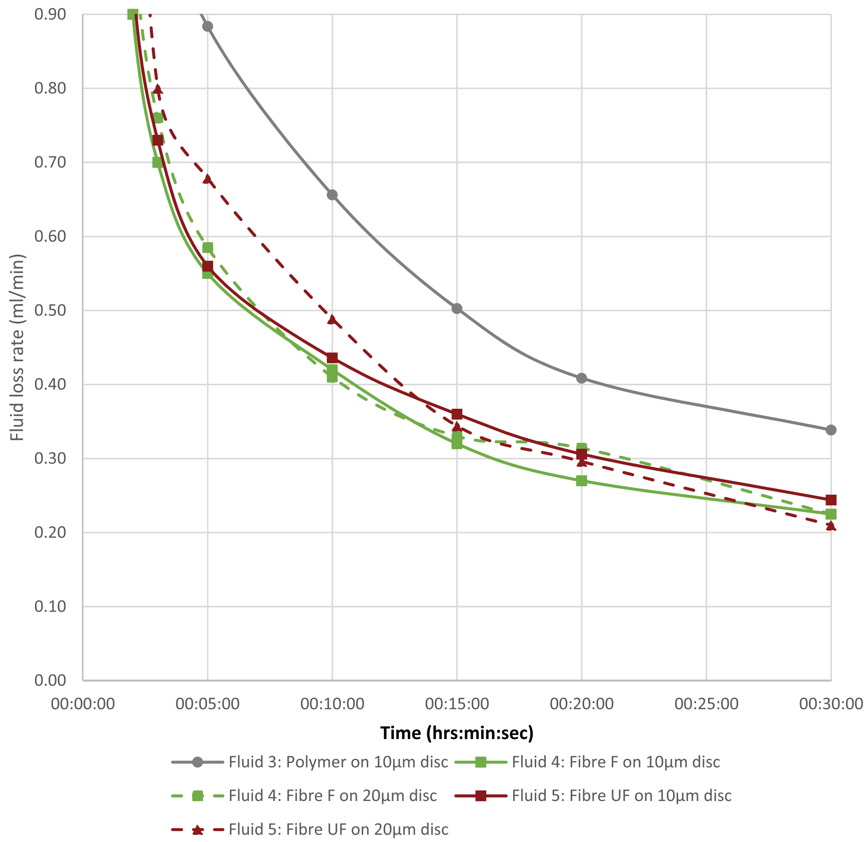


Fig. 10. Fluid loss rate development of Fluid 3-5.

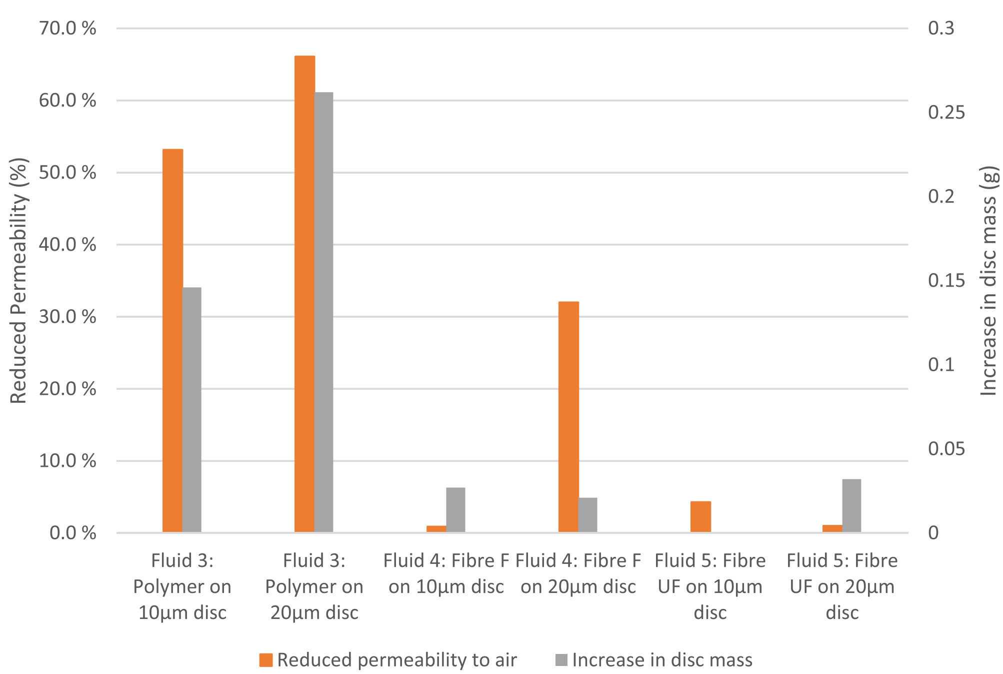


Fig. 11. Indicators of formation damage after testing with Fluid 3-5.

a D90 value that is equal to or greater than 3/2 times the pore-throat size. Klungtvedt et al. (2021a,b) tested fibres containing cellulose with D90 values of around 0.8 times the pore-size and found that this led to very low fluid loss, but with significant increases in disc mass. Such application may be ideal for wellbore stabilisation purposes but may induce formation damage in a reservoir drilling application.

By viewing the fluid loss rate development together with the measurement of changes in disc mass, it may be possible to assess if the development of the fluid loss rate was dictated by the building of an internal or external filter-cake. For the tests with Fluids 4 and 5, the fluid loss rate fell much faster than for Fluid 3. At the same time, the disc mass increases were considerably lower. This indicates that for Fluids 4 and 5, relative to Fluid 3, the improvement in fluid loss over time was a result of lower external filter-cake permeability rather than more particles migrating to form a low-permeability internal filter-cake.

2.3. Overall discussion of test results

The tests show that fluid loss is reduced when $CaCO_3$ and fibres are added to a KCl polymer drilling fluid, and that an effective sealing may be achieved all the way up to differential pressures of 34.5 MPa (5000psi) in certain cases. Further, it shows that the formation damage is considerably reduced when fibres with a D90 $\geq 3/2$ the pore size is added to the fluid. This suggests that the fibres can form a more impermeable external filter-cake which prevents solids from entering the formation, given that the size exceeds 3/2 times the median pore-throat size.

Considering that $CaCO_3$ particles are known to degrade rapidly after exposure to shear, there results of this study indicates that application of sized $CaCO_3$ particles to prevent fluid loss and formation damage will only have temporary effect. For optimum results, $CaCO_3$ particles need to be combined with materials where the PSD deteriorates much less during a typical drilling operation.

The analysis has been based on comparing the D90 value of the fibers with the median pore size of the permeable discs. In a permeable rock formation, there will likely be heterogeneity in the pore-sizes, where the largest pore-networks may yield higher permeability than the average of the formation. If such heterogeneity is significant, the high permeability parts of the formation is likely to provide an above average fluid flow when the well is brought into operation. To optimise the retention of the formation permeability, it may therefore also be important to ensure that particles are of a sufficiently large size to protect the largest pore openings from solids invasion and polymer damage. It may also be the case that the ceramic discs are heterogenous and hence that fibres with a larger D90 value than then median pore size are particularly important in protecting the high-permeability parts of the discs.

3. Conclusions

The tests provided good evidence with regards to understanding how fluid loss and formation damage may be reduced. It was shown that polymer fluids alone and in combination with $CaCO_3$ can lead to substantial formation damage. The main variable factor in the tests were the inclusion of fibres with a known D90 value $\geq 3/2$ the pore size, to both reduce the fluid loss and the formation damage.

- It was identified that a solids-free polymer fluid without cellulose fibres led to large formation damage on permeable discs with 10 μm and 20 μm pore sizes.
- It was identified that $CaCO_3$ particles can lead to formation damage when the D90 value is around the pore size. The tests showed a permeability reduction of 17–18%.
- When cellulose fibres with D90 value $\geq 3/2$ the pore size were introduced, the formation permeability reduction was limited to 6–7%. This indicates that the recognised particle size selections methods may be further optimised when applying fibrous materials, and that larger fibre particles prevent migration of solids and polymers into the formation.
- When higher differential pressure was applied, the measured formation damage increased.
- The recognised particle selection methods focussing on either D50 or D90 values proved to provide good fluid loss values. However, such particle selection method led to formation damage, measured as reduction in permeability and increased disc mass.
- The tests conducted at 6.9 MPa (1000 psi) indicated that the permeability of the external filter-cake was reduced when fibre particles were added to the fluid.

Credit author statement

Karl Ronny Klungtvedt: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Arild Saasen**: Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The special experimental set-up was as follows:

- Ohaus MB120 Moisture Analyser
- Custom built transparent acrylic cell with stand for enabling of reverse flow of fluid through the ceramic discs
- Festo pressure regulator LRP-1/4–2.5 and LRP-1/4–0.25
- Festo Pressure Sensor SPAN-P025R and SPAN-P10R
- Festo Flowmeter SFAH-10U
- Nitrogen source and manifold for pressure up to 1350 psi, Ofite #171-24
- Vacuum machine, DVP EC.20-1
- Custom build Permeability Plugging Apparatus with hydraulic pump for testing on slotted discs or ceramic discs up to 35 MPa (5076 psi)
- AEP Transducers JET Pressure Gauge with Data Logger

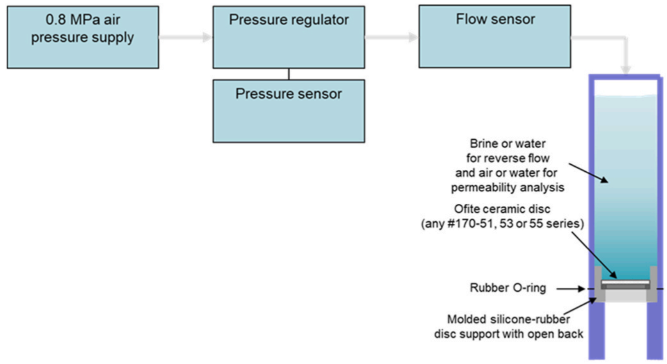

Fig. 12. Schematic of equipment for reverse flow and permeability measurement.

In additional, the following equipment was used for the conventional preparation of the fluid and HTHP fluid loss testing according to ANSI/API 13B:

- Hamilton Beach Mixer, for mixing of drilling fluids
- Ohaus Pioneer Precision PX3202, for weighing the drilling fluid ingredients
- Ofite Filter Press HTHP 175 ml, Double Capped cell for HTHP fluid loss test
- Ofite Viscometer model 900, for measuring fluid rheological parameters
- Ofite roller-oven #172-00-1-C, for aging the drilling fluid samples
- Apera pH90, pH meter, for pH measurements

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