Analysis of Gelling Properties of Drilling Fluid and Improved Modelling of Gelling Behaviour

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ABSTRACT

Stress overshoots at start-up of shear has been analysed for three water-based drilling muds and one oil-based mud by using a scientific rheometer. The measurements have been performed for a larger span of gelling times than found in many other works, and the sensitivity to the input test parameters, *target shear rate* and *ramping time* has been investigated. The analysis is performed on a scientific rheometer were the target shear rate and ramping time are controlled and varied, as well as on two typical field instruments where these parameters in practice are fixed. Our measurements showed that the field instruments gave significantly lower values than the scientific rheometer did, a result that should be taken into account when using the gel strength measurements from the drilling rigs for modelling and estimation purposes. Except for gelling times greater than 1-2 hours, the increase in stress overshoot for increasing gelling times follows in all cases quite closely a logarithmic function. The different input parameters mainly gave a vertical shift in this curve, leaving the slope almost unchanged. Two models in the literature, designed to predict this behaviour, have been compared to our data. In addition, the same two models have been adjusted to give better match for the lowest gelling times, which has not been accounted for earlier. We show how the new modified models can be calibrated by using the two standard gel strength measurements as inputs.

INTRODUCTION

The drilling mud fulfils a range of important functions during drilling operations, varying from providing lubrication, building mud cake and transporting cutting, to being the primary barrier for avoiding catastrophic incidents such as kick[1]. The rheological properties of the mud are often quite complex and dictated by such major considerations as mentioned above, and the effect of this complexity must be handled best possible way when dealing with other tasks like flow modelling and optimization of drilling speed.

The ability to quickly build gel structure is for example necessary to keep the cuttings at rest during pauses in the mud circulation, while it gives extra challenges when optimizing the pump start-up sequence without fracturing the well[2]. We also normally want the mud to exhibit both shear thinning and thixotropic properties to minimize the frictional pressure drop during steady pumping at high rates[3].

An improved understanding of evolution of gelling can give better models, improved prediction of downhole pressure surges during pump start-up or tripping and faster procedures without sacrificing safety[4]. To help such pressure predictions, it is standard procedure in the drilling industry to measure the "gel strength" at the rig at certain intervals. This is per definition done by pre-shearing a mud sample in a rotational rheometer and let it stay at rest for specified resting times (10 s and 10 m and sometimes 30 m), and then starting rotation at 3 RPM while recording the highest stress obtained during the start-up of rotation. The stress will normally show an overshoot before it approaches a steady value given by the shear rate at 3 RPM. The magnitude of the overshoot is dependent on various properties related to thixotropy, elasticity and yield point of the mud.

The main objective of this work is to acquire a better understanding of the gelling process of drilling mud and to evaluate if the standard measurements performed at the field can be better utilized to predict the flow behaviour of the mud. This is done by measuring the build-up of gel strength on an Anton Paar MCR 302 rheometer for an extended range of input parameters, as well as comparing these results to measurements performed on the type of instruments normally available at the rigs (Ofite 800 and Fann 35SA), following the standard field procedures.

With only a few exceptions, data we have found in the literature mostly treats gelling times between 10 s and 30 m. In this work we have extended this range in both ends. The extreme values on both sides of gelling times are important as sometimes the mud starts flowing after only a few seconds of standstill, while other times the flow circulation could be stopped for several hours.

As explained above, the gel strength is defined as the stress overshoot obtained by ramping up the shear stress to 3 RPM, which corresponds to 5.1 s^{-1}. In this work we measure the stress overshoot for other values of this target shear stress, as well as how fast the shear rate is ramped up, giving us a means to test for different acceleration rates.

An objective here is to investigate how sensitive the gel strength/stress overshoot values are to differences in these input test parameters and indicate the potential inaccuracies we have if the results are used for modelling of transient thixotropic behaviour of drilling mud.

In the last part of the work, we will plot and analyse the stress overshoot values obtained and check if any of the published equations/models for extrapolating these values match our data. Some adjustments to the models are suggested to give better match for the lowest gelling times which has not been accounted for earlier.

It is not within the scope of this paper to find a dynamic/transient thixotropic shear stress model that describes the *time response* of shear stresses for various time-varying input shear rates. However, it is a goal that the result can give some knowledge that can be helpful when field measurements are used as input to such models.

TEST METHODOLOGY

To perform tests, Anton Paar Rheometer have been operated in controlled shear rate mode at constant fluid temperature of 20 degrees Celsius (293.15K) in a smooth concentric cylinder system.

TABLE 1: Description of shear target rates (starting at zero) and ramping times for the case scenarios.

Mud type	Case A	Case B	Case C
WBM	Target: 0.2 s^{-1}. Time: 0.5 s.	Target: 0.51 s^{-1}. Time: 0.5 s.	Target: 0.51 s^{-1}. Time: 1.25 s.
OBM	Target: 0.2 s^{-1}. Time: 0.25 s.	Target: 0.51 s^{-1}. Time: 0.25 s.	Target: 0.51 s^{-1}. Time: 0.625 s.

For all tests, the mud was pre-sheared for about 5 minutes at a shear rate of 1021 s^{-1}. Thereafter different resting times were applied before the share rate was ramped up from zero to a target shear rate during a specified ramping time. The target shear rate and ramping time were varied as shown **Table 1**. In this way, stress overshoot is estimated for that specified resting time.

The four drilling muds used in the experiments are named as given in **Table 2**.

TABLE 2: Drilling muds used in experiments

1. KCl Polymer WBM 1	2. KCl Polymer WBM 2
3. Envriomul OBM	4. Aqua Drill WBM

EXPERIMENTAL RESULTS

The fact that the stress overshoot increases with increased resting/gelling time is a well-known behaviour. Some of the questions we want to investigate here is if the logarithmic trend proposed by others[5] is valid for these muds in general, and to which degree this trend is valid for very short and very long gelling times.

In Fig. 1-4 the test results from the MCR 302 are shown for the four test muds. Both the dynamic stress response and the stress overshoot values as function of gelling time are plotted. For two of the muds, all case scenarios A, B, and C are shown, while for the other two muds, only case scenario A has been performed.

In general, the plots reveal that the logarithmic increase is followed quite well for all gelling times below 1-2 h. Above 2 h, the results get scattered around the logarithmic trend on both sides. Due to various effects that may have a significant impact for such long gelling times, like evaporation, particle sagging, wall slip and shear banding[6] we are not sure about the validity of these results. More experiments for these cases are therefore planned.

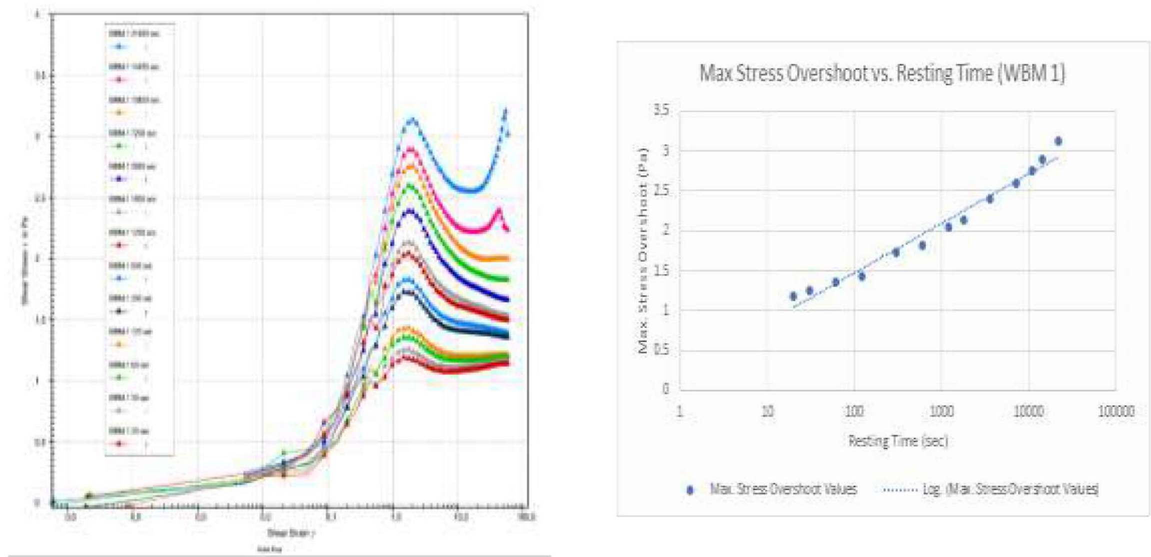

FIGURE 1: Stress overshoots for KCl Polymer WBM 1 for different resting times and case scenario A. Left side: Dynamic response as function of shear strain. Right side: Only the stress overshoot values as function of resting time in logarithmic scale.

Comparison of these results to *models* of the stress overshoot as function of gelling times is done in next section. Here we analyse how the choice of target shear rate and ramping time/ acceleration affects the values. From viscoelastic and thixotropic theory[6,7] we expect the stress overshoot to be greater if the target shear rate is large, and lower if the ramping time is long.

One reason for the latter effect, when assuming an gradual change from elastic dominated deformation to viscous flow[7], is that for long ramping times, the thixotropic structures in the mud have more time to break before the stress overshoot is reached. From Fig. 2-3 we get this theory confirmed, as the overshoot increases with increasing target shear rate and with decreasing ramp time. This is seen from the right side of the figures showing stress overshoot values as function of gelling times.

To have consistency in results from such stress overshoot tests, we suggest that the ramping should be performed as fast as possible without getting excessive inertia effects[6,8]. Our argument for this is that since the gel breaking is dependent on both time, shear rate and fluid properties, it is very difficult to back-calculate what the gel state was at start-up of shearing if the time until the overshoot is significant. Thus, a short ramping time will give stress overshoot values that give more directly information about the gel state after a given gelling time.

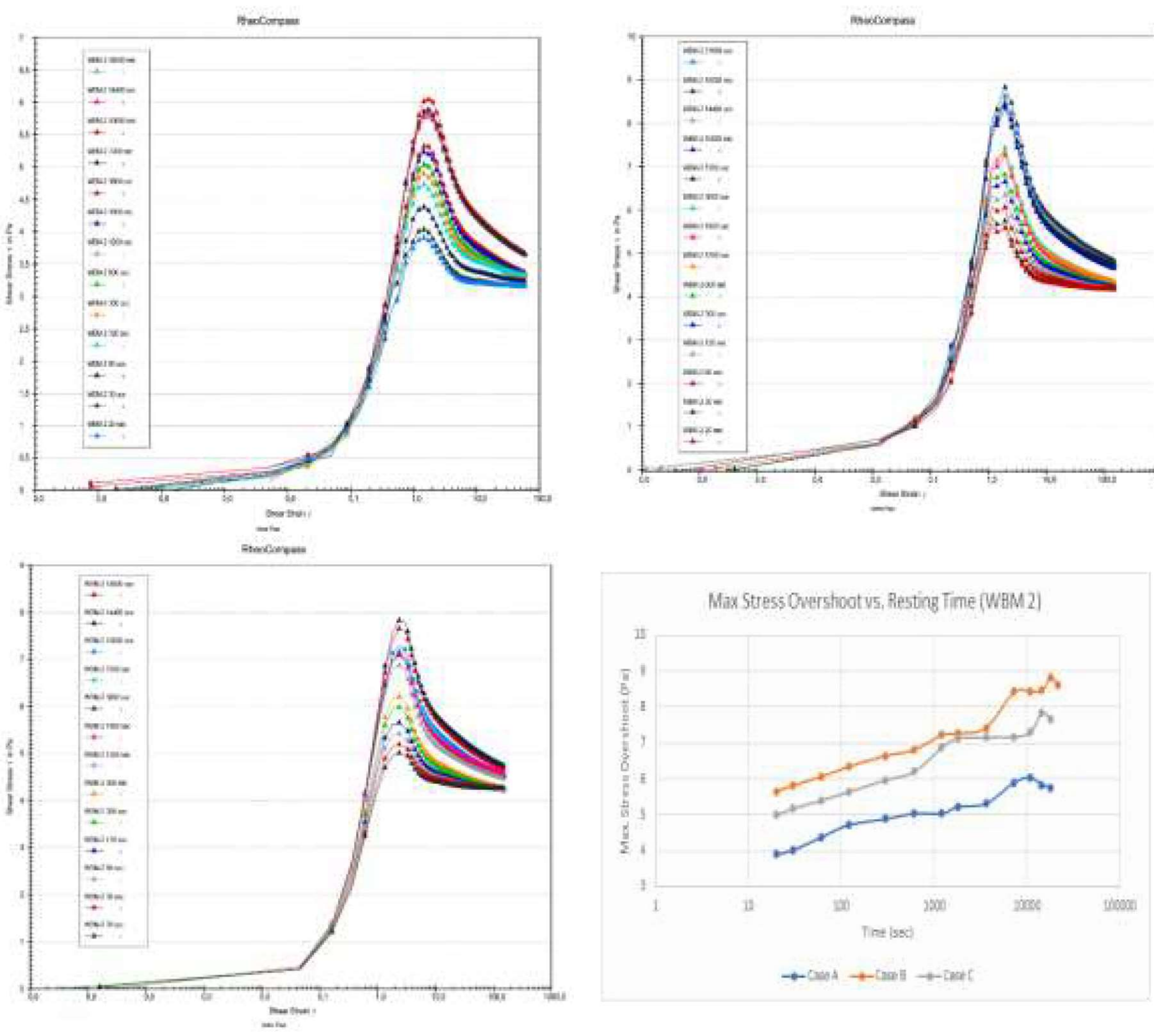

FIGURE 2: Stress overshoots for KCl Polymer WBM 2 for different resting times. Upper left: Dynamic response as function of shear strain for Case scenario A. Upper right: Dynamic response as function of shear strain for Case scenario B. Bottom left: Dynamic response as function of shear strain for Case scenario C. Bottom right: Only the stress overshoot values as function of resting time in logarithmic scale for all case scenarios.

In Fig. 5-6 stress overshoot values as function of gelling times are plotted for the field instruments Ofite 800 and Fann 35 and compared to the results from MCR 302. For the field instruments, the gel strength is measured for 10 s, 10 m and 30 m, since this is the most extensive test we can expect to be performed at the rigs. Only the two muds where we have ramped up to 5.1^{-s} are relevant to compare to, i.e., case scenarios B and C.

From these figures we observe that the field instruments give somewhat lower values than both case B and C. All instruments are calibrated and verified, so our hypothesis was initially that this is because the ramping time for the field instruments is longer than the longest used for MCR 302 (1.25 s and 0.625 s for WBM and OBM respectively). For KCl Polymer WBM 2, the results from Fann 35 are quite close to the results from case C, so the ramping time for Fann 35 might not be too far from 1.25 s.

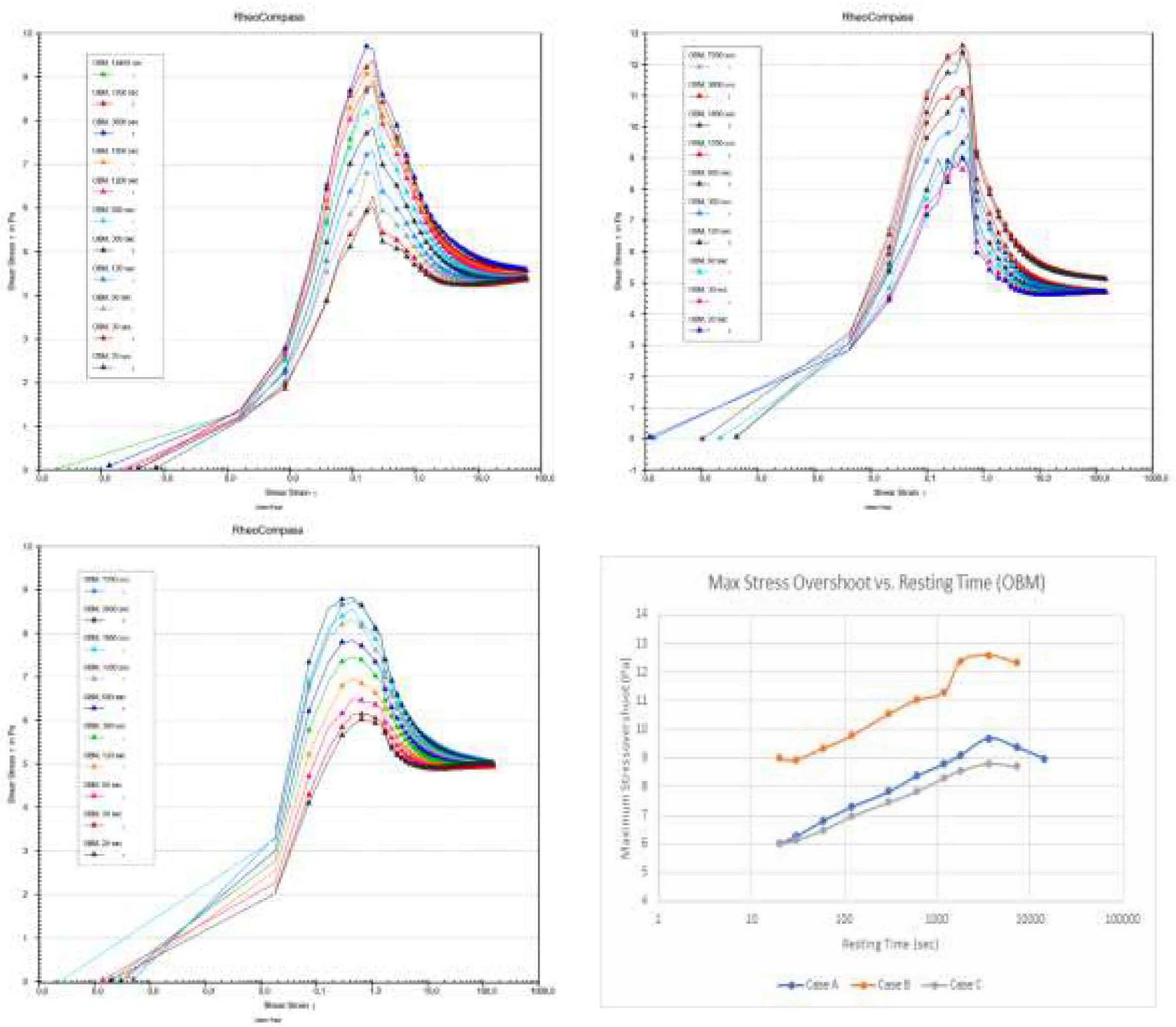

FIGURE 3: Stress overshoots for Enviromul OBM for different resting times. Upper left: Dynamic response as function of shear strain for Case scenario A. Upper right: Dynamic response as function of shear strain for Case scenario B. Bottom left: Dynamic response as function of shear strain for Case scenario C. Bottom right: Only the stress overshoot values as function of resting time in logarithmic scale for all case scenarios.

Based on our arguments above, that the shorter ramping times give more direct information about the gelling state, these differences are important to consider when using field data for modelling purposes. Assuming that case B gives optimal ramping time, the results from the Ofite 800 underestimates by 14%-23% for the WBM and by 39%-45% for the OBM compared to case B. Since the OBM used ramping time as short as 0.25 s to reach to 5.1^{-s} we wonder if this large difference could be caused by the inertia effects. This effect is largest for MCR 302, as for this configuration the torque sensor is connected to the rotational bob, which also has to be accelerated, while for the two others, it is the outer cup that rotates. The MCR 302 is calibrated to compensate for inertia effects, but we are not sure about the accuracy of this compensation for such high accelerations.

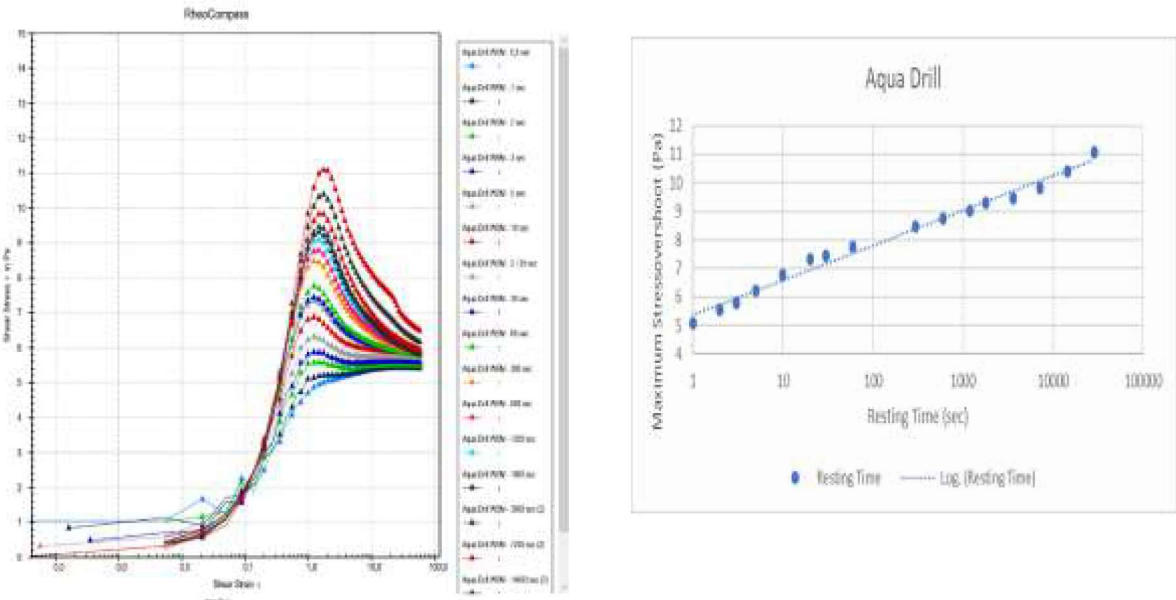

FIGURE 4: Stress overshoots for Aqua Drill WBM for different resting times and case scenario A. Left side: Dynamic response as function of shear strain. Right side: Only the stress overshoot values as function of resting time in logarithmic scale.

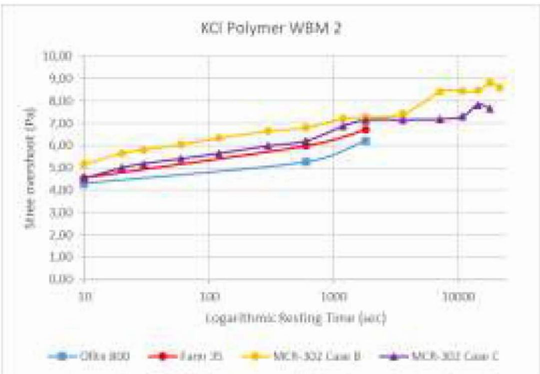

FIGURE 5: Comparison of KCl Polymer WBM 2 stress overshoot values from the field instruments Ofite 800 and Fann 35 and the scientific Anton Paar MCR 302 rheometer.

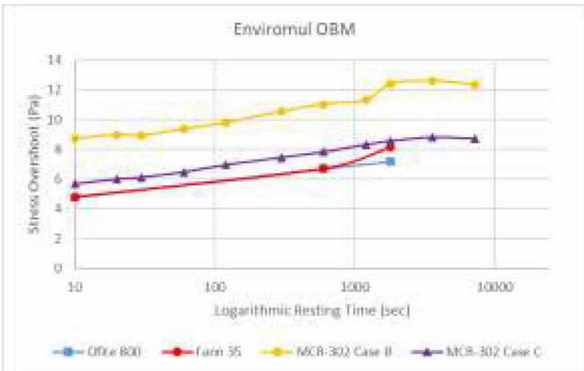

FIGURE 6: Comparison of Enviromul OBM stress overshoot values from the field instruments Ofite 800 and Fann 35 and the scientific Anton Paar MCR 302 rheometer.

COMPARISON OF OVERSHOOT MEASUREMENTS TO EXISTING MODELS

We have selected two models for the gel strength/ stress overshoot as function of gelling time and adjusted them based on our results for the lowest gelling times. The principle is that measured gel strength from the field can be used as input for modelling the gel strength for any gelling time.

The first function we consider was presented by Cayeux [9] as,

$$\tau_{g(t)} = \begin{cases} \tau_y + \dfrac{t}{t_1}\left(\tau_{gm(t_1)} - \tau_y\right), & \forall t \in [0, t_1] \\ \tau_{gm(t_1)} + \dfrac{\tau_{gm(t_2)} - \tau_{gm(t_1)}}{\log_{10}(t_2 - t_1)} \log_{10}(t - t_1), & \forall t > t_1 \end{cases}, \qquad (1)$$

where τ_{gm} is measured gel strength, and t_1 and t_2 are the two gelling times for which we have measurements. This model constructs a function that is forced to go through $\tau_{gm(t_1)}$ and $\tau_{gm(t_2)}$. It furthermore assumes that $\tau_{g(t)}$ starts at a yield stress given by τ_y, and increases linearly to $\tau_{gm(t_1)}$ at time t_1. Thereafter it increases according to the logarithmic expressions.

Since we have found the gel strength to closely follow the same logarithmic trend for gelling times less than 10 s (as for larger than 10 s), we modify this function by expanding the logarithmic range down to the lowest measured gel strength we have. We denote this lowest gelling time, which is 2 s in our case, for t_{min}.

Also, for several of our fluids we found that the stress overshoot for these lowest gelling times and low target shear rates is lower than the Herschel-Bulkley yield the stress calculated from steady flow curve. Hence, we cannot anymore start at a yield stress calculated this way. Instead, we let the function start at zero and increase linearly to $\tau_{gm(t_1)}$. This first linear range is now shorter and steeper than before and represents a range of gelling times where there may be difficult to get stable measurements (as the fluid motion might have to start before it everywhere has come completely to rest).

We let the modified function be expressed by,

$$\tau_{g(t)} = \begin{cases} \dfrac{t}{t_{min}} \tau_{g(t_{min})}, & \forall t \in [0, t_{min}] \\ \tau_{gm(t_1)} + \beta\,(\log_{10} t - \log_{10} t_1), & \forall t > t_{min} \end{cases}, \quad \beta = \frac{\tau_{gm(t_2)} - \tau_{gm(t_1)}}{\log_{10} t_2 - \log_{10} t_1}, \qquad (2)$$

Note that since t now can be less than t_1, the function will extrapolate the slope between t_1 and t_2 down to t_{min}. We also emphasize that since all our muds show logarithmic trends down to at least 2 s we can use this approach as a best guess for situations where only the standard 10 s and 10 m field measurements are available. In these cases, since we haven't measured the shear stress at t_{min}, the linear part of Eq. (2) has to be computed after the logarithmic part such that we can use the calculated $\tau_{g(t_{min})}$ from the logarithmic part as input to the linear part.

Finally, note that logarithmic expressions in Eq. (1) does follow a pure logarithmic increase, and will therefore not give a linear line in a logarithmic plot. Since our data seems to follow a logarithmic increase quite strictly, we have modified our function accordingly (i.e., we take the difference of the log-functions instead of log of the differences). The difference is not large, but important to be aware of.

The second model we will test was proposed by Garrison [10] as early as in 1939 during work with California bentonite suspensions. Adapted to our notations, his model for the gel strength as function of gelling time t can be expressed as,

$$\tau_{g(t)} = \frac{\tau_\infty\, K\, t}{1 + K\, t}, \qquad (3)$$

where τ_∞ is a maximum gel strength as gelling time approaches infinity and K is a growth rate constant. A fundamental difference between this model and the type presented in Eqs. (1) and

(2) is that the model in Eq. (3) approaches an asymptote given by τ_∞, and thus has an absolute upper limit.

Similar to the model in Eq. (2) we have adjusted the Garrison model by letting it increase linearly with a hight slope for the first few seconds and thereafter switch over to an equation of the form in Eq. (3). For cases where we only have the 10 s and 10 m measurements, we utilize Eq. (2) to find an estimate for $\tau_{g(t_{min})}$ since this was readily possible without any more data. The result is,

$$\tau_{g(t)} = \begin{cases} \dfrac{t}{t_{min}} \tau_{g(t_{min})}, & \forall t \in [0, t_{min}] \\ \tau_{g(t_{min})} + \dfrac{(\tau_\infty - \tau_{g(t_{min})})\, K\, (t - t_{min})}{1 + K\,(t - t_{min})}, & \forall t > t_{min} \end{cases}, \tag{4}$$

where $\tau_{g(t_{min})}$ is computed from Eq. (2).

When it comes to finding the two model parameters τ_∞ and K, we utilize the 10 s and 10 m measurements. This means that $\tau_{g(t1_2)}$ and $\tau_{g(t_2)}$ are known, which from Eq. (3) gives us two equations with two unknowns. Solving first for the parameter K in the original Garrison model and then for τ_∞ gives,

$$K = \frac{60\,\tau_{g(t_1)} - \tau_{g(t_2)}}{600\left(\tau_{g(t_2)} - \tau_{g(t_1)}\right)}, \quad \tau_\infty = \frac{1 + 10\,K}{10\,K}. \tag{5}$$

For the modified Garrison model, we follow the same principle, just that the starting point for the function is now at the coordinates t_{min} and $\tau_{g(t_{min})}$. This results in that the stresses in Eq. (5) must be shifted downwards by $\tau_{g(t_{min})}$ and the time values must be shifted downwards by t_{min}.

The four models above are now plotted and compared to our measurement results. In all cases we have calculated model parameters from only the 10 s and 10 m measurements and forced the models to go through these points.

In FIGURE 7 we have compared the models to the mud denoted KCl Polymer WBM 2, and we have included all the three test case scenarios (A, B and C). For the original Cayeux model we had to enter a yield stress τ_y, which may be hard to determine for such thixotropic fluids. Here we have estimated it to be 2.5 Pa.

We observe that in all cases the two modified versions are closer to the measurements for the shortest gelling times, where they have been improved. Another point to note is that both the original and modified Garrison models seem to flatten out too early. However, as mentioned in previous section, we are not sure about the validity of the results after approximately one hour, so a strict conclusion cannot be drawn. Furthermore, the modified Garrison model perform better than the original one *between* the two measurements.

The logarithmic-based models continue to grow approximately according to the data all the way up to 5 h. Although this might be a reasonable correct behaviour, the increasing trend should end at some point, meaning that these two models should be truncated with an upper limit at which they stop to grow. However, due to the uncertainty regarding longest gelling times we are not sure when this happens.

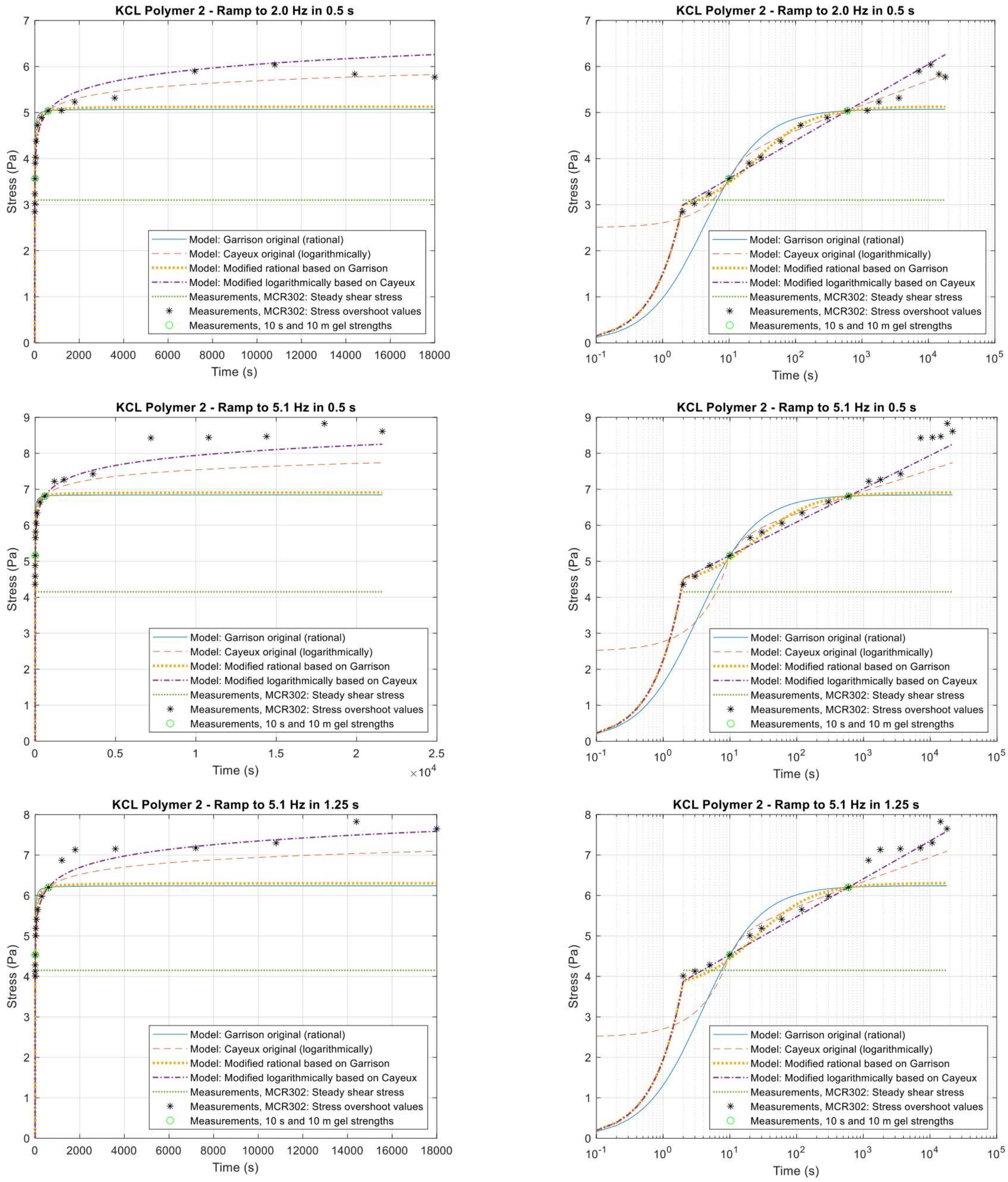

FIGURE 7: Models of gel strength as function of gelling times compared to measurements for the mud denoted "KCl Polymer WBM 2". The measurements were taken when ramping from 0 to 2 s^{-1} in 0.5 s (uppermost figures), when ramping from 0 to 5.1 s^{-1} in 0.5 s (middle figures) and when ramping from 0 to 5.1 s^{-1} in 1.25 s (lowermost figures). The left-hand side figures show linear time scale while the right-hand side is in logarithmic time scale. The models are forced to match the measurements at 10 s and 10 m gelling time.

In FIGURE 8 we have performed similar comparison of the models to the mud denoted Enviromul OBM. Note that the ramping times for the three case scenarios, A, B and C are now all half of what they were in the previous test and the yield stress τ_y is estimated to be 3.5 Pa.

The same pattern as for the KCl mud emerges clearly. It is observed that the two modified versions are closer to the measurements for the shortest gelling times. The same is the conclusion of comparison of the last two muds. The plots for these are, however, due to space limitations, not included here.

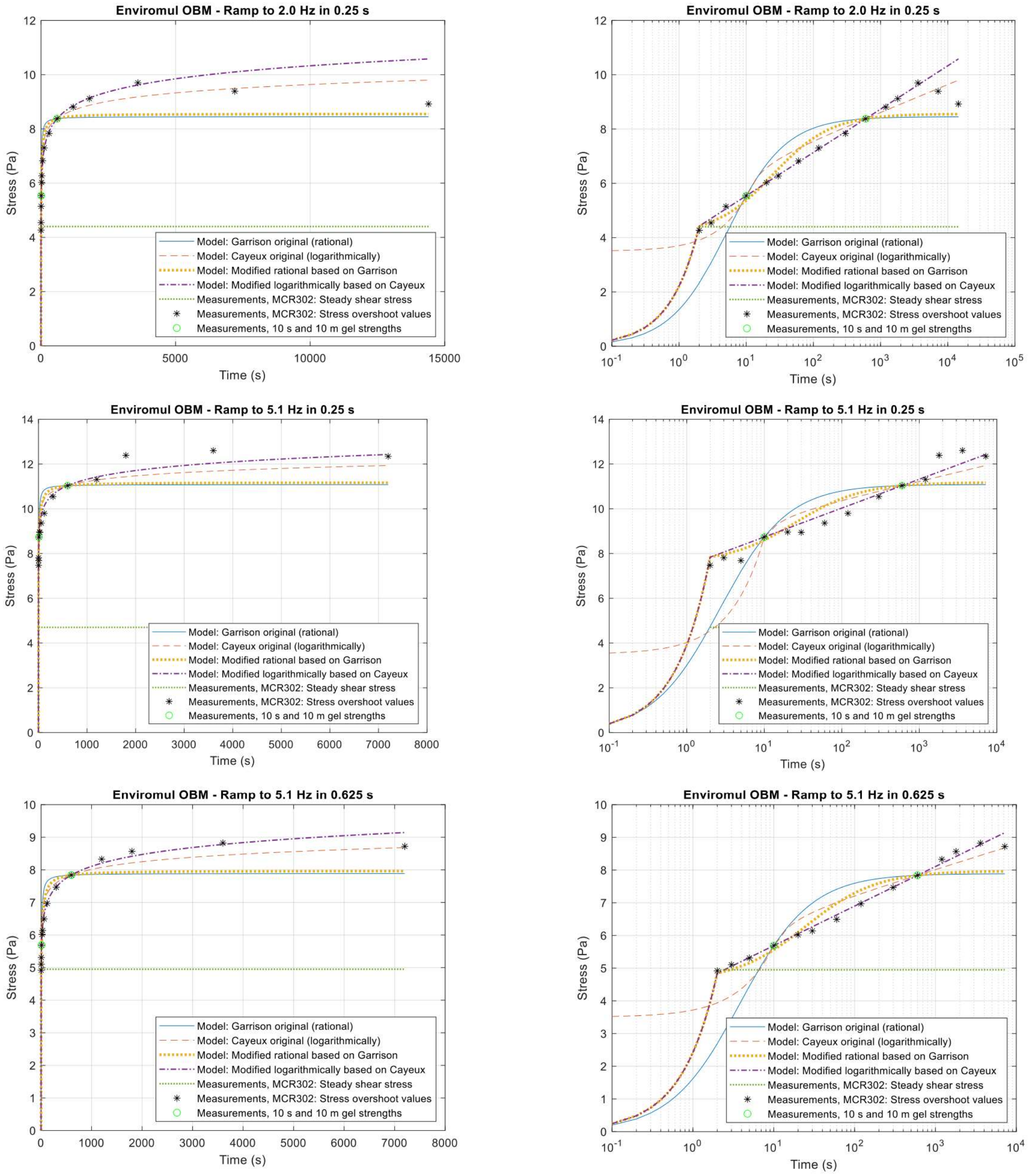

FIGURE 8: Models of gel strength as function of gelling times compared to measurements for the mud denoted "Enviromul OBM". The measurements were taken when ramping from 0 to 2 s^{-1} in 0.5 s (uppermost figures), when ramping from 0 to 5.1 s^{-1} in 0.5 s (middle figures) and when ramping from 0 to 5.1 s^{-1} in 1.25 s (lowermost figures). The left-hand side figures show linear time scale while the right-hand side is in logarithmic time scale. The models are forced to match the measurements at 10 s and 10 m gelling time.

In all cases we can also see by visual inspection that the logarithmic-based functions are closer to the measurements until approximately 1-2 h gelling time, where the measurements start to deviate from a clear trend. For these four muds we therefore suggest the logarithmic type of model over the rational function proposed by Garrison.

CONCLUSION

Stress overshoots after start-up of shear for four different drilling muds are analysed together with their sensitivity to the input test parameters, *target shear rate* and *ramping time*. It is shown that the magnitude of the stress overshoots is quite sensitive to these input parameters. A pattern is that the larger the target shear rate is and the larger the acceleration is, the larger is the stress overshoot.

We argue that, as long as the inertia effects are compensated for properly, will high acceleration rates give more direct and valuable information about the gel state after a given time of gelling in stagnant fluid. Analysis is performed on a scientific rheometer were the target shear rate and ramping time are controlled and varied, as well as on two typical field instruments where these parameters in practice are fixed.

Our results showed that the field instruments gave overall lower values than the scientific rheometer did. Compared to the parameters that gave the fastest acceleration on the scientific rheometer (case B) the Ofite 800 field instrument underestimated the stress overshoots by 14%-23% for KCl Polymer WBM 2 and by 39%-45% for Enviromul OBM. Whether this may be due to non-compensated inertia effects should, however, be investigated further.

Nevertheless, if these test parameters are constant during a test, the development of the stress overshoots as function of gelling time followed the same pattern for all combination of parameters. I.e., from 2 s, to approximately 1 - 2 h of gelling time, the stress overshoots followed quite closely a logarithmic increase. The different input parameters mainly gave a vertical shift in this curve, leaving the slope almost unchanged.

For higher gelling times, instead of approaching an expected maximum value, the measurements showed an unsystematic variation around the logarithmic trend. As the measurements were not performed in a closed container, evaporation could be one reason for this behaviour. Other reasons could be shear banding, wall slip effects, or sagging of particles, leading to clogging at the bottom of the bob. However, since this behaviour was more pronounced for the KCl Polymer WBM 2, which was without barite, than for the Enviromul OBM, the sagging theory is probably not the main reason.

The stress overshoots as function of gelling time were compared to two models from the literature. In addition, these models were improved to give better match for the lowest gelling times which had previously not been accounted for. Also, a small error was fixed for one of the models. For the muds tested here it was clear that the new adjusted models performed better than the original ones, and the models based on a logarithmically increase performed in general better than the ones based on a rational function.

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