The object of research in this study is viscoelastic systems used as spacer systems in well casing during drilling. Polymer network-metal ion systems display distinctive properties, facilitating effective well coverage through their normal stresses.

The primary problem addressed in this research was optimizing viscoelastic system composition for well casing. Researchers sought the ideal sodium dichromate concentration to maximize viscosity in polyacrylamide-based spacer fluids. This optimization is crucial for enhancing casing cementing quality, especially in challenging geological conditions.

Utilizing a precise HAAKE MARS III rheometer, various tests, including shear, oscillatory, frequency, creep, and recovery tests, were performed to assess viscoelastic system rheology. Obtained results of optimal deformation interval for a solution with sodium bichromate is 40 Pa and aluminum sulfate, the yield strength was equal to 110 Pa.

This research optimized cross-linker concentration, increasing spacer system viscosity. This enhancement improves well cementing efficiency and allows for operation in challenging geological conditions. The precise rheometer unveiled previously unexplored rheological characteristics.

The optimized viscoelastic spacer fluid is invaluable in well casing, especially in challenging geological settings. This research guides the design of process fluids, enhancing casing cementing quality, and improving drilling efficiency and safety. Engineers and researchers can leverage the rheological data for informed decisions and better field performance

Keywords: oil well cement, cement composite materials, basalt fiber, strength, deformation characteristics

UDC 622.245.422.4
DOI: 10.15587/1729-4061.2023.292252

IDENTIFYING APPLICABILITY VISCOELASTIC SYSTEMS IN THE CONTEXT OF IMPROVING WELL CASING PROCESSE

Arman Kabdushev
PhD*

Dinara Delikesheva
Corresponding author
PhD**
E-mail: d.delikesheva@satbayev.university

Darkhan Korgasbekov
PhD**

Bauyrzhan Manapbayev
PhD*

Marzhan Kalmakhanova
PhD*

*Department of Oil and Gas and Mining
M.Kh. Dulaty Taraz Regional University
Suleymenov str., 7, Taraz, Republic of Kazakhstan, 080012

**Department of Petroleum Engineering
Satbayev University
Satbaev str., 22a, Almaty, Republic of Kazakhstan, 050013

Received date 08.09.2023
Accepted date 27.11.2023
Published date 22.12.2023

How to Cite: *Kabdushev, A., Delikesheva, D., Korgasbekov, D., Manapbayev, B., Kalmakhanova, M. (2023). Identifying applicability viscoelastic systems in the context of improving well casing processe. Eastern-European Journal of Enterprise Technologies, 6 (6 (126)), 71–79. doi: https://doi.org/10.15587/1729-4061.2023.292252*

1. Introduction

When constructing wells with complex profiles and significant deviations from the vertical, critical problems arise related to ensuring effective cementing of casing pipes [1]. These problems are made worse by the difficulty of cleaning the wellbore and the need to ensure that the drilling fluid is completely displaced by the cement mixture. Due to the unsatisfactory rheological properties of the spacer systems used, which provide an unsuitable flow profile and flow regime in the annulus, their effectiveness is often limited [2].

Studies have shown that viscoelastic systems capable of generating normal stresses are one of the most effective buffer systems for cementing, since they are able to displace drilling fluid even from pinched zones [3, 4]. However, it remains a challenge to design the compositions of these systems without detailed knowledge of their behaviour under various loads. Moreover, it is important to consider that materials with a yield point begin to flow when exposed to external forces exceeding the forces of their internal structure, while below the yield point, they exhibit the properties of an elastic body. In this regard, the study of the internal structure and rheological properties is an extremely urgent task, which directly affects the successful implementation of drilling.

To create viscoelastic systems (VES), polymers are used, which are actively used in various industries, including drilling. It is important to note that the production of polymer materials continues to grow every year, which is accompanied by an increase in the variety of types of polymers and an improvement in their characteristics. This is due to the unique performance properties of polymer materials, which can be specially adapted to the specific purposes and requirements of the project. The complex rheological properties of polymeric materials have a significant effect on their behavior under operating conditions and correct and physically substantiated assessments of these properties provide reliable modes of operation of the samples used. The variety of types of viscoelastic spacer system compositions also determines the variety of their properties, the study of which is undoubtedly the most important task, because it is they who determine the scope and features of their use.

Considering the foregoing, it is important to emphasize the need to continue and expand experimental studies of the rheological properties of viscoelastic fluids.

2. Literature review and problem statement

High-quality cementing of wells depends on many factors, including proper displacement of drilling fluids. Therefore, the role of spacer fluids is crucial, as are other fluids used in well construction. Undoubtedly, the main task of spacer fluids is to ensure maximum cleaning of the annular space from drilling fluids [5]. Despite other requirements, the main requirement for a spacer fluid is usually its density, which should be higher than that of the drilling fluid but lower than the density of the cement slurry [6].

Analysis of the nature of research work on the improvement of spacer fluids shows that it is multi-vector, which are aimed at solving existing problems in the primary cementing of wells [7, 8]. For instance, some researchers suggest to solve problems associated with loss of circulation during well cementing proposes to create spacer fluids that minimize the occurrence of this problem by reducing permeability [9]. Although in some works, more optimal approaches to the solution are reflected. For example, the use of effective cement materials such as dry polyelectrolyte, which reduces fluid loss of the fluid itself, which in turn reduces the risk of problems with loss of circulation and, most importantly, reducing fluid loss of the cement fluid prevents contamination of the bottomhole formation zone [10]. However, there are spacers based on biodegradable polymer that do not reduce the initial capacity-filtration properties of the bottomhole zone, and which simultaneously solve the problem of loss of circulation, and some of them are well used in HTHP (high temperature high pressure) conditions [11, 12].

Many researchers consider the strength of the cement bond with the casing, the compatibility of the spacer fluid with the drilling fluid, and insufficient wetting inversion as the main requirements for spacer fluids [13, 14]. Also, in the work [15], to increase the efficiency of flushing, it is suggested to increase the contact time of the spacer fluid with the casing. The authors of this work determined the optimal contact time to be 6 minutes, during which the efficiency of removing the clay crust reaches 63 %. Some researchers [8] propose spacer fluids that contribute to simultaneous solidification with packer fluids. In the work [16], the authors suggest using water-based spacer fluids containing glycol, hematite, surfactants, and quartz sand for wells with high pressure and high temperature. However, the authors emphasize the importance of low viscosity. Summarizing the aforementioned works, it should be noted that these works do not take into account the rheological characteristics of spacer fluids.

It should be noted that many studies are aimed at obtaining multi-functional spacer fluids. One of the directions of improvement of spacer fluids come from the point of view of temperature and the required rheology. For instance, some of researchers work on unconventional spacers for long horizontal wells which operating in HPHT. In addition, authors emphasize incompatibility of non-aqueous drilling fluids with aqueous based cement slurry [17]. In [18], the authors developed spacer fluids with low density for cementing operation in wells with low temperature on offshore conditions. However, authors [19] suggest water based high density spacers which are necessary to ensure hydrostatic equilibrium in the wellbore formation system.

Let assume that the solution shows excellent performance in all technological properties, but has temperature limitations, which do not allow to use it in wells with high temperatures and, accordingly, with HTHP [20]. Depending on the injection rate, well profile, casing location, and fluid rheology, preliminary flushing before well cementing can be carried out in turbulent or laminar modes, which also depend on the rheology of the spacer. Therefore, the study and subsequent regulation of the rheology of spacers is highly relevant [21, 22]. During the construction of wells with a compound section and large deviations from the vertical, serious problems arise when cementing casing strings, associated primarily with cleaning the wellbore and ensuring the most complete displacement of the drilling fluid with a cement slurry.

Spacer fluids used for this purpose are not always effective due to unsatisfactory rheological properties that do not provide the required flow profile and flow regime of the spacer fluid in the annulus [23]. The experience of well construction has shown that one of the most effective spacer fluids are viscoelastic systems with normal stresses, which make it possible to displace drilling fluid even from pinched zones during cementing [24]. At the same time, it is difficult to design compositions without knowing their behavior under various loads. Substances with a yield point begin to flow when external forces exceed the forces of the internal structure. Below the yield point, substances exhibit the properties of an elastic body.

In general, like other process fluids, spacer fluids impose requirements on characteristics such as density, low fluid loss, which are aimed at preserving the original parameters of the well wall, preventing loss of circulation and accidents. However, all the requirements presented are related to the rheological characteristics of the solution. Rheological properties are associated with the influence of various stresses and the state of the elastic body, which in turn is of interest for obtaining new characteristics that make it possible to correctly design the composition of the spacer fluids.

3. The aim and objectives of the study

The aim of the study is identifying new characteristics viscoelastic systems and determines their applicability in the context of improving well casing processes.

To achieve this aim, the following objectives are accomplished:

– to examine the impact of different cross-linkers added to PAM solutions, analyzing their effects on the linear viscoelastic properties;

– to determine the yield limits of the investigated solutions and categorize their rheological behavior as either viscous or viscoelastic through creep and recovery curve analysis.

4. Materials and methods

The object of this research is viscoelastic systems utilized as spacer mechanisms within well casings during the drilling process.

In this work let's present the results of experiments in which it is possible to investigate the effect of the concentration of metal ions for the viscoelastic properties of the system, with specific ratios of polyvalent chromium metal and PAM.

The rheological characteristics of viscoelastic systems were obtained using a modern high-precision rheometer HAAKE MARS III by the plane-plane method (Fig. 1), where the shear stress is determined as:

$$\tau = \frac{F}{A}, \tag{1}$$

and the deformation as:

$$\gamma = \frac{S}{h}. \tag{2}$$

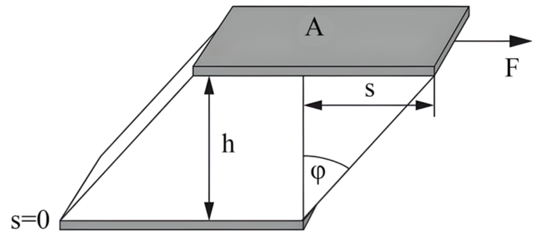

Fig. 1. Model of two planes, shear test

Authors studied samples of two solutions based on polyacrylamide (PAM). Solution No. 1 – 4.5 % PAM with the addition of 0.5 % $Al_2 (SO_4)_3$ and solution No. 2 – 4.5 % PAM and 1 % sodium dichromate. On this equipment, the rheological characteristics of these systems were obtained using the main types of tests, such as shear test, oscillatory and frequency test, creep test and recovery. In this work, the effect of the concentration of dichromate $Na_2Cr_2O_7$ on the viscous properties of the spacer based on polyacrylamide FlodrillPAM 1040 and FlodrillPAM 705 was investigated by the method of the shear test. Flodrill PAM 1040 is a high-molecular-weight anionic acrylic polymer with low hygroscopicity, existing as a water-soluble powdered product. It facilitates the flocculation of excavated rock and is intended for stabilizing collapsing shales, controlling solution viscosity, and water loss. Flodrill PAM 705 is a sodium polyacrylate with a medium molecular weight, appearing as a light-yellow powdered substance, highly soluble in water and exhibiting minimal hygroscopicity. It demonstrates significant lubricating abilities. Notably, it is ineffective in the presence of Ca_2^+ and Mg_2^+ ions.

The preparation procedure for the solution involved several key steps, which are as follows:

– warming the service water to a temperature ranging between 60 °C and 80 °C;

– adding the metal salt gradually while maintaining continuous stirring at low speeds;

– introducing the PAM slowly and subsequently engaging in vigorous mixing at high speeds;

– allowing the spacer fluid to settle undisturbed for a duration of 30 minutes.

The rheological characteristics of viscoelastic spacer fluid compositions were investigated at the following concentrations of $Na_2Cr_2O_7$ in relation to PAM 1:1; 3:4; 1:2; 1:4; 1:6; 1:8; 1:16 using a modern high-precision HAAKE MARS III rheometer using the plane-plane method at a temperature of 25 °C. The volume of water did not change and remained 150 ml. Shear rates were chosen in accordance with the tubular space (500 s^{-1}) and annular space (227 s^{-1}) models, which occur when cementing real wells.

5. Results of experimental investigation of viscoelastic systems rheological characteristics

5. 1. Investigation of influence of various cross-linking agents incorporated into polyacrylamide solutions the linear viscoelastic characteristics

The rheological characteristics of viscoelastic spacer fluid compositions were investigated at the following concentrations of $Na_2Cr_2O_7$ in relation to PAM 1:1; 3:4; 1:2; 1:4; 1:6; 1:8; 1:16 using a modern high-precision HAAKE MARS III rheometer using the plane-plane method at a temperature of 25 °C. The volume of water did not change and remained 150 ml. Shear rates were chosen in accordance with the tubular space (500 s^{-1}) and annular space (227 s^{-1}) models, which occur when cementing real wells. When assessing the role of the concentration of polyvalent metals, it was established that in order to obtain a gel structure with the required strength and toughness, it is necessary to take into account the valence of the metal. The greater the valency of the metal, the less amount of this additive must be used. However, at high concentrations of the additive, especially in polyvalent metals, the polymer quickly coagulates.

So, PAM is polycondensate, its network structure becomes more complete, which in turn gives water molecules little room for assimilation [3]. Subsequently, the polymer precipitated out in the form of beads.

The assessment of the role of sodium dichromate on the viscosity of the viscoelastic spacer fluid compositions is shown in Fig. 2.

Analysis of the Fig. 3 shows that at the ratio $Na_2Cr_2O_7$: PAM (1:8), the viscosity of the spacer liquid is optimal [3].

Results of oscillatory tests of solutions based on polyacrylamid with two types of crosslinker, namely sodium dichromate $Na_2Cr_2O_7$ (Fig. 3) and aluminum sulfate $Al_2(SO_4)_3$ (Fig. 4).

When examining a sample in oscillation mode, the first test is always an amplitude sweep test, because this test allows to determine the range of linear viscoelasticity (LVErange). Knowing this information, it can be determined the range of deformation values in which the structure of the test sample does not collapse under the action of deformation. From Fig. 3, in the amplitude sweep in the LVE range, the plots of the accumulation and loss moduli run parallel to the *X* axis, thus it can be obtained a voltage of 40 Pa for the sample of the composition based on polyacrylamid with the addition of sodium dichromate. This means that for this sample the limit yield is 40 Pa, this characterizes the stress at which deformations continue to grow without increasing the load. After passing this limit, irreversible plastic deformations begin to occur in the solution. In addition, flow points are observed in Fig. 2 – these are values at $G'=G''$. At ω=0.1 Hz – τ_F=140Pa, ω=1 Hz – τ_F=190Pa, ω=10 Hz – τ_F=300 Pa.

From Fig. 4 in the amplitude sweep in the LVE range for a sample of the composition based on polyacrylamide with the addition of aluminum sulfate, the yield stress is 110 Pa, which characterizes the stress at which deformations continue to grow without increasing the load. In addition, in Fig. 4, one point of the flow is observed in the same coordinates – these are the values at $G'=G''$ at ω=0.1 Hz τ_F=305 Pa.

During oscillatory measurements, the LVE range was determined and the frequency sweep of the samples under study was constructed (Fig. 5, 6). Most oscillatory measurements are carried out in the controlled shear deformation (CSD) mode. Oscillatory measurements provide unique information about the rheological characteristics of the sample, due to the possibility of separating elastic and viscous components. The elastic modulus (storage modulus) G' characterizes the accumulated deformation energy in the system and reflects the characteristics of the sample as a solid (elastic component). The value of the viscous modulus (loss modulus) *G*" determines the energy dissipation and is responsible for the behavior of the sample as a liquid (viscous component). The measurement of these two parameters is most often of interest to researchers when conducting an oscillation test. The long-term storage stability of dispersions is evaluated at low frequencies, thus the polyacrylamide solution with dichromate is quite stable. Frequency sweep mode is used to study the behavior of samples at different exposure times. The setting of high frequency oscillations corresponds to a short exposure time, and a low frequency – to a long exposure. The shape of the curves G' and G" gives infors mation about the internal structure of the sample.

From the graphs for both solutions *G'>G"*, which shows of the gel-like structure of the viscoelastic body, and the elastic properties are better for the solution with the crosslinker of aluminum sulfate $Al_2(SO_4)_3$, since the value of the storage modulus (elastic modulus) is higher than that of a solution with sodium dichromate.

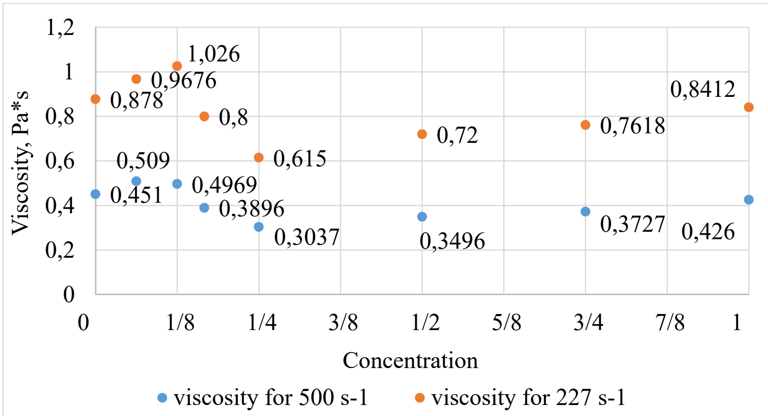

Fig. 2. Influence of $Na_2Cr_2O_7$ on the viscosity of a viscoelastic system

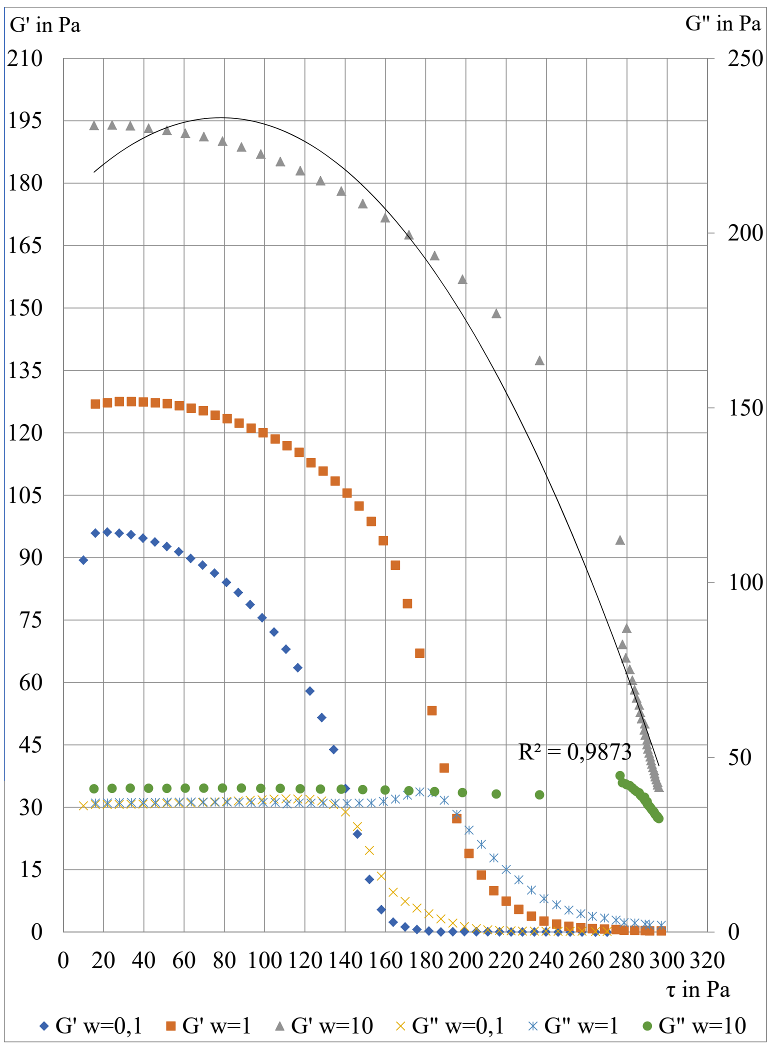

Fig. 3. Oscillation tests (sweep τ) of compositions based on polyacrylamide with the addition of sodium dichromate

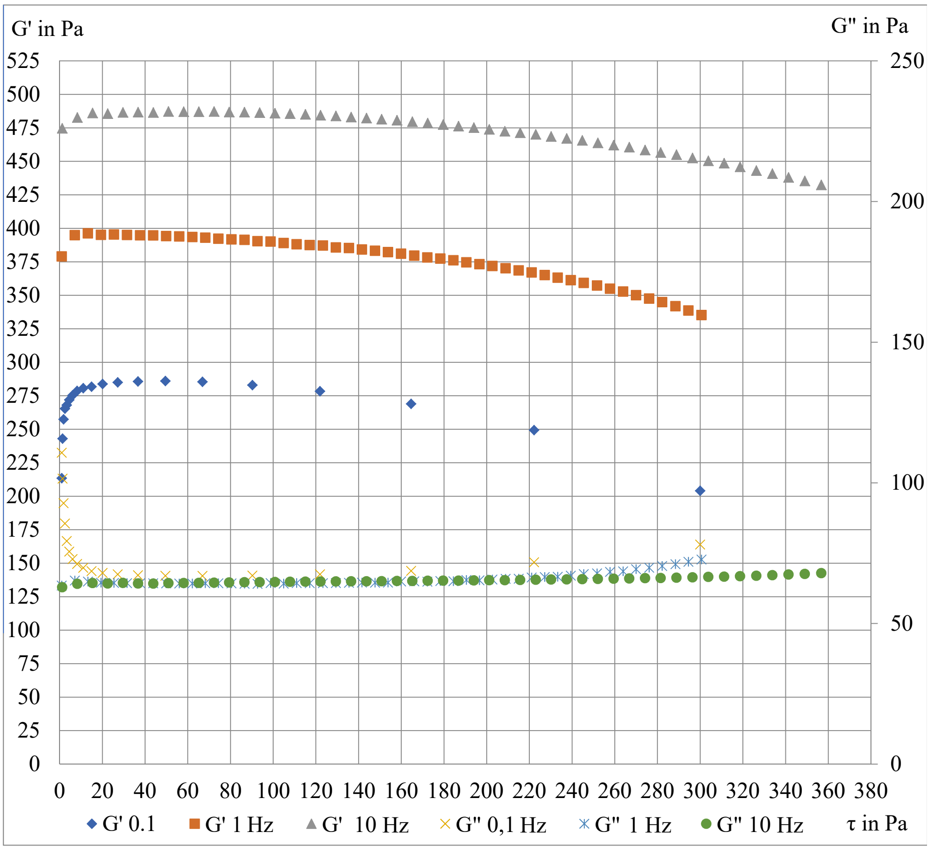

Fig. 4. Oscillation tests (sweep τ) of compositions based on polyacrylamide with the addition of aluminum sulfate $Al_2(SO_4)_3$

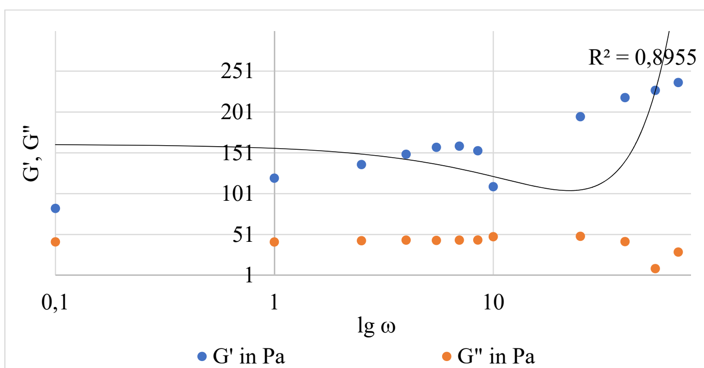

Fig. 5. Frequency sweep (sweep ω) of the composition based on polyacrylamide with the addition of sodium dichromate

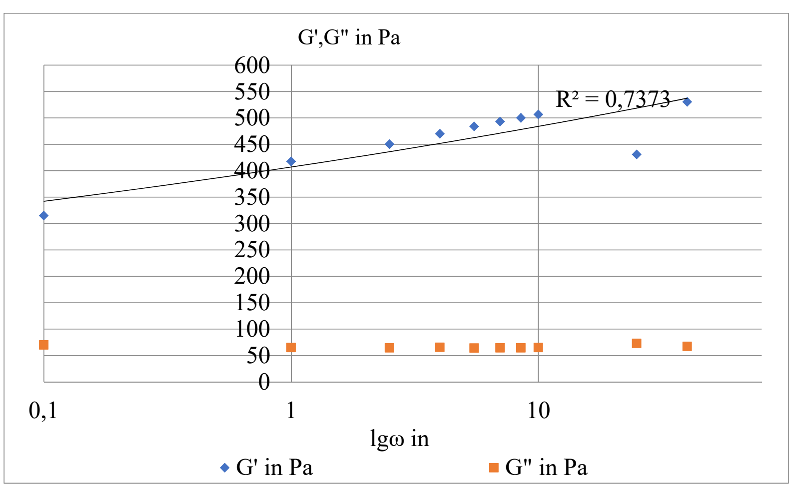

Fig. 6. Frequency sweep (sweep ω) of the composition based on polyacrylamide with the addition of aluminum sulfate $Al_2(SO_4)_3$

Oscillatory measurements can also be used to obtain the value of the complex dynamic viscosity η*, which reflects the total resistance to dynamic shear. The dependence of the complex viscosity of the studied samples on the shear rate is shown in Fig. 7.

In the region of low shear, the viscosity value in a polyacrylamide solution with $Al_2(SO_4)_3$ practically does not change (Cox-Merz rule), which is not observed in solution with bichromate. All this shows a certain stability at rest [19].

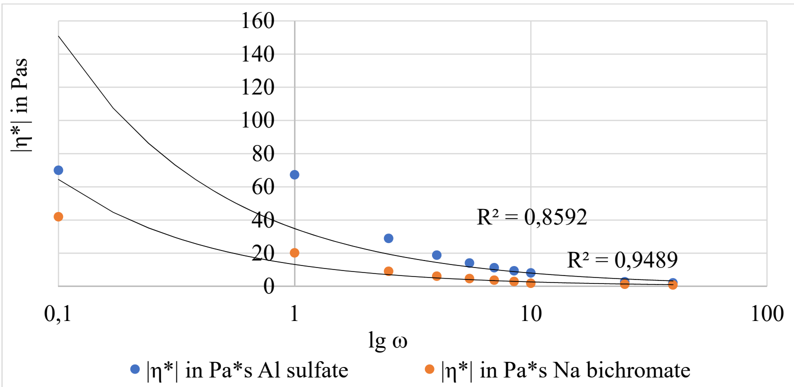

Fig. 7. Frequency curve of the complex viscosity of the investigated solutions based on polyacrylamide with the addition of aluminum sulfate $Al_2(SO_4)_3$

5. 2. Investigation spacer systems rheological ree sponse by analyzing creep and recovery curves

By the method of creep and voltage recovery, a new parameter is introduced for the studied viscoelastic systems – the "response time" of the system. Under the influence of constant shear stress τ_0 – the yield point applied to the upper plane of the sample; the latter is twisted. The angle of this twisting is determined by the modulus of elasticity. The stress and the resulting strain are linearly related: doubling the stress leads to a doubling of the strain. When twisted, such a rubber sample behaves like a metal spring that expands or contracts under load. The deformation persists as long as the stress is applied, and when the load is removed, it disappears completely and instantly. The deformation energy resiliently stored in a spring or in a rubber sample can be returned 100 % when the load is removed.

The dependence of the load (deformation) on the time of solution No. 1 is schematically shown in Fig. 8.

By the nature of the behavior, this is a viscous reaction. Put the case that the solution is poured from a vessel onto the surface of a table. It forms a puddle that spreads until it becomes as thin as the surface tension will allow. The kinetic energy of the solution flowing down to the surface of the table and the gravity of the layers force the solution to flow. When this energy is completely expended, it will stop flowing. Lacking elasticity, this solution will not flow back. The energy that set the solution in motion was completely transformed into heat; energy cannot be restored. The recovery phase is a straight line. Fig. 9 shows the dependence of creep and recovery of solution No. 2 and it is typical for a viscoelastic fluid. Judging by the reaction to the applied stress (110 Pa), viscoelastic fluids, which can be considered as dispersions of macromolecules with spring-like segments in high-viscosity oil, are characterized by a behavior that lies somewhere between a purely elastic or purely viscous body. The curve of the dependence of deformation on time first increases rapidly, and then its slope gradually decreases. Subsequently, this curve asymptotically turns into a straight line with a constant slope, which indicates a completely viscous reaction to the applied stress.

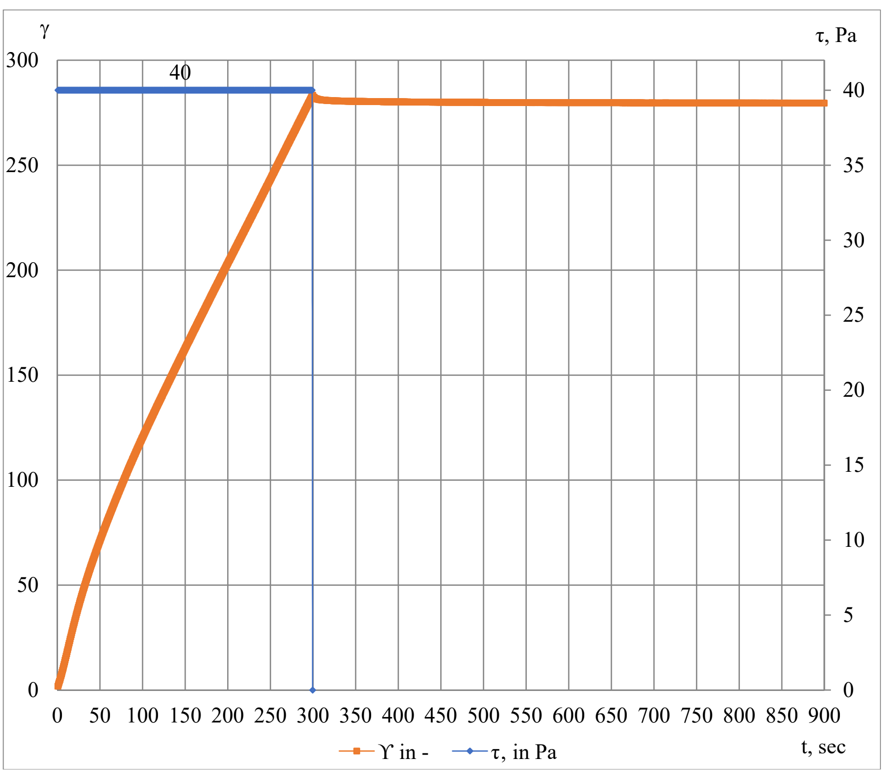

Fig. 8. Dependence of creep and recovery of polyacrylamide solution with sodium dichromate

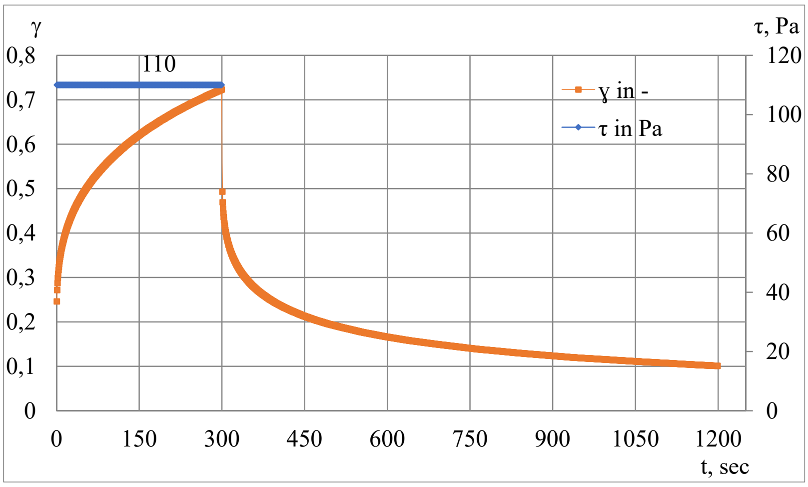

Fig. 9. Dependence of creep and recovery of polyacrylamide system with aluminum sulfate

If a sample, which is a viscoelastic (viscoelastic) solid, is subjected to stress below the yield point, and the deformation eventually asymptotically reaches a constant value, and the deformation curve will be parallel to the time axis. When measuring the creep of a viscoelastic fluid under the action of an applied stress, the transient processes are estimated as a whole, while the individual contributions of the elastic and viscous components cannot be clearly established. This is the advantage of the next phase – recovery after stress relief, which makes it possible to estimate the percentage of viscous and elastic components in the total deformation of the sample. The recovery phase, like the creep phase, is very time dependent.

6. Discussion of the experimental investigation of viscoelastic systems rheological characteristics

The effect of sodium dichromate on the viscosity of viscoelastic spacer fluid compositions was assessed. The analysis indicated that at a $Na_2Cr_2O_7$: PAM ratio of 1:8, the viscosity of the spacer liquid reached its optimum level, signifying the importance of this specific concentration ratio (Fig. 3).

As shown by the results of oscillatory tests of solutions. The obtained ranges of linear viscoelasticity showed that the optimal deformation interval for a solution with sodium bichromate is 40 Pa (Fig. 4). However, when using a solution with the addition of aluminum sulfate, the yield strength was equal to 110 Pa (Fig. 5). Curves of creep and recovery of the investigated samples showed that solution No. 1 has a viscous reaction, and solution No. 2 has a viscous-elastic reaction(Fig. 8, 9).

In general, these studies have shown that when a viscoelastic fluid moves, the concentration of the metal ion and its valence affect its structural properties. By means of these characteristics of the tests carried out, it is possible to determine the type of reaction of solutions.

The obtained new characteristics of viscoelastic fluids make it possible to design compositions of more efficient spacers and improve the quality of well anchoring.

The limitations of this study may be the temperature, since according to the methodology presented in the section "Materials and methods", the heating of process water to a temperature of 60–80 °C.

However, in our opinion, our research has drawbacks due to the fact that the results and characteristics obtained are directed only for buffer solutions created on the basis of viscoelastic systems.

The obtained new characteristics of viscoelastic compositions will allow to design compositions of more effective buffer fluids and will improve the quality of well casing.

7. Conclusions

1. It has been found that when a viscoelastic system moves, the concentration of a metal ion affects its structural properties. In the range of ratios of polyvalent chromium metal and PAM in a ratio of 1:8–1:16, the maximum value of the viscous properties of the test solution has been observed. When various cross linkers are added to the PAM solution, the LVE range changes. For solution No. 1, LVE range is limited to 40–45 Pa and points of three flow points are observed – these are values at $G=G''$: at ω=0.1 Hz – τ_F=140 Pa, ω=1 Hz – τ_F=190 Pa, ω=10 Hz – τ_F=300 Pa. For solution No. 2, LVE range is limited by the limiting stress of 110 Pa and one flow point is observed at $G'=G''$: ω=0.1 Hz – τ_F=305 Pa.

2. The yield limits of the investigated solutions based on PAM with the addition of 0.5 % $Al_2(SO_4)_3$ – 110 Pa and 1 % sodium dichromate – 40 Pa have been obtained. Curves of creep and recovery of the investigated samples showed that solution No. 1 has a viscous reaction, and solution No. 2 has a viscous-elastic reaction.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this re-search, whether financial, personal, authorship or otherwise, that could affect the re-search and its results presented in this paper.

Financing

The article was prepared within the framework of the project AP09058636 "Development of cement slurries with differential properties" within the framework of the ongoing competition for grant funding of fundamental and applied research of young scientists on scientific and (or) scientific and technical projects for 2021–2023 by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgements

We thank Professor Farit Agzamov for the necessary materials provided and the joint work carried out.

References

1. Kabdushev, A., Delikesheva, D., Korgasbekov, D., Manapbayev, B., Kalmakhanova, M. (2023). Identifying the influence of basalt fiber reinforcement on the deformation and strength characteristics of cement stone. Eastern-European Journal of Enterprise Technologies, 5 (6 (125)), 58–65. doi: https://doi.org/10.15587/1729-4061.2023.288551
2. Doan, A., Holley, A., Kellum, M., Dighe, S., Arceneaux, C., Conrad, K. (2018). Application of an Innovative Spacer System Designed for Optimal Performance in HTHP Wells. Paper presented at the IADC/SPE Drilling Conference and Exhibition. doi: https://doi.org/10.2118/189682-ms
3. Brandl, A., Doan, A. A., Alegria, A. E. (2017). Advances in Spacer Technologies for Improved Zonal Isolation Results in Challenging Deep Deviated HPHT Wells Containing Heavy Oil Based Muds. Paper presented at the SPE Kuwait Oil & Gas Show and Conference. doi: https://doi.org/10.2118/187658-ms
4. Gumerova, G. R., Yarkeeva, N. R. (2017). Technology of application of crosslinked polymeric compositions. Oil and Gas Business, 2, 63–79. doi: https://doi.org/10.17122/ogbus-2017-2-63-79
5. Docherty, K. E. et al. (2016). Mud Removal – Clearing the Way for Effective Cementing. Oilfield Review, 28 (1), 20–25.
6. Elochukwu, H., Samansu Douglas, E., Chikere, A. O. (2022). Evaluation of methyl ester sulphonate spacer fluid additive for efficient wellbore clean-up. Energy Geoscience, 3 (1), 73–79. doi: https://doi.org/10.1016/j.engeos.2021.11.002
7. Kędzierski, M., Rzepka, M., Kremieniewski, M. (2019). The effects of cement slurry contamination with the drilling mud and spacer fluid on its setting. Nafta-Gaz, 75 (11), 691–699. doi: https://doi.org/10.18668/ng.2019.11.04
8. Li, J., Li, Z., Tang, S., Sun, J., Wu, H., Su, D., Chen, W. (2020). Mechanism for the promotional effect of a novel solidifiable spacer fluid system on the cementation quality of cement sheath/formation interface. Energy Science & Engineering, 8 (12), 4212–4221. doi: https://doi.org/10.1002/ese3.805
9. Li, L. et al. (2016). A novel spacer system to prevent lost circulation in cementing applications. Proceedings of the 2016 AADE Fluids Technical Conference and Exhibition. Houston.
10. Ghoussoub, Y. E., Zerball, M., Fares, H. M., Ankner, J. F., von Klitzing, R., Schlenoff, J. B. (2018). Ion distribution in dry polyelectrolyte multilayers: a neutron reflectometry study. Soft Matter, 14 (9), 1699–1708. doi: https://doi.org/10.1039/c7sm02461d
11. Li, L., Alegria, A., Doan, A. A., Kellum, M. G., Castanedo, R. (2016). Application of a Novel Cement Spacer with Biodegradable Polymer to Improve Zonal Isolation in HTHP Wells. Paper presented at the Offshore Technology Conference. doi: https://doi.org/10.4043/27048-ms
12. Ramos, V., Doan, A., Ekwue, A.-M., Kellum, M. (2020). An Innovative Spacer System Designed with Biodegradeable Polymer and Loss Circulation Material to Aid in Formation Damage Control. Paper presented at the SPE International Conference and Exhibition on Formation Damage Control. doi: https://doi.org/10.2118/199242-ms
13. Quintero, L., Passanha, W. D., Aubry, E., Poitrenaud, H. (2015). Advanced Microemulsion Cleaner Fluid Applications in Deepwater Wells. Paper presented at the OTC Brasil. doi: https://doi.org/10.4043/26344-ms
14. Curbelo, F. D. S., Garnica, A. I. C., Araújo, E. A., Paiva, E. M., Cabral, A. G., Araújo, E. A., Freitas, J. C. O. (2018). Vegetable oil-based preflush fluid in well cementing. Journal of Petroleum Science and Engineering, 170, 392–399. doi: https://doi.org/10.1016/j.petrol.2018.06.061
15. Kremieniewski, M., Kędzierski, M., Błaż, S. (2021). Increasing the Efficiency of Sealing the Borehole in Terms of Spacer Pumping Time. Energies, 14 (20), 6702. doi: https://doi.org/10.3390/en14206702
16. Loginova, M. Ye., Agzamov, F. A., Ismakov, R. A. (2022). Investigation of viscoelastic properties of buffer fluids to improve the quality of well anchoring. Prom. Proizvod. Ispol'z. Elastomerov, 3-4, 39–48. doi: https://doi.org/10.24412/2071-8268-2022-3-4-39-48
17. Pernites, R., Brady, J., Padilla, F., Clark, J., McNeilly, C., Iqbal, W. et al. (2019). Unconventional Advanced High Performance Micromaterial for Enhancing Drilling Mud Cleaning Performance of Spacer Fluids in Horizontal Wells: From Laboratory Development to Field Applications. Proceedings of the 7th Unconventional Resources Technology Conference. doi: https://doi.org/10.15530/urtec-2019-60
18. Fang, E., Li, H., Zhang, H., Chen, X., Luo, Y., Gu, J. (2020). Development and performance evaluation of a low temperature low density solidifiable spacer fluid. Drilling Fluid and Completion Fluid, 37 (1), 86–92. Available at: http://www.zjyywjy.com.cn/en/article/doi/10.3969/j.issn.1001-5620.2020.01.014
19. Tabatabaee Moradi, S. S., Nikolaev, N., Nikolaeva, T. (2020). Development of spacer fluids and cement slurries compositions for lining of wells at high temperatures. Journal of Mining Institute, 242, 174. doi: https://doi.org/10.31897/pmi.2020.2.174

20. Sarap, G. D., Sivanandan, M., Patil, S., Deshpande, A. P. (2009). The Use of High-Performance Spacers for Zonal Isolation in High-Temperature High-Pressure Wells. All Days. doi: https://doi.org/10.2118/124275-ms
21. Théron, B. E., Bodin, D., Fleming, J. (2002). Optimization of Spacer Rheology Using Neural Network Technology. All Days. doi: https://doi.org/10.2118/74498-ms
22. Cao, C., Pu, X., Wang, G., Zhao, Z. (2020). True rheological behaviours of spacer fluid with consideration of wall slip effect. International Journal of Oil, Gas and Coal Technology, 23 (1), 30. doi: https://doi.org/10.1504/ijogct.2020.104969
23. Brand, F., Peixinho, J., Nouar, C. (2001). A Quantitative Investigation of the Laminar-to-Turbulent Transition: Application to Efficient Mud Cleaning. All Days. doi: https://doi.org/10.2118/71375-ms
24. Koptiaeva, E. I., Karazeev, D. V., Strizhnev, V. A., Vezhnin, S. A., Telin, A. G. (2014). New cross-linked polymer compositions at the basis of partially hydrolyzed PAA for water shut-off and conformance control. Oil. Gas. Innovations, 10 (189), 45–49.