The International Journal of Engineering and Information Technology

journal homepage:www.ijeit.misuratau.edu.ly

Evaluating the Mechanical and Rheological Behavior of Mud-contaminated Well Cements

Gheith A. Alnadeif
Misurata University

Walid O. Ben Saleh
Mabruk Oil Operations

Abstract— **Oil and gas well cementing is the process of filling the gap between wellbore and casing with cement to support casing and prevent communication between formations behind casing. A good and consistent cement slurry is critical for cement job success and, consequently, very important for well integrity and performance throughout the life of the well.**

When cement slurry is pumped down the casing in a cementing job, it comes in a direct contact with drilling fluids used to drill the uncased section. These fluids, if mixed with cement slurries, can act as contaminants causing an alteration in the properties of cement. It is, therefore, critical to evaluate the extent of cement properties alteration due to contamination by drilling and completion fluids.

In this work, an experimental study was carried out to investigate the effect of contamination by drilling fluids; water based, oil based (50% Diesel, 50% water) and oil based (70% diesel, 30% water) on cement physical, mechanical and rheological properties.

Cement slurries were prepared according to the API procedures and were mixed with different concentration of contaminants and cured at ambient temperature for 1, 2, 3 and 21 days. Physical, rheological, and mechanical properties were measured using API recommended practices and apparatus.

It is observed and as expected that regardless of mud base fluid, as contaminant percentage increases, density of cement slurry decreases due to dilution of cement by water in contaminant. For oil-based invert emulations (50/50 and 70/30), as contamination percentage increased plastic viscosity increased, but yield stress decreased. It was also found that clean and less contaminated cement samples develop higher compressive strength in shorter times than mud contaminated samples.

Index Terms: **Cement, Contamination, Cement slurry, Rheological, Mechanical, Oil-based mud, water-based mud.**

I. INTRODUCTION

Drilling for oil and gas requires the use of fluids that are specifically designed to perform well under certain conditions, and that are consistent with whatever material they may encounter, such as geological formations, downhole equipment, and cements. Today, most drilling fluids used in well drilling are based on water; natural, such as freshwater, seawater and natural brines, or prepared as in brines used in water-based and oil-based fluids (A. T. Bourgoyne, et al, 1991).

While water-based fluids are recognized to offer economic and environmental advantages, oil-based fluids are known to provide some other advantages, such as wellbore stability, especially when drilling salty or shaley formation, temperature stability and better lubricity. Nevertheless, it has been stated that the success of drilling operations depends not only on the drilling fluids used, but also on cements, spacers, mud cement and mud spacer compatibilities (Scott et al., 2015, Arbad, N. et al.,2020).

Over the last ten years, there have been numerous experimental studies examining the effect of drilling fluids contamination on the properties of cement slurries. (Liu et al., 2010; Li et al., 2014; 2016) studied the impact of WBM and OBM on cement thickening time and compressive strength. They have observed a significantly different behavior of cement thickening times and compressive strengths. Unlike water-based fluids, oil-based fluids appear to extend the thickening time of cement slurries. Compressive strength, on the hand, was significantly reduced due to contamination by OBM. In a study conducted by (Gu et al., 2005, 2006) on the effect of cement on well integrity and well performance, it was noted that an inadequate cement bonding strength can result in a poor zonal isolation and well integrity issues.

As the reliance on OBM systems in drilling operations has grown significantly in the last years, due to their ability to mitigate and solve many drilling challenges, a more emphasis has been placed on understanding the mechanism of cement mixing with oil-based muds than any other drilling fluid. Furthermore, since OBMs typically contains diesel/mineral oils as the continuous phase, they tend to have an oil-wetting fluids characteristics, and consequently, it becomes very challenging to displace an OBM completely from the annular before pumping the cement and mixing with cement seems inevitable. In fact, it has been widely reported that bad cement in many wells was associated with the use of OBM for drilling the well (Fakhreldin et al. 2011; Katherine et al., 2014; Li et al.,2016).

The aim of this work is to investigate, in a laboratory setting, the influence of both water-based and oil-based

Received 31 May , 2022; revised 25 Aug, 2022; accepted 30 Sep, 2022.

Available online 1 Dec, 2022.

drilling fluids contamination on the physical, rheological, and mechanical properties of cement slurries. This paper will discuss in detail the methodology, the equipment used, the procedures followed, and the results obtained.

II. MATERIALS AND EXPERIMENTAL PROCEDUURES

2.1 Experimental Materials

For this study, basic cement and drilling fluid systems were utilized. A plain cement slurry consisting only of a class G cement and water with no other additives. The water-based drilling fluid consisted of bentonite as a viscosity control, barite as a weighting material, caustic soda for PH control and water. On the other hand, the oil-based drilling system consisted of bentonite, barite, primary and secondary emulsifiers, diesel as the continuous external phase and water. The primary emulsifier is used for the stabilization of oil-water mixture. The emulsion is created by mixing diesel, water, and emulsifier under high-speed agitating mixer.

2.2 Experimental Equipment and Procedures

The cement slurry used for the experimental work was prepared according to the API recommended practices and procedures (RP 2013). Each batch is 600 cc in volume and consists of 349 grams of class G cement and 393 grams of water. For every experimental round, the same mixing procedures are performed.

Water is poured into the constant speed blender cup shown in figure 1.a. While the blender is rotating at 4000 rpm, cement material is slowly added to the water within 15 seconds. Once all the cement has been added, blender mixing speed is increased to 12000 rpm for 35 second. The constant speed blender from Ofite has the feature of automating the mixing procedure according to the API recommended practices. Prepared slurry is then conditioned in the Ofite atmospheric consistometer shown in figure 1.b at room temperature for 20 minutes.

Figure 1. Cement mixing and conditioning equipment

After conditioning, the cement slurry is ready for further testing. It undergoes physical and rheological properties measurements before it is mixed with drilling fluid to assess the impact of contamination. The density of cement slurry is measured using the pressurized fluid density scale shown in figure 2.a

The fully automated viscometer from Ofite is utilized for slurry viscosity measurements and all other relevant rheological properties, such as gel strength, yield stress and rheological fluid model parameters.

Figure 2. Cement slurry density and rheology measurements equipment

2.2.1 Effect of drilling fluids on the physical and rheological properties of cement slurries

To assess the impact of drilling fluids contamination on the physical and rheological properties of cement slurries, one basic WBM system is considered with three different concentrations: 0% (no contamination), 10% and 25% per weight of cement slurry, and for the OBM system, two diesel-based fluid invert emulsion systems were considered: 50/50 and 70/30. Recommended contaminant concentrations for the OMB were 2.5%, 5% and 10% per weight of cement slurry.

First, the designated percentage of contaminant fluid is added to the already prepared and conditioned slurry, and thoroughly mixed using a stirring rod, as recommend by RP 10B for cement testing, to simulate the actual mixing that would occur downhole during cement operations.

Second, the mixture density is measured using the pressurized fluid density scale from Ofite and reported in pounds per gallon.

Third, a sample from the mixture is transferred to the automated viscometer cup for rheological evaluation. Using the cement test built-in feature, plastic viscosity (using two methods), gel strength (10 sec and 10 min), yield stress, rheological model parameters are determined.

2.2.2 Effect of drilling fluids on the mechanical properties of cement slurries

To evaluate the impact of drilling fluids contamination on the mechanical properties of cement slurries, specifically, the compressive strength, the remaining volume of the prepared slurry is poured into the cement mold for curing and hardening. To comply with the API practices of cement testing, mold chambers are filled in two stages: filling the first half of the chamber, stirring for few seconds with a rod, and then filling the other half of the mold to top. This ensures that no air is trapped inside the cement samples after solidifying. The mold is immersed in a water bath at room temperature for curing. Each sample (concentration) is cured for 1, 2, 3 and 21 days before it undergoes a destructive mechanical test.

The Caver top bench standard press laboratory equipment is used for testing the compressive strengths and bonding strengths of mixed cement slurries. After the designated curing time is reached, the concrete sample is detached from the mold and is left to dry for at least 45 minutes before the test. The sample is loaded into the press equipment and the load is increased uniformly while monitoring the gauge until the sample breaks. The force and compressive strength at which the sample crashed is reported.

Figure 3. Cement slurry sample preparation for compressive strength testing

III. DISCUSSION OF RESULTS

3.1 The performance of cement slurries contaminated by WBM

The density and the rheological properties (plastic viscosity, yield stress, and rheological model parameters) of the neat and contaminated cement slurries are shown in table 1. The density of cement decreased from 16.4 ppg for an uncontaminated cement to 13.4 ppg and 11.8 ppg by adding 10% and 25% of WBM respectively. All the measurements are reported at room temperature of about 20 degrees Celsius.

As can be seen from table 1, the density of cement slurry is reduced as more WBM is introduced into the system. This behavior is well expected as adding more water in the mixture dilutes the cement and eventually results in a lighter cement slurry weight.

Table 1. Properties of cement slurries contaminated with WBM (8.5 ppg)

Contaminant Conc. Per weight of cement	**0%**	**10%**	**25%**
Density, lb./gal	16.4	13.4	11.8
Rheology model	yield power-law	yield power-law	yield power-law
Plastic vis. cp	21.60	7.97	12.85
Yield stress lb./100 ft^2	69.60	76.44	54.5
Power-law exponent n	0.084	0.033	0.063
Consistency index k	53.6	68.7	44.95

The rheological models of the clean and contaminated cement slurries are shown in figure 4. It is evident from the graph that both clean and contaminated cement slurries (10% and 25%) follow a yield power law model. However, even though the 10% WBM contamination sample were interpreted as a yield power law model, the model fit was not satisfactory (r^2=0.53).

Looking at table 1, we can observe that contaminant percentage and rheological properties do not appear to be linearly related. When 25% per weight of WBM was added to the neat cement, mixture plastic viscosity dropped from 21.60 cp (of neat cement) to 12.85 cp, and yield stress also went from 69.60 lb./100 ft^2 (for neat cement) down to 54.5 lb./100 ft^2. However, with a less contamination ratio, 10%, yield stress increased instead of decreasing. This can be

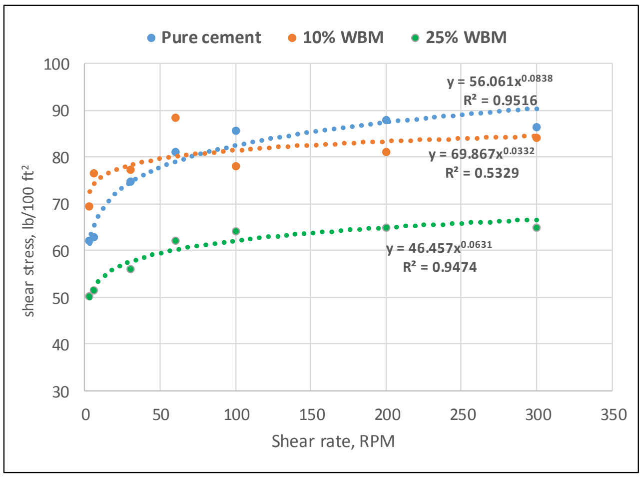

Figure 4. Rheological behavior of cement slurries contaminated by a WBM

Figure 5 shows the compressive strength of clean and contaminated cement slurries cured at room temperature and 20 C water temperature for 1,2,3 and 21 days. Clean cement slurry achieved compressive strength of 1000 psi after only 24 hours. Compressive strength then increased by 600 psi within the next 24 hours, 900 psi within 72 days and 1600 psi in three weeks.

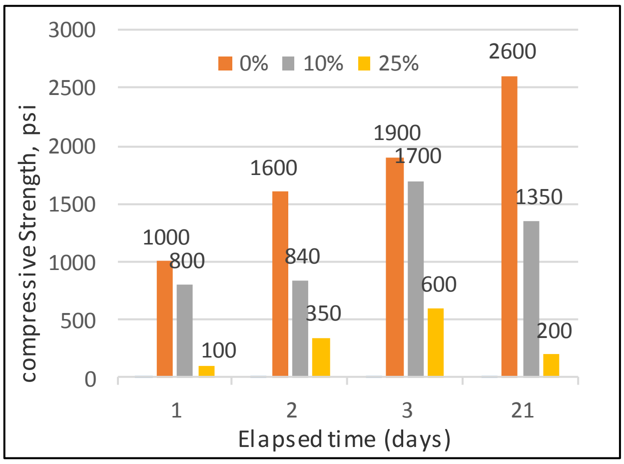

Figure 5. Compressive strength of cement samples contaminated by a WBM

Evidently, as the cement sample curing time is extended from a day to 21 days, the slurry tends to achieve higher compressive strengths. Similarly, for a certain curing period, as the contaminant percentage in the cement slurry increases, the maximum attainable compressive strength decreases significantly. However, contaminated slurries tend to develop hardness much slower than clean slurries.

3.2 The performance of cement slurries contaminated by (70/30) invert emulsion OBMs

Table 2 shows the density and rheological properties of cement slurries contaminated by a 70/30 diesel-based mud (invert emulsion). The cement slurry density dropped from 16.4 ppg for a clean cement to about 15.8 ppg by adding only 2.5% of 70/30 OBM. Adding higher ratios of contaminants into the system, 5% and 10% per weight, reduced the density of slurry to 15.5 ppg and 15.1 ppg, respectively. All measurements are reported at average room temperature of around 20 C.

Apparently, unlike in the water-based drilling fluids where the contaminant just adds more water and dilutes the mixture, when an invert emulsion oil-based fluid mixes with a cement slurry, the reduction in slurry density is relatively small. One obvious reason for that is that, in invert emulsion OBMs, there are more oil phase fluid (which has a lesser density) in the drilling fluid than water phase (which has a higher density).

Table 2. Properties of cement slurries contaminated with invert 70/30 OBM (7.4 ppg)

Contaminant Concentration Per weight of cement	**2.5%**	**5%**	**10%**
Density, lb./gal	15.8	15.5	15.1
Rheology model	YPL	YPL	YPL
Plastic vis. cp	2.10	6.53	9.26
Yield stress lb./100 ft^2	111.6	86.40	67.54
Power-law exponent n	0.0628	0.064	0.048
Consistency index k	84.5	66.87	57.57

Figure 6 shows the rheological behavior of cement slurries contaminated by 2.5%, 5% and 10% per weight of a 70/30 OBM. As expected in a cement slurry, and regardless of the contamination ratio, all slurry samples exhibited a yield power-law rheology model. Nonetheless, as the percentage of OBM in the mixture is decreased, the flow behavior of the cement slurry starts to deviate from a yield power low. At 2.5% and 5% concentrations, there is a high discrepancy in the shear stress measurement between the up and down shear rate reading. This ultimately results in a poorly fitted model.

Yield stress appears to decrease as more OBM is added into the cement slurry. However, the behavior of plastic viscosity is rather ambiguous. Adding a smaller amount of contaminant seems to bring the plastic viscosity to a very low value and vice versa.

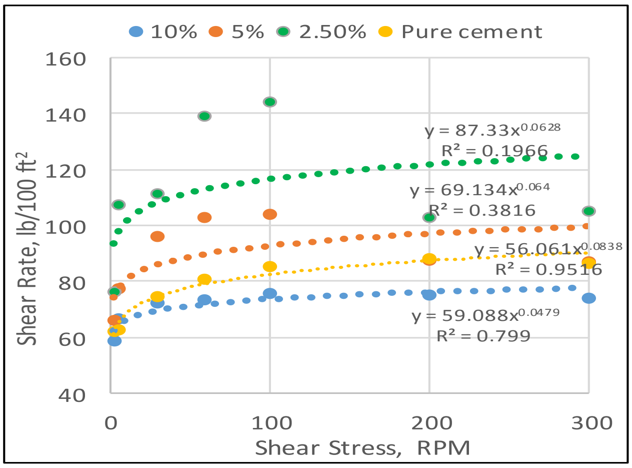

Figure 6. Rheological behavior of cement slurries contaminated by a 70/30 OBM.

Compressive strength of the 70/30 OBM contaminated cement slurries is shown in figure 7. The sample with lowest contamination percentage (2.5%) developed a reasonably good compressive strength over the three weeks. also, as more OBM is added to the slurry, cement sample becomes weaker. However, the contrast in compressive strength between all the samples decreases as samples curing time is extended.

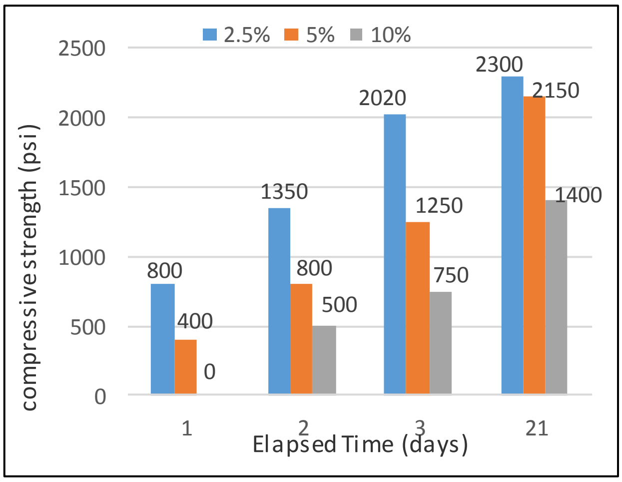

Figure 7. Compressive strength of cement samples contaminated by a 70/30 OBM.

3.3 The performance of cement slurries contaminated by (50/50) invert emulsion OBMs

Table 3 shows the density and rheological characteristics of cement slurries contaminated by a 50/50 invert emulsion diesel-based drilling fluid. As more OBM is added into the slurry, the density of slurry is reduced. Density reduction here is slightly more that of the 70/30 OBM for the same contaminant ratio.

Plastic viscosity increased as contamination ratio increased. In contrast, yield stress is dropped as more OBM was added into the slurry.

Table 3. Properties of cement slurries contaminated with invert 50/50 OBM

Contaminant Concentration Per weight of cement	2.5%	5%	10%
Density, lb./gal	15.6	15.5	14.8
Rheology model	YPL	YPL	YPL
Plastic vis. cp	6.69	9.713	14.58
Yield stress lb./100 ft^2	102.16	67.94	62.54
Power-law exponent n	0.10	0.059	0.0713
Consistency index k	208	55.12	49.66

From figure 8, it can be shown that all cement slurries follow a yield power law model with an excellent regression fitting factor. This suggests a consistent preparation procedures and mixing techniques were achieved prior testing.

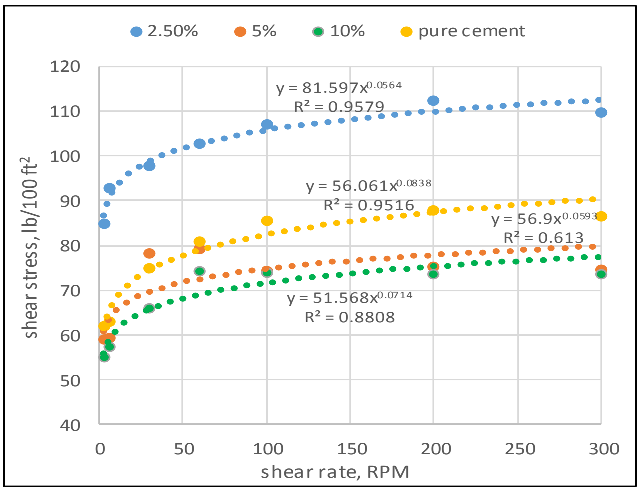

Figure 8. Rheological behavior of cement slurries contaminated by a 70/30 OBM.

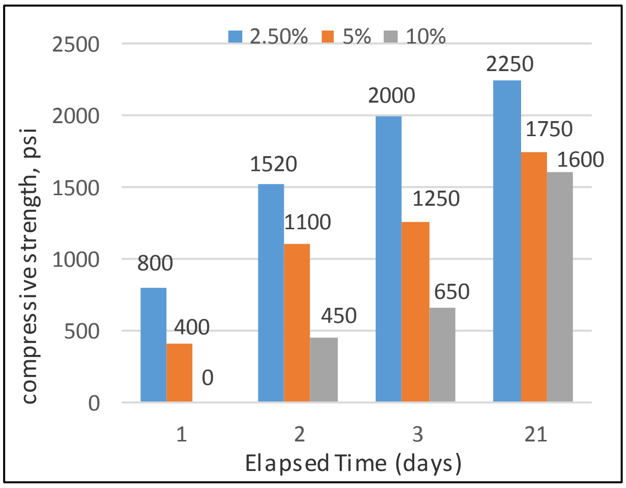

figure 9. Compressive strength of cement samples contaminated by a 70/30 OBM.

Compressive strength measurement of the 50/50 OBM contaminated cement samples are shown in figure 9. A very similar behavior to the 70/30 OBM can be seen here. As more fluid is added, the compressive strength is reduced. However, since the 50/50 OBM contains more water than diesel if compared to the 70/30, this additional water contributed to slurry dilution and a less compressive strength were attained for the same contamination percentage.

IV. CONCLUSION

In this paper the effect of water-based and oil-based drilling fluids contamination on cement slurries were studied to quantify the effects on cement slurry density, cement plastic viscosity, slurry yield stress, cement rheological flow model properties and cement compressive strength.

1. It is noticed form the experimental results that cement slurry testing conditions, such as, type of blinder, conditioning time, stirring rate, time span between mixing and measurement and contaminant slurry mixing procedures, have a considerable impact on the rheological measurements. In addition, measurements reproducibility is difficult in cement testing. This all has been well reported in several related studies.
2. It is observed form the rheological measurements that clean cements as well as contaminated cement slurries, regardless of drilling fluid type, follow a yield power law rheological flow model. Nevertheless, introducing an oil phase fluid into a cement slurry may alter the flow behavior slightly, and effects the rheological characteristics of the flow model considerably.
3. High percentages of WBM and OBM contamination (15% or more) can have a detrimental impact on cement compressive strength. The slurry could lose the ability to harden even after long curing times.
4. The experimental results show that even a small amount of contamination by oil-based drilling fluids can alter the mechanical properties of cement significantly. Small amounts of OBM may reduce the compressive strength of cement by 30 to 50 percent, which could have a catastrophic influence on well integrity.

It is recommended that a similar study is conducted under reservoir conditions and for different curing times to evaluate the impact of temperature on the mechanical and rheological properties of cement slurries contained by drilling fluids.

REFERENCES

[1] A. T. Bourgoyne, et al, Applied Drilling Engineering. 2nd Edition Book, SPE, 1991

[2] Scott, P.; Broussard, P.; Freeman, M.; Growcock, F.; Bland, R. Drilling Fluids Manual, 12th ed.; 2015;ISBN 9780991509546.

[3] Arbad, Nachiket & Teodoriu, Catalin. (2020). A Review of Recent Research on Contamination of Oil Well Cement with Oil-based Drilling Fluid and the Need of New and Accurate Correlations. ChemEngineering. 4. 28. 10.3390/chemengineering4020028.

[4] Zaoyuan Li, Honghua Liu, Xiaoyang Guo, Hongjuan Ou, Tao Gu,Contamination of cement slurries with oil based mud and its components in cementing operations, Journal of Natural Gas Science and Engineering, Volume 29, 2016, Pages 160-168

[5] Ming, L., Yujia, Y., Guanhua, Z., Youzhi, Z., Xiaowei, C., & Xiaoyang, G. (2014). Impact of a biological tackifier in a drilling fluid system on the performance and structure of a cement slurry. Natural Gas Industry, 34(9), 93-98.

[6] Liu, S.B., Zheng, K., Zhang, C., et al., 2010. An experimental study on the prevention of cement slurry contamination during deep or ultradeepwell cementing at Sichuan and Chongqing oil/gas fields. J. Nat. Gas. Ind. 30 (08), 51-54.

[7] Gu, J., Gao, D.L., Shi, F.Q., et al., 2005. The two contacts cementing system in cementing job and its importance. J. Drill. Fluid Complet. Fluid 22 (2), 7-10.

[8] Gu, J., Gao, X.Y., Liu, H., 2006. Two-interface isolation system of oil/gas well cementing and its damage model. J. Nat. Gas. Ind. 26 (07), 74-76.

[9] Fakhreldin, Y., Al-Sharji, H., Aghbari, S., et al., 2011. Novel technique to determine cement contamination. In: Paper Presented at SPE/IADC Middle East Drilling Technology Conference and Exhibition.

[10] Katherine, A., Nair, S.D., Cowan, M., et al., 2014. Contamination of deepwater well cementations by synthetic-based drilling fluids. In: Paper Presented at SPE Deepwater Drilling and Completions Conference.

[11] Tao C, Kutchko BG, Rosenbaum E, Massoudi M. A Review of Rheological Modeling of Cement Slurry in Oil Well Applications. Energies. 2020; 13(3):570. https://doi.org/10.3390/en13030570

[12] D. Lootens, P. Jousset, L. Martinie, N. Roussel, R.J. Flatt, Yield stress during setting of cement pastes from penetration tests, Cement and Concrete Research, Volume 39, Issue 5, 2009, Pages 401-408, ISSN 0008-8846.