Ten Years After the Deepwater Horizon Disaster - Lessons Learned for a Better Cementing Job

Ghada Bassioni(✉)

Chemistry Division, Faculty of Engineering, Ain Shams University, P.O. Box 11517, Cairo, Egypt
Ghada_bassioni@eng.asu.edu.eg

Abstract. The impacts on the Gulf of Mexico's environment and population are enormous after the Deepwater Horizon accident in 2010. Ten years later investigations on the real causes of that accident with systematic simple lab tests started to use all data available at that time and mimic what happened to overcome similar accidents. The approach in this study shows that risk assessment by experiment cannot be replaced by the mathematical models, which many companies use prior oil production. The models are simply too vague to rely on and are not putting into consideration the many factors that play a crucial role for proper oil well cementing in reality. The compatibility between chemical additives is here demonstrated. The cement additives are characterized by different methods. The additives showed slight changes in the dispersant's molecular weight and particle charge that had in turn significant impact on the mechanical properties of the slurry. Static gel and compressive strengths of the different mixtures are tested. The dosage that shows optimum mechanical characteristics is identified for all individual systems as well as for the mixtures. The results show how important experimentation is and that mathematical models would not be able to differentiate between the two implemented chemicals if we rely on chemical composition only. The study is particularly important for future Africa with increasing potential for oil production.

Keywords: Gelation · Chemical additives · Oil well cement

1 Introduction

In 2010 a large trans-ocean drilling rig was operational in the Gulf of Mexico for the Macondo well. The job at the so-called Deepwater Horizon was behind schedule and over budgeted by $58 million facing a lot of challenges: the well was at high pressure, below the seabed by about 4 km. Sixteen hours after the cementing engineering had confirmed that the cementing job went well, hydrocarbons were escaped into the well bore upon which the drilling rig experienced a disastrous blowout. The high pressure oil and gas leaked from the rig and into the ocean causing a huge oil spill [1]. Eleven people died when the rig caught fire. A lot more people were seriously injured [2]. The fire lasted for 36 h until the rig sank. Hydrocarbons continued to leak from the reservoir

A. D. Mambo et al. (Eds.): InterSol 2022, LNICST 449, pp. 175–186, 2022.
https://doi.org/10.1007/978-3-031-23116-2_14

through the wellbore for almost 90 days [3]. The expenditures from this accident are not yet fully captured, but it is clear that the impacts on the region's environment and population are enormous, and that financial losses exceed tens of billions of dollars. As part of the US governmental response, a well integrity crew assessed the geological hazards and determined the factors under which shutting in the well could securely be undertaken. The estimated high shut-in pressure made leakage of oil below the seafloor very likely. This leak could probably result in new geological routes for discharge into the Gulf of Mexico [4].

Shortly after the accident, a project team was established to learn from it and to recognize parallels and variances with other severe incidents. The goal was to identify best practices for improving the authority's supervision and to implement actions which can improve HSE in the oil and gas sector [2].

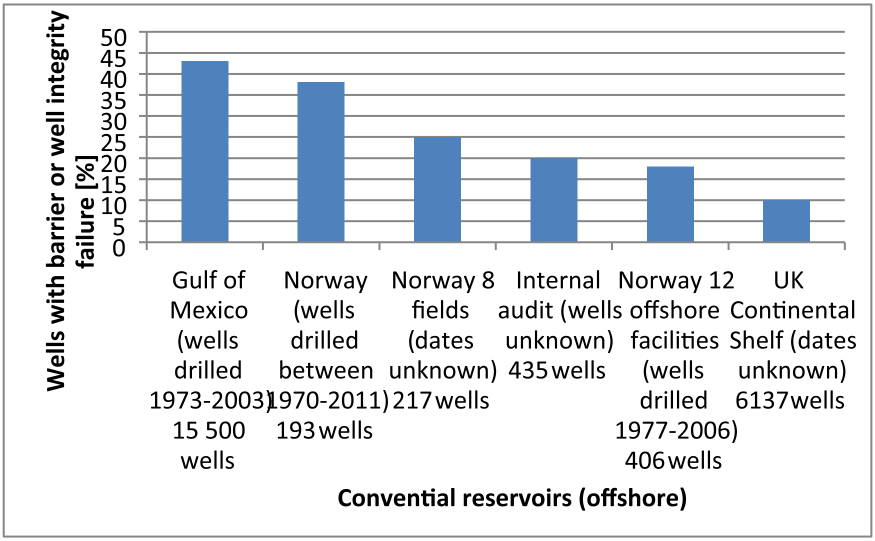

Fig. 1. Percentage of wells with well or barrier integrity failure in different conventional offshore reservoirs.

For enhanced HSE security, wells are planned with multiple fences. The number of these fences or barriers depends on the hazard severity. Figure 1 shows the fraction of wells that have barrier or well integrity failure in different conventional offshore reservoirs. Well documented is the Gulf of Mexico with 15,500 failures resembling 43% of the wells drilled from 1973 to 2003. The documented failures show that about 5% are due to a bad cementing job [5, 6]. The wells that have been affected by sustained casing pressure have been reported in correlation to the well age in years [7]. In the vast majority of cases, wells develop leaks with aging as can be seen in the Fig. 2.

According to the National Commission investigations the oil spill of the Deepwater Horizon was caused by a failure to encompass hydrocarbon pressures in the well. The chief council's report of the National Commission stated that there are several issues that may have contributed to the cement failure. These events incorporate that cement in

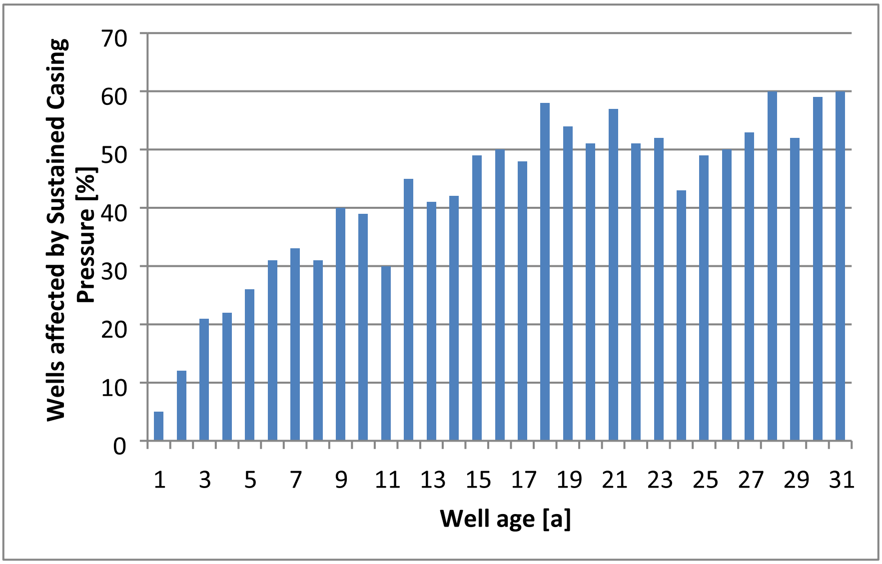

Fig. 2. Percentage of wells affected by sustained casing pressure in aging wells [7].

the annulus may have flown back due to U-tube pressure and drilling mud might have contaminated the cement, cement displacement wasn't properly done leaving channels of mud behind, characteristics of the cement slurry like base slurry stability and rheology, retarder concentration. Sealing properties of the cement might have been compromised due to foam instability and allowed nitrogen gas to escape the slurry. According to a previous statement, large portions of the reservoir strata were not cemented allowing oil and gas to flow at high pressure (900 bar) into the borehole. Another factor proposed that over-retardation of cement slurry exhibited a thickening time more than 10 h and developed no compressive strength even after 24 h. This allowed the gas to migrate through the still plastic cement and ascend to the surface where the blow-out preventer failed.

The percentage of reported wells developing leaks after a certain lifetime in years are represented in Fig. 3 [8]. Surprisingly, the wells between 1970 and 1979 develop the highest number of leaks in comparison to other well-documented data between 1958 to 1970.

A sharp focus on risk assessment is already implemented, compliance, simplification and improvement of the available R&D methodologies and the technical reliability of the lab facilities. Certainly, there will be increasing focus on the team's actions and how to regulate systems and procedures. That means that the importance of precision, quality and excellent HSE performance will increase. A sharp reminder is this accident in the Gulf of Mexico that one can never reduce the efforts to continuously improve HSE [3]. According to the latest statistics, Africa accounts for about 8% of the global oil output in 2020. Nearly 330 million tons (metric) of oil were generated in Africa the same year. The continent produced around 7 million barrels per day, the lowest production level since 2000. Nevertheless, oil remains a crucial driver for the producing countries

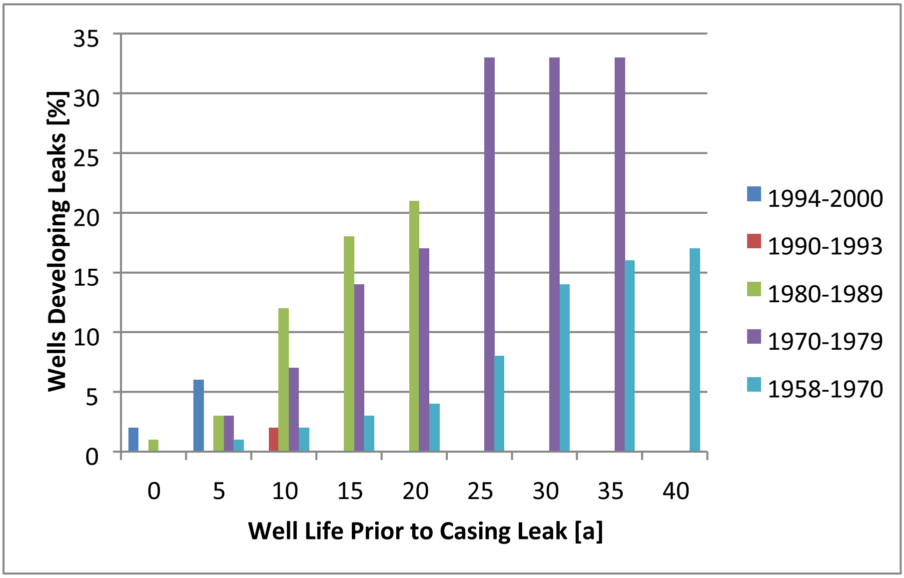

Fig. 3. Percentage of wells developing leaks in correlation to the well life prior casing [8].

economically, and its huge reserves may unveil other African countries as new producers (Fig. 4) [9].

Oil-well cementing is essential for all oil-producing countries. Appropriate design of the used slurry is crucial to a successful cementing job. The best way to get the anticipated compressive strength is by lab experiments which involve testing different recipes and choosing the optimum chemical mixture for a certain cementing job.

Compressive strength is particularly useful to test trustworthiness of the cementing operation since it is the capability of a material to resist distortion with increasing load. It depends on the type and number of raw materials and additives used, method and time of curing of the cement slurry as well as exposure conditions [8]. Good compressive strength means withstanding extremely high temperature, corrosive formations and gas intrusion. Challenges accompanying cementing jobs have led to a lot of investigation in this field using different approaches. Labibzadeh et al. concluded that, in connection to temperature and pressure variations, rapid early-age compressive strength could result in decrease in thickening time in oil well cement class G [10]. It was also reported that the strength of the cement could decrease in case of crystalline silica addition. Despite the ability to withstand pressure, temperature, and sulfate, additives are required to improve the properties of the cement [11]. It was concluded that compressive strength increased by the addition of 0.2% of lignosulfonate [12]. Beyond this value a reduction in compressive strength was observed. Enhancement of cement compressive strength depends on the correct quantity of each of the additives. The optimum dosages of these additives need to be identified by time consuming experimental runs, a process that is tedious and costly [13].

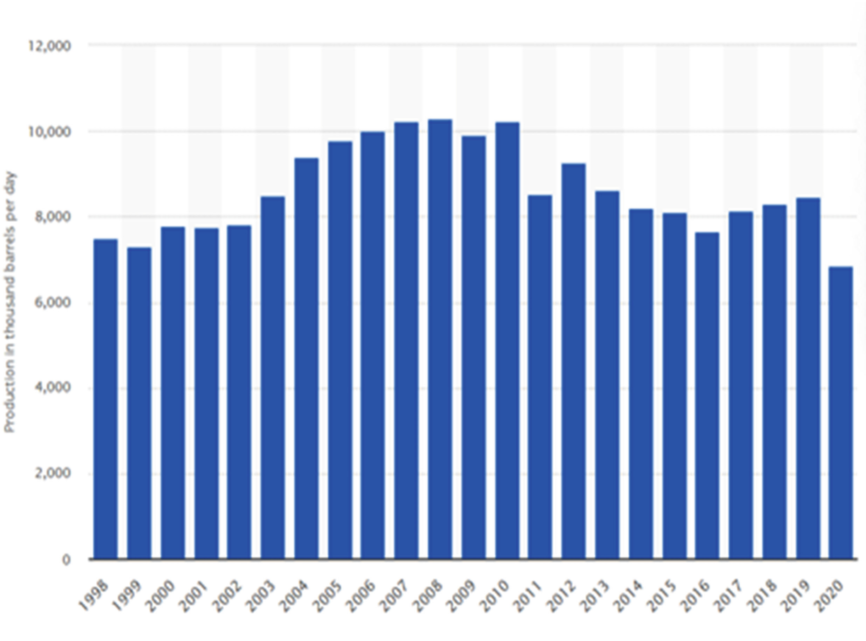

Fig. 4. Oil production in Africa from 1998–2020 [9].

The cement is required to have a minimum strength of about 500 psi before restarting the drilling operations [14]. The time necessary to attain that stage is the so-called wait-on-cement (WOC) which relates to the hydration time and consequently to the drilling cost per hour. That means that a longer waiting time will cause extra cost while a shorter waiting time could cause cement failure due to inadequate setting time of cement. Therefore, correct assessment of required cement strength is significant to reduce cost, in particular at those stages when mechanical and physical characteristics of oil well cement considerably change with time.

The main challenges that face drilling of an oil well include inhibiting gas migration after cementing. This phenomenon bears high risk since the gas can travel to the surface producing annular pressurization leading to a blowout with tragic results and eventually complete loss of the well.

This study presents a methodology to assess gas migration probability after cementing operations by means of the critical static gel strength concept. This study examines one retarder with two dispersants that seem chemically identical but come from two different service companies, namely sodium lignosulfonate (A) as a retarder and naphthalene sulfonate formaldehyde (B1 and B2) as a dispersant, respectively, with the focus on competitive adsorption [15, 16], steric position of anchor groups along with the main chain as well as adsorbed conformation of macromolecules on the cement grain [17, 18]. This work shows that models would fail if they would depend on theoretical structures only.

2 Methodology

2.1 Particle Charge Detection

The electro-kinetic technique is based on the distortion of counter ions resulting from the motion of charged particles with regard to its surrounding [19]. Each particle bears a dipole that affects its velocity in the electric field (electrophoretic mobility). This technique provides information about the effective particle charge that resembles a significant role in the electrostatic interaction between charged particles. The stability of colloidal suspensions is echoed consequently [19].

The chemical admixture solutions are of 100 ppm concentration. The solution sample (10 mL) is placed into the measuring cell and titrated with a cationic polymer (0.001 N polydadmac) solution until the isoelectric point is reached. The anionic charge density is then calculated accordingly.

2.2 Gel Permeation Chromatography

This method is used to determine polymers molecular weight distributions. The calculations are based on comparing the obtained sample chromatograph with standard polymers with known molecular weight distribution at the same mobile phase. Choosing the suitable standards is important in order to get reproducible results. For polydisperse polymers a weight average molecular weight M_w and a number average molecular weight $M_n$can be calculated using Agilent.

HPLC 1200, Agilent Technologies, USA. $NaNO_3$ aqueous solution of concentration 0.2 mol/L is used as an eluent. By adding 10 drops of 0.01 mol/L NaOH the solution is adjusted to pH = 8. The sample is injected with volume of 50 μL at a flow rate of 1 mL/min. Calibration of the column is carried out using polyethylene oxide/polyethylene glycol (PEO/PEG) standards (separation range = 100 to 1000k Da (Dalton)). Calculations of the molecular weight are carried out using the GPC software and a sixth order polynomial fit.

2.3 Cement Slurry Preparation

The cement paste is prepared at ambient temperature and at a water to cement ratio (w/c) of 0.4.

Preparation and mixing of the cement slurries followed ASTM C-305 using a cement blender,

ToniMIX, Toni Technik Baustoffprüfsysteme GmbH, Germany [20].

2.4 Static Gel and Compressive Strength Development

The compressive strength of oil well cement is important in acquiring long-term integrity of the wellbore. Its development is experimentally not easy to achieve once the cement is placed into the wellbore. During early cement hydration monitoring cement strength development is crucial and failure to do so may necessitate secondary cementing job. The static gel and compressive strengths are measured using a non-destructive method based on an ultrasonic technique as a function of time using Static Gel Strength Analyzer model 5265, Chandler Engineering, USA. After the sample is prepared as in 2.1, the slurry is poured into the autoclave cell and cured for 24 h at 25 °C and atmospheric pressure. The minimum accepted compressive strength for oil well cement is expected to be 500 psi in order to resist the shocks caused by the drilling operation and provides sufficient support to the casing in the wellbore [10]. According to API specifications [21], the static gel strength elapsed time is recorded and compared for different cement/additives slurry systems.

2.5 Compressive Strength by Crush Test

The compressive strength by crush test for different cement/additive systems is measured using an Automated Compressive Load Frame model 250, OFI testing equipment, USA and compared with the results gained by using the ultrasonic method described in Sect. 2.3. A cubical mold with dimensions of $5 \times 5 \times 5$ cm^3 is used. The mold interior surfaces are coated with mold sealing grease and the bottom cover plate is tied enough to prevent any cement leakages. After that, the cement slurry for different studied systems is poured into the prepared mold to approximately one-half of the mold depth [22]. Then, the sample is puddled for 30 times by using a puddling rod. The remaining sample is stirred and poured into the mold until it is overflowing with the slurry, the second layer of the slurry is puddled and any slurry excess is stroked off using a straight edge. The top cover is placed on the mold structure and tied in order to prevent any penetration of water into the sample. The mold is transferred to a water bath (Clifton NE4-14D, Nickel-Electro, England) and the sample is cured at 25 °C and atmospheric pressure for 24 h. The compressive strength is calculated based on the ratio of load applied per unit area of cement sample.

3 Results and Discussion

3.1 Chemical Characterization

The range of molecular weights of the different cement additives in any cementing job is considered as one of the main factors that affect the adsorption behavior of these additives on cement. The results for A, B1 and B2 are demonstrated in Fig. 5.

In case of B1 and B2, the molecular weights distribution results show minor differences and the values are almost identical as can be seen in Fig. 5. Nevertheless, other previous chemical characterization results didn't show any remarkable differences between B1 and B2. As a result, it is expected that both of them behave in the same way on the cement system.

The particle charge densities are evaluated as displayed in Fig. 5. The results show that the dispersants' systems have higher anionic charge density (ACD) by 22% to 26% compared to the retarder's system. Furthermore, B2 shows 4.3% higher anionic charge density than B1. These differences can be attributed to the variation in the degree of sulfonation. In more details, different polar groups are found in lignosulfonate such as phenylic hydroxyl and alcoholic hydroxyl groups as well as sulfonic groups [23] so that the value of charge density for the retarder represents the summation of the charge densities of all those groups Fig. 5. Quyang et al. altered lignosulfonate performance by increasing the sulfonation degree (sulfonic groups) and associated this with zeta potential measurements. It was reported that the modified components possess higher charge densities and thus a higher zeta potential was achieved [24]. These results were in consistence with other work on dispersants in presence of fluid loss additive.

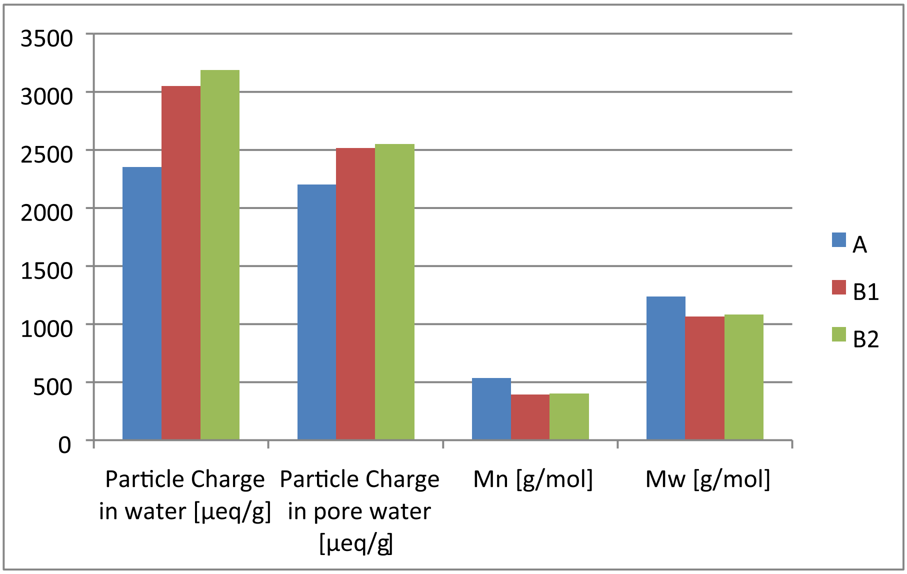

Fig. 5. Particle charge densities of the additives A, B1 and B2 at 0.2% in water and in pore water as well as number average (Mn) and weight average (Mw) molecular weights.

While free A and B1 and B2 show a certain particle charge as can be seen in Fig. 5, only about 8090% of that amount is found in the pore water of the cement under investigation attributed to complexation to free Ca ions in the pore water.

3.2 Mechanical Properties of Oil Well Cement Slurries

Development of high compressive strength and rapid static gel strength are considered as important and critical functions in oil well cementing jobs. That is attributed to the fact that both are directly involved in preventing unpleasant incidences in case the cement fails to achieve zonal isolation. Gas migration through cement matrix can badly compromise the cement job as well as the well production. Gas migration can occur in different ways in addition to bubble flow in a viscoelastic fluid. It can be found in the form of a lengthened slug as channels along cement-formation and cement-casing boundaries, or as a growing plume, where an almost spherical chamber is connected to the formation by a narrow umbilical conduit.

The cement slurry needs to develop rapid and sufficient compressive strength in order to ensure both structural support and hydraulic/mechanical isolation of borehole intervals [10]. Therefore, measuring both early compressive and static gel strengths are conducted for proposed cement/additives systems and compared to the neat cement system in order to evaluate their workability as well as their capability to deliver zonal isolation. Furthermore, the effect of compatibility between the additives on the mechanical properties is studied. As can been seen in Fig. 6 the static gel strength development is measured at 25 °C and atmospheric pressure for different systems at 0.2% bwoc. Unlike the neat cement system, the time to reach certain gel strength for all the cement/additives system is prolonged due to the retardation effect at constant water to cement ratio.

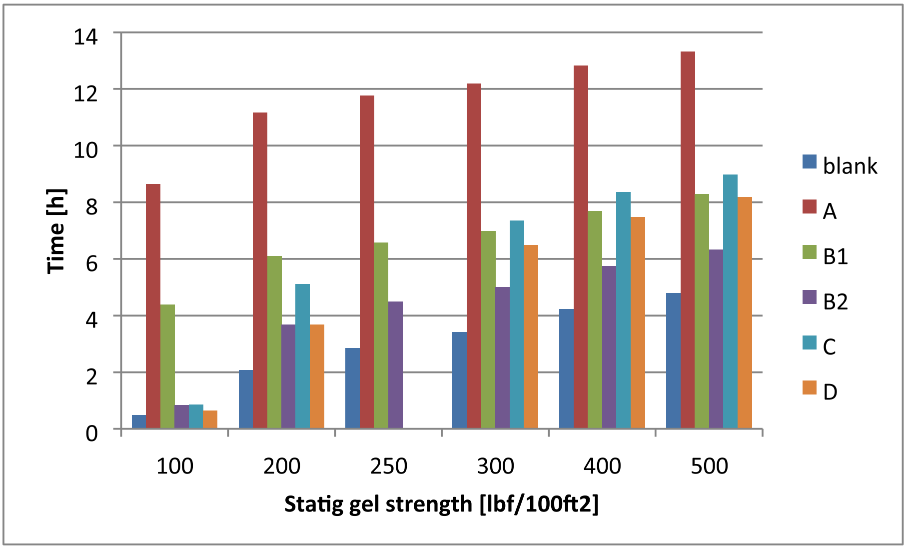

Fig. 6. Static gel strength as a function of time at 0.2% bwoc for the different admixtures.

As illustrated in Fig. 6, for the blank cement system the gel strength at 250 Ibf/100ft2 is reached at 2.85 h while at 0.2% A bwoc and 0.2% B1 bwoc the same gel strength is observed after 11.77 and 6.57 h, respectively. That means that the gel strength is retarded due to the addition of both additives on the cement slurry. For 0.2% B2 bwoc the gel strength at 250 Ibf/100ft2 is obtained approximately after 4.5 h as displayed in Fig. 6. The difference between both dispersants can be attributed to the variation in adsorption amounts as shown in previous results [15].

The systems C (a mixture of A and B1) at 0.2% bwoc and D (a mixture of A and B2) at 0.2% bwoc are negatively affected by the cement hydration time as well as the gel strength development due to competitive adsorption.

During the hydration process the consumption rate for NSF is higher than the rate for lignosulfonate due to variation in anionic charge and adsorption conformation. After a certain time, free NSF concentration in the solution will drop to zero allowing free lignosulfonate to adsorb with higher amounts. Because the compatibility is minimized drastically, the lignosulfonate will adsorb in higher amounts and effectively retard the system. However, the retardation will not be as effective as when lignosulfonate is added

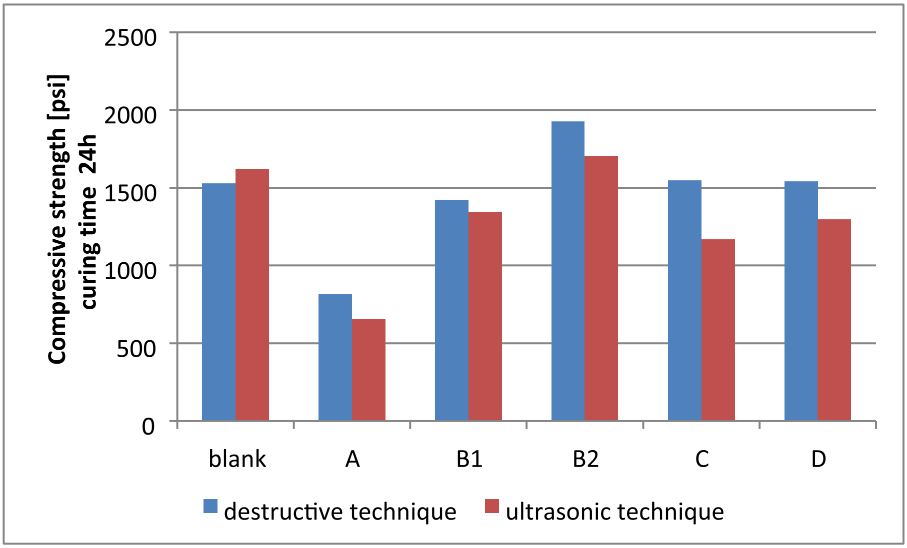

Fig. 7. Compressive strength measurements by destructive and ultrasonic techniques at 0.2% additives bwoc and a curing time of 24 h.

in the beginning of the cement hydration process. The impact of different additives recipes on compressive strength development is studied for 24 h and compared to the neat cement. Figure 7 shows the compressive strength development of all the cement systems is characterized by two methods: (1) API crush test, (2) The ultrasonic cement analyzer (UCA). The former method describes the cement compressive strength by dividing the pressure at which failure occurs by the cross sectional area of the specimen. The latter method is depending on measurement of the sonic travel time of ultrasonic energy through the cement sample while it is curing. As can be seen, there are differences between the results due to the measuring principle. The results obtain by API crush test are higher in compressive strength than the ones by using UCA except for the blank sample. It can be seen that all additives have reduced the compressive strength and prolonged its development for a certain time at constant water to cement ratio.

According to Fig. 7 the blank cement reached 500 psi compressive strength after 13.46 h and its maximum compressive strength value within 24 h is observed to be 1620 psi. Furthermore, the mixtures C and D exhibit the lowest compressive strengths and the minimum value for strength is not reached within the first 24 h. Therefore, those systems have failed to meet the minimum specifications and it's not recommended to be applied in the field at those conditions. The delay in strength development can be attributed to synergistic retardation when higher dosages of additives are used. For B1 and B2 systems the minimum value is reached after 17.93 and 15 h, respectively. This behavior can be attributed to the adsorption amount of B1 in comparison to B2, since by increasing the adsorption amount the compatibility question will arise. Although, all the proposed dosages have good workability, the additive systems can be enhanced by reducing the water to cement ratio with maintaining approximately similar obtained viscosities.

4 Conclusion

The Macondo blowout in 2010 was a wake-up call for seeking better risk assessment tools by experimentation rather than relying on old or imprecise mathematical models. It is crucial for the African countries as oil producers to get improved knowledge on the compatibility of chemical additives and their interactions on class G cement while undertaking oil well cementing. The chemical characterization results show that a retarder in presence of two dispersants of the same chemical structure but from different vendors can lead to misleading expectations and consequently models. The study shows that molecular weights can be considered as one of the factors that play an important role on adsorption behavior. While free A, B1 and B2 show a certain particle charge, only about 80–90% of that amount is found in the pore water of the cement under investigation attributed to complexation to free Ca ions in the pore water. The adsorption capacity and further the understanding of the compatibility between different cement additives is significant. In summary, particle size and microstructure play an essential role in assessing optimum recipes for a successful cementing job. The recommended optimum dosages are 0.2% bwoc for the individual systems under investigation and 0.1% for the combined mixtures due to evaluated synergistic effects. For the blank cement system the gel strength at 250 Ibf/100ft2 is reached at 2.85 h while at 0.2% A bwoc and 0.2% B1 bwoc the same gel strength is observed after 11.77 and 6.57 h, respectively. For 0.2% B2 bwoc the gel strength at 250 Ibf/100ft2 is obtained after 4.5 h. Competitive adsorption is observed in the mixture solutions. The retardation effects for the different systems emphasize that experiment is key, even if theoreticians believe they have reliable models.

Acknowledgement. The author would like to thank Mohammed M. Ali for providing some experimental data. The team at the microanalytical lab of the Technische Universität München is also greatly appreciated for their assistance with the experimental measurements.

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