An Elastomer Additive Improving Elastic Properties of Heavy Weight Oil Well Cement: A Laboratory Study

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ABSTRACT

The use of elastomer additives to solve the problems in oil well cementing has been investigated in recent years by several research groups in the petroleum industry. This study includes the laboratory examination of the effect of elastomer additives on the physical properties of heavy-weight oil well cement. In the research process, a candidate well is selected and the properties of the cement slurry used in a problematic section of the well are tested in the laboratory. Then, elastomer additives are added as an elastic agent and the improvements in the cement slurry and stone properties are studied. This article discusses the problems associated with the conventional heavy-weight oil well cement used in the candidate well and reports the detail of the improvements in cement properties obtained by adding an elastomer additive to the cement slurry formulation as an elastic agent. These properties include cement slurry rheological properties, free water, fluid loss, thickening time, cement stone elasticity properties, and compressive strength. The elastomer additive increases the yield point and plastic viscosity, but it decreases the free water and fluid loss of cement slurry. In addition, the cement stone compressive strength decreases; however, there is an optimum concentration of the elastomer additive at which the maximum compressive strength is reached. Moreover, the elasticity properties of the cement stone are improved and a lower value for the Young's modulus and a higher value for the Poisson's ratio are achieved. The theories supporting the results are discussed in the discussion section. The results of this study can be used to optimize the cement slurry design in any given set of conditions.

Keywords: Elastomer Additive, Oil Well Cement, Compressive Strength, Young's Modulus, Poisson's Ratio

INTRODUCTION

Primary cementing in oilfield applications includes the placement of cement slurry between the drilled formations and the well casing. The main goals of well cementing are casing protection and zonal isolation [1-4]. Zonal isolation must be maintained throughout the lifetime of the well. Correct cement design and cement placement are the key factors in achieving the primary cementing goals. The required properties for the cement stone and slurry are determined by the well conditions. These properties include cement slurry weight, cement slurry rheology, cement

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slurry thickening time, cement stone compressive and tensile strength, cement stone elasticity properties, and cement stone durability. The set cement sheath should withstand the stresses induced by the well events and maintain integrity during the life of the well [5-8]. Mechanical forces from the adjacent formations may damage the cement sheath and casing string. It has been found that in order to prevent mechanical damage to the cement, the best type of cement in terms of mechanical durability is the one with higher elasticity properties than the adjacent formation. The uniform distribution of the in situ stress acting upon the outside of the cement sheath can be achieved by a softer and more ductile cement stone, which means lower values of Young's modulus and higher value of Poisson's ratio. This will also enhance the collapse resistance of the casing string [9-11]. Successful application of high-density elastic cements to solve HP/HT challenges in the south Texas is reported in the literature [11- 12]. The elastic properties of the cement stone can be improved by adding an elastomer additive in low volumetric fractions to the cement formulation. Similar works are carried out by other researchers to improve the elastic properties of medium weight oil well cement by adding latex and fiber additives. In studies conducted by Khalaf (1985), the effects of styrene-butadiene latex and fiber polymers on the elastic behavior of the cement stone are verified. Five light- to medium-weight cement slurry samples with different formulations are prepared and the mechanical properties of the cement stones are determined. Figure 1 shows the mechanical behavior of the five cement stone samples, cement stone without additives, standard cement stone, cement stone containing fiber, cement stone containing latex, and cement stone containing fiber and latex. From Figure 1, cement stones including fiber and latex show higher tensile strength and more elastic behavior comparing with other cement stones [13]. In studies conducted by Le Roy-Delage (2000), in order to design proper cement slurries for long term zonal isolation purposes, common oil well cement additives with elastic additives and expanding additives are used. Table 1 shows the Young's modules and compressive strength of 16 ppg cement stones cured at 114°C. From the Table 1, in cement samples containing an elastic additive Young's modules and compressive strength are decreased, but the cement stone elastic behavior is increased [6]. Heavy weight oil well cements with proper mechanical properties are used by Barry Wray in 2009 in the south Texas HP/HT oil wells to increase the oil well life time. Nitrogen gas as an impact damper to increase the mechanical strength and fiber additives to increase the tensile strength of the cement stones are used in the cement slurry formulations. The formulations of the cement slurries are not reported in the article and just the cementing operation results are analyzed by strain analysis software [12]. None of the above examples is suitable for Iran's HP/HT oil and gas well conditions because of low cement slurry weight. In this study, for the first time, a new different elastomer additive is used in heavy weight oil well cement. Maroon oil field has been known in the oil industry for its HP/HT Gachsaran formation. Drilling wells to safely and effectively extract the contents of these reservoirs often proves to be a formidable exercise. In addition to the difficulties of dealing with high pressure and temperature, low-pressure zones can also be present. In recent years, well designs have also become more complex as fields mature and operators search for new sources of oil and gas. Cementing the casing and liner strings in place in these wells is a critical phase in the well construction process. The cement sheath is vital since it serves to protect and support the casing and deliver the necessary zonal isolation for the well. Once the well is completed, a whole new set of challenges that can stress an initially competent cement sheath are encountered. For example, some Maroon field HP/HT wells require high-pressure fracturing operations to unlock their full production potential, while, in other wells, the heavy weight drilling fluid, with which the well is drilled, is swapped out to lightweight brine at some point during the well completion process. In both cases, the loads imposed on the cement sheath can be extreme, potentially leading to debonding and even the catastrophic failure of a conventional cement sheath. When this occurs, the situation generally cannot be effectively remediated, and a well operator might find that they have lost a wellbore which is costly to construct.

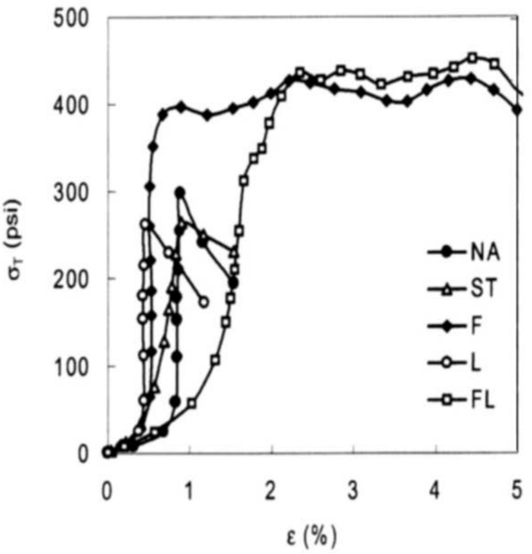

Figure 1: Tensile strength (σ_T) versus strain (ε) curve [13].

Table 1: Compressive strength and Young's modulus for 16 lbm/gal designs at 114°C (238°F) [6].

Formulation	Flexible Additives	Young's Module (MPa)	Compressive Strength (MPa)
G	Without	9041	39.2
H	With	6242	35.5
I	With	2594	21.1
J	With	1023	10.9

EXPERIMENTAL PROCEDURES

Materials

The materials used in this study include API well cement class E from Tehran Cement Company, tap water, Hidense as weighting agent, fluid loss control (Hallad 413), friction reducer (CFR-3) from Halliberton Company, boric acid as a retarder and salt (NaCl) from Petrokavir Company, antifoam (D047) from Dowell Company, and an elastomer additive. Figure 2 shows the shape and size distribution of the elastomer additive. The elastomer is a kind of modified terpolymer rubber containing 0.1 to 1 percent carboxylated monomer to enhance the adhesion of rubber to cement and improve the interaction at their interface. Rubbers have got the highest Poisson's ratio between other materials and are the best choice for increasing the Poisson's ratio of cement and decreasing its elastic modulus.

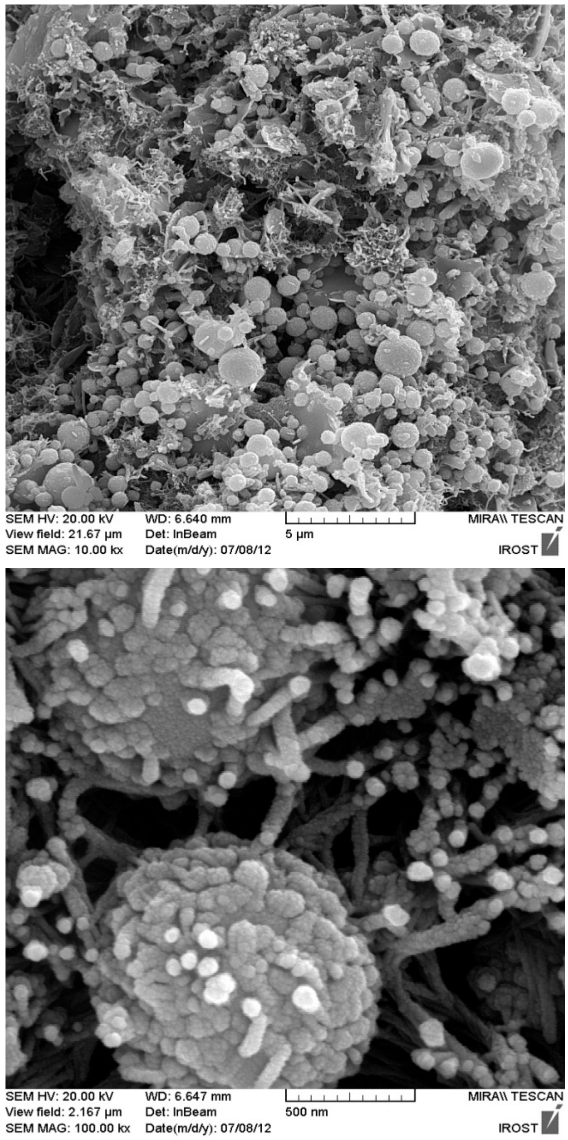

Figure 2: SEM micrograph of the elastomer additive.

The elastomer particles adsorb and damp the stress and stop the crack growth. The specifications of the elastomer additive are presented in Table 2.

Table 2: Physical and chemical properties the elastomer additive.

Size (micron)	Specific gravity	Humidity (%)	Color	Phase
75	1.1	4-5	Dark brown	solid

Study Method

This study is based on the laboratory testing of the improvements in the cement slurry and stone by using an elastomer additive at five concentrations. Well # 179 is selected as a candidate well in Maroon oilfield in the southwest of Iran. Recently, many casing collapse problems have occurred in this field in 9 5/8" casing string, which covers Gachsaran formation. Gachsaran formation is made of gypsum-anhydrite rocks and exhibits a plastic behavior. This imparts a horizontal stress to the casing string. More elastic cement sheath can enhance the protection of casing. The conventional and modified cement slurries are mixed in the laboratory and their properties including weight, rheology, free water, fluid loss, and thickening time are measured according to API RP 10B-2. The compressive strength of cement stones is measured by UCA. The elastic properties are measured on cylindrical samples by an uniaxial compressive strength tester equipped with axial and radial strain gauges (Figure 3).

The elastic properties of cement stone is determined based on the ISRM and ASTM rock mechanic standards. The cylindrical cement stone samples are prepared by curing the cement slurry for 48 hours at 210°F and 3000 psi in a rubber mold with a diameter of 68 mm and a length of 210 mm in a curing chamber. After the ends of the sample are cut flat, they are cooled down and kept saturated by merging in the saturated water; the loading rate is 4000 psi/min which is the maximum loading rate of the available equipment. Table 3 shows the conventional cement recipe in well # 179 and four other recipes modified by different amounts of the elastomer additive. Table 4 shows the elasticity properties measured for five samples.

Figure 3: Uniaxial compressive strength tester equipped with axial and radial strain gauges.

Table 3: Cement slurry compositions.

Component	Unit	Slurry 1	Slurry 2	Slurry 3	Slurry 4	Slurry 5
Cement Class E	**lb**	110	110	110	110	110
Elastomer Additive	**lb/SK**	-	3.3	6.6	9.9	13.2
Salt	**lb/ SK**	15.51	15.51	15.51	15.51	15.51
Hidense	**lb/ SK**	60.5	60.5	60.5	60.5	60.5
Boric Acid	**lb/ SK**	0.33	0.33	0.33	0.33	0.33
Fluid Loss Control	**lb/ SK**	-	0.33	0.33	-	-
Cement Friction Reducer	**lb/ SK**	-	0.55	0.55	0.11	1.32
Antifoam	**Gal/ SK**	0.02	0.02	0.02	0.02	0.02
Water	**ft^3**	0.6696	0.6696	0.6696	0.6696	0.6696

Table 4: Cement stones elasticity properties.

Sample	Elasticity Properties	
	Young's Modulus (GPa)	Poisson's Ratio
1	2.86	0.04
2	2.76	0.06
3	2.48	0.16
4	1.94	0.25
5	1.76	0.31

RESULTS AND DISCUSSION

Rheological Properties

According to the measured rheological properties of five slurry samples (Table 6), the increase of the elastomer additive will increase the plastic viscosity and yield point of the cement slurry. To have proper pumpable slurries, cement friction reducer additive is added in different amounts to the samples and the small differences in the rheological properties of 5 slurry samples are due to their different compositions. Sample number 1 had the settling problem of the Hidense and samples number 2 to 5 needed the cement friction reducer. Thicker slurry has more suspending capability and leads to a more homogenized cement sheath and constant cement stone properties along the casing string. The settling of the Hidense on the real well will result in a cement sheath with nonuniform properties along the well. At the bottom, high concentration of the Hidense will lead to heavy cement with a low compressive strength, and at the top, there will be light, thin, and two-phase slurries.

Free Water and Fluid Loss

Free water and fluid loss of cement slurries are determined according to the recommended method of API-RP-10B **[14].** Free water and fluid loss decrease by increasing the elastomer additive content (Table 5). It could also be deduced that the effectiveness of the elastomer additive in decreasing the free water and fluid loss decreases by increasing the concentration. Similar results are found in other studies [15-17]. High free water of the cement slurry causes problems in zonal isolation especially in horizontal wells and creates heterogenic cement stone properties along the cement sheath. High free water means thicker cake and weaker bonding between cement sheath and the formation. Loss of the water content of the cement slurry to the formation causes the cement slurry dehydration and increases the formation damage. It will also reduce the possibility of annular bridging by dehydrated cement [18-19]. Fluid loss control is also important in controlling the water-sensitive formation and gas migration problem.

Table 5: Cement slurries properties.

Slurry Number	Slurry Weight (PCF)	Free Water (cc)	Fluid Loss(mL) (T=180°F, P=1100 psi)	Thickening Time(min) (T=180°F, P=9000 psi)	Compressive Strength 24 hr(Psi) (T=210°F, P=3000 psi)
Slurry 1	149	1.5	30	145	3650
Slurry 2	147	1	27	160	3100
Slurry 3	145	1	30	180	2770
Slurry 4	143	0.5	31.5	193	2150
Slurry 5	141	0	33	203	1900

Thickening Time and Compressive Strengths

The elastomer additive in the cement slurry increases the thickening time, which will decrease the amount of the retarder additive needed and the total cost of the cement slurry (Table 5). The compressive strength of five cement samples is measured by ultrasonic cement analyzer (UCA). Figures 4-8 show the compressive strength of the 5 samples. It can be seen from these figures that the compressive strengths of the samples containing the elastomer additive are lower. According to Figures 4-8, by increasing the concentration of the elastomer additives up to 13.2 lb/sk in slurries, compressive strength decreases.

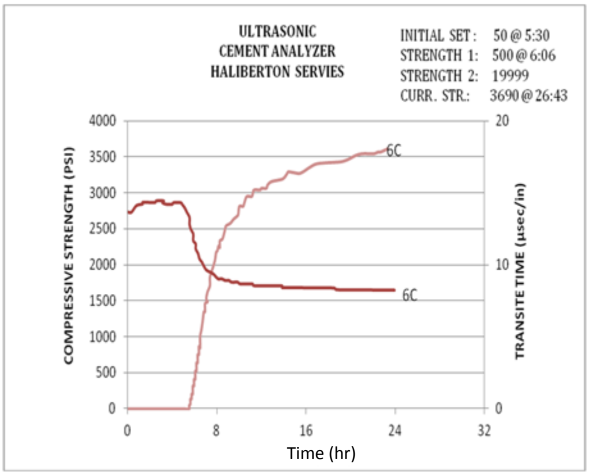

Figure 4: Compressive strength for cement slurry number 1.

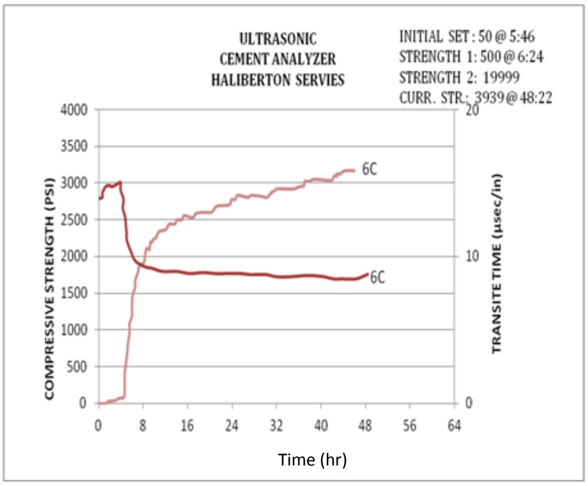

Figure 5: Compressive strength for cement slurry number 2.

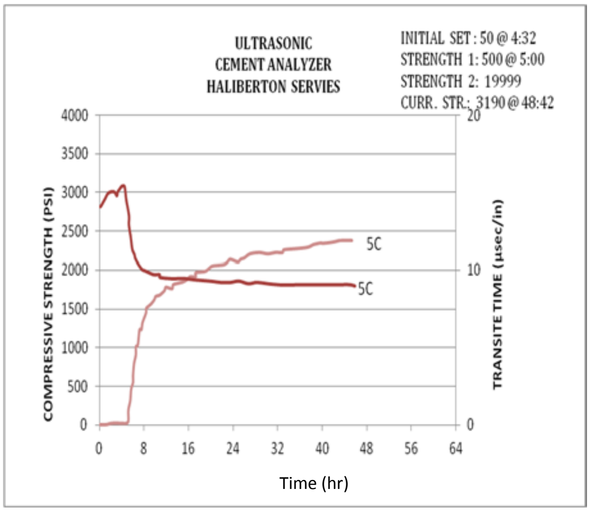

Figure 6: Compressive strength for cement slurry number 3.

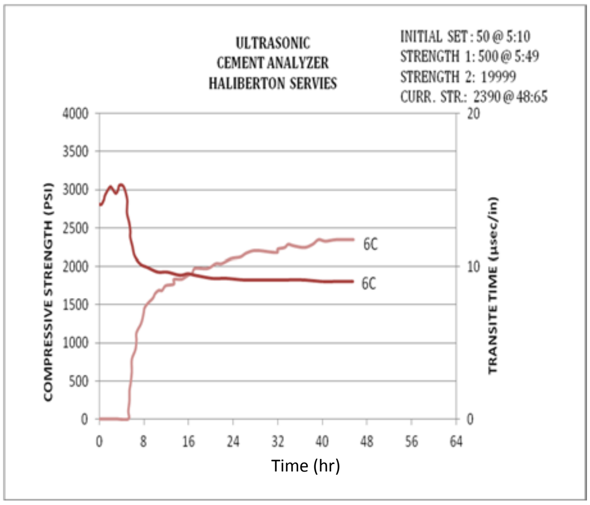

Figure 7: Compressive strength for cement slurry number 4.

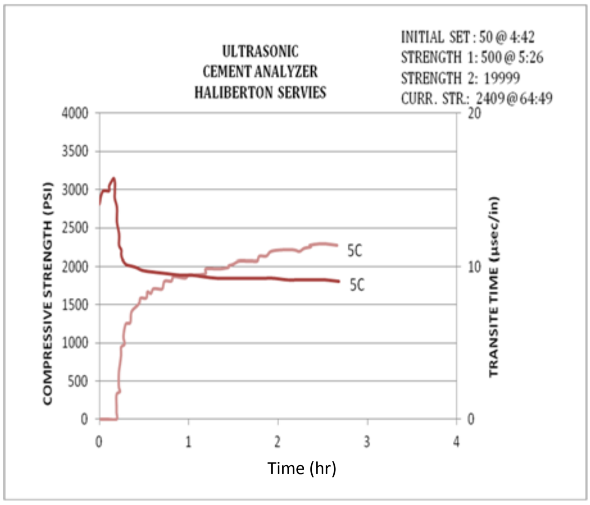

Figure 8: Compressive strength for cement slurry number 5.

Improving the Mechanical Properties of Cements

As could be expected, the mechanical properties of cement are strongly dependent on the particular additives incorporated to the slurry. Even when cements prepared with no admixtures or with a standard slurry design presenting high compressive strengths, they show a fragile behavior characterized by a low tensile strength (σ_T) and toughness (*T*). On the other hand, its high Young's modulus (E) and low Poisson's ratio (v) reduce its deformation capacity. The use of the elastomer additive improves the elastic behavior of cement as it reduces its Young's modulus and increases the Poisson's ratio. The elastic properties of the cement stone for the modified cement compositions with 4 concentrations of the elastomer additives are also measured in this study (Table 3). Figures 9-13 show the axial and radial stress-strain curve of five cement stone samples. The Young's modulus and Poisson's ratio are determined from the curve. Young's modulus is the slope of the best straight line to the axial strain-stress curve and the ratio of diametrical strain and axial strain is defined as Poisson's ratio. Similar to the previously mentioned properties, an increase in the Poisson's ratio and a decrease in Young's modulus can be observed (Table 4). Elastic cement systems showed an improvement in the collapse resistance of the casings. Casing collapse resistance is very sensitive to cement Poisson's ratio and cement Young's modulus [11]. A higher Young's modulus means that cement stone will have temporary and reversible deformations under a certain stress and will withstand higher stresses without breaking. A higher Poisson's ratio can distribute stresses and prevent the creation of high-stress points. The forces will be distributed along the cement sheath and the whole cement sheath will show an elastic behavior avoiding breakage by elastic deformation. In other studies, it has been shown that the compressive and flexural strengths of cement mortars are enhanced with adding latex [7].

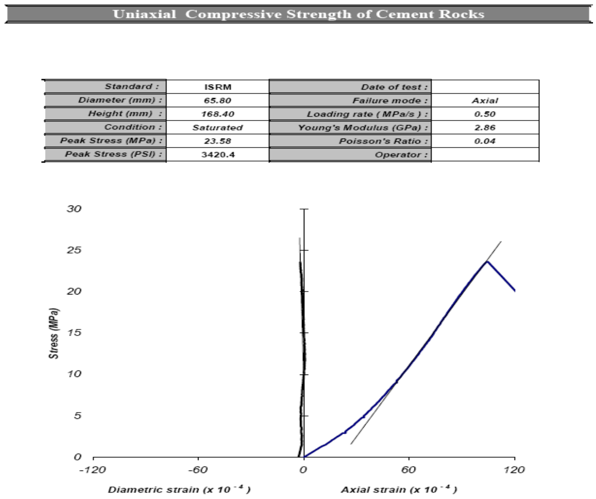

Figure 9: Axial and radial stress strain curve for cement slurry number1.

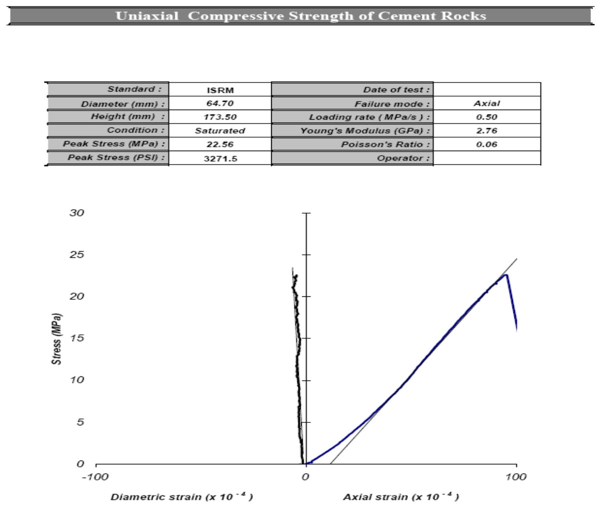

Figure 10: Axial and radial stress strain curve for cement slurry number 2.

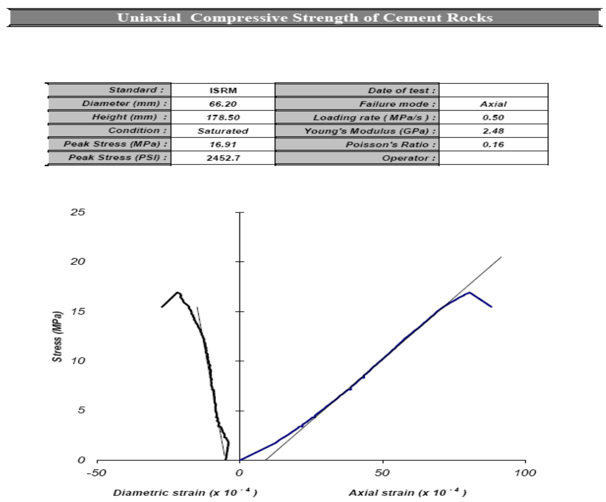

Figure 11: Axial and radial stress strain curve for cement slurry number 3.

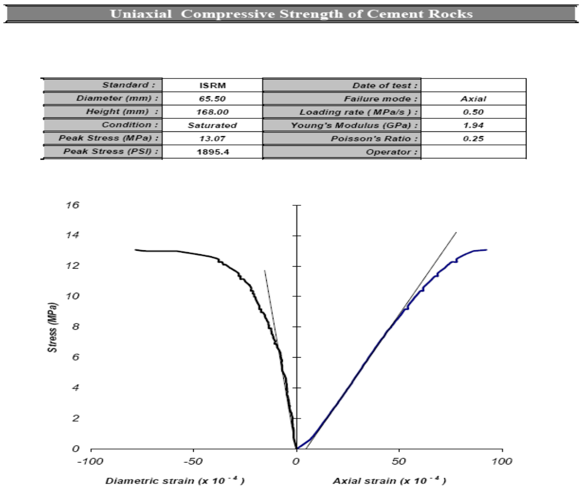

Figure 12: Axial and radial stress strain curve for cement slurry number 4.

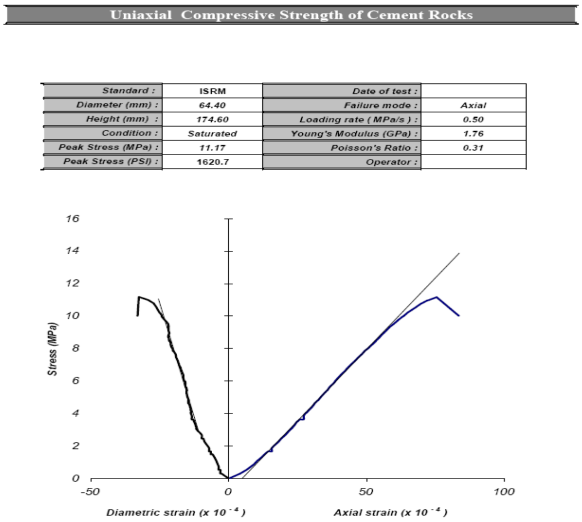

Figure 13: Axial and radial stress strain curve for cement slurry number 5.

In Maroun oil field, Gachsaran formation with plastic properties transmits the overburden pressure to the casing and leads to casing collapse [6-7]. The conventional cement slurry used in cementing this string has very poor properties and cannot resist against the stresses. Improving the elastic properties of the cement sheath covering this string can help solve the problem. Casing collapse resistance is improved by lowering the Young's modulus and increasing the Poisson's ratio [11-12]. More elastic cement can resist higher stresses [8] and the deformable cements can distribute the stress evenly [7]. The properties of the heavy-weight oil well cement used in this section of the well are improved by using the elastomer additives and the following results are obtained:

1. Elastomer additives increase the viscosity of cement slurry. High surface area of the elastomer additives in the cement slurry, when the water content is kept constant, will lead to more water adsorption by the solid content, and thereby decreasing the free water. The elastomer additives fill the voids between cement grains decreasing the volume of pores between them, which finally results in less free water. Therefore, there is a higher internal friction between solid particles, and viscosity rises.

2. The elastomer additives decrease the free water, fluid loss but increase the thickening time of the samples.

3. Adding the elastomer additives decreases the compressive strength but increases the elastic properties of the cement stone. Slurry samples numbers 2, 3, 4, and 5 have a lower compressive strength than the base cement. By increasing the elastomer additive content the compressive strength drops. Adding an elastic phase to the cement composition can improve the elastic properties of the cement stone, which means achieving a decrease in Young's modulus and an increase in Poisson's ratio. Cement stone matrix consists of two elastic and rigid phases. Under the exposed tensions, rigid phase resists and the elastic phase deforms. By increasing the elastic phase the whole system tends to increase the overall elasticity, which results in the elastic phase playing the major role.

CONCLUSIONS

This study confirms the results obtained in the previous studies and provides new experimental results on the improvement of the elastic properties of cement stone by elastomer additives. Elastomers improved the properties of the cement slurry and stone. From SEM micrographs (Figure 14) analysis, the elastomer additive acts as bridges between cracks and pores and guarantees the force transfer under stress. Elastomers keep their granular nature under downhole conditions even when they are soft and melted. They are like rubber particles or liquid droplets in the matrix of cement stone, and they do not form films on hydrated cement particles. They act as stress release spots, which improves the mechanical properties of the cement stone. Adding the elastomer additives decreases the compressive strength and Young's modulus, but it increases the Poisson's ratio of the cement stone samples. Furthermore, the elastomer additive in the cement slurry increased the viscosity and improved the suspending ability of the slurry. Free water and fluid loss also decreased by increasing the concentration of the elastomer additive. The effectiveness of the elastomer additive in decreasing the free water and fluid loss is higher at lower concentrations. It was also observed that the thickening time increased by increasing the concentration of the elastomer additives. The elastomer additive replaces the cement particles and decreases the hydration rate and retarder additive consumption, which consequently cuts the overall costs. More tests at higher concentrations of the elastomer additive have not been carried out since the purpose of the current study is to design a heavy weight oil well cement (heavier than 140 PCF) with the minimum required compressive strength, which, in this case, is 1600 psi; higher concentrations of the elastomer additive will lead to a further decrease in the slurry weight and reduces the compressive strength of the cement stone to the extent that it would be out of our acceptable range.

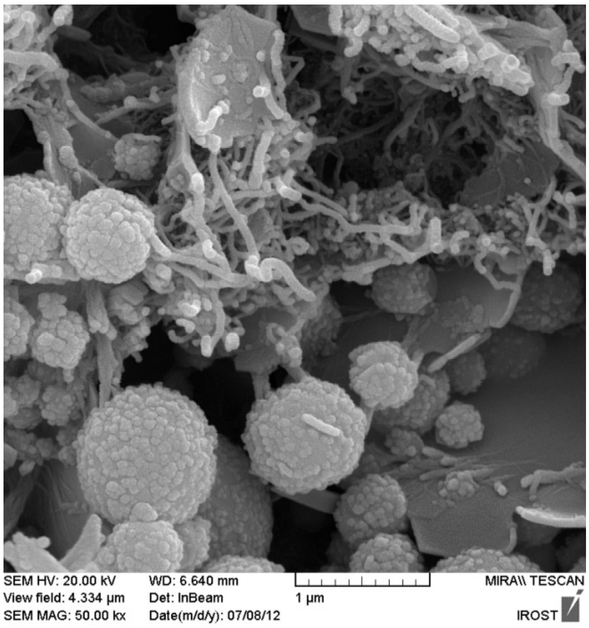

Figure 14: SEM micrograph of the cement stone including the elastomer additive.

Table 6: Cement slurries rheological properties.

Slurry number	(θ_{600})	(θ_{300})	(θ_{200})	(θ_{100})	(θ_6)	(θ_3)	PV (cP)	YP (lb/100ft^2)
Slurry 1	>300	273	190	107	15	13	249	24
Slurry 2	>300	250	177	98	20	16	228	22
Slurry 3	>300	286	181	100	19	15	249	17
Slurry 4	>300	276	165	107	17	13	253.5	22.5
Slurry 5	>300	248	177	98	29	19	225	23

REFERENCES

[1] Boukhelifa L., Moroni N., James S. G., Le Roy-Delage S., et al., "Evaluation of Cement Systems for Oil and Gas Well Zonal Isolation in a Full Scale Annular Geometry," SPE 87195-MS, Dallas, Texas, **2004**.

[2] Bannister C.E., "Evaluation of Cement Fluid Loss Behavior under Dynamic Conditions," SPE 7592-MS, Houston, Texas, **1978**.

[3] Destrade M., Gilchrist M. D., Motherway J., and Murphy J. G., "Slight Compressibility and Sensitivity to Changes in Poisson's Ratio,"

International Journal for Numerical Methods in Engineering, *90*, 403-411, **2011**.

[4] Fleckenstein W. W., Eustes A. W., Rodriguez W. J., Berger A., et al., "Cemented Casing: the True Stress Picture," AADE-05-NTCE-14, National Technical Conference and Exhibition, Houston, Texas, **2005**.

[5] El-Hassan H., Sultan M., Saeed A. A., Johnson C., et al., 'Using a Flexible, Expandable Sealant System to Prevent Microannulus Formation in a Gas Well: A Case History," SPE 92361, SPE Middle East Oil & Gas Conference, Bahrain, 12–15 March, **200**5.

[6] Le Roy-Delage S., Baumgarte C., Thiercelin M., and Vidick B., "New Cement Systems for Durable Zonal Isolation," SPE 59132-MS, IADC/SPE Drilling Conference, New Orleans, Louisiana, USA, 23-25 February, **2000**.

[7] Mack J. and Dillenbeck L. R., "Cement: How Tough is Tough enough? A Laboratory and Field Study," SPE 78712-MS, SPE Eastern Regional Meeting, Lexington, Kentucky, USA., 23-26 October, **2002**.

[8] Morris W., Criado M. A., Robles J., and Bianchi G., "Design of High Toughness Cement for Effective Long Lasting Well Isolations," SPE 81001-MS, SPE Latin American and Caribbean Petroleum Engineering Conference, Port-of-Spain, Trinidad and Tobago, 27-30 April, **2003**.

[9] Mueller D. T., "Producing Stress-resistant High-temperature/High-pressure Cement Formulations through Microstructural Optimization," SPE 84562-MS, SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, 5-8 October, **2003**.

[10] Ravi K., Bosma M., and Gastebled O., "Safe and Economic Gas Wells through Cement Design for Life of the Well," SPE 75700-MS, SPE Gas Technology Symposium, Calgary, Alberta, Canada, 30 April-2 May, **2002**.

[11] Yuan Z., Schubert J., Teodoriu C., and Gardoni P., "HPHT Gas Well Cementing Complications and its Effect on Casing Collapse Resistance," SPE 153986-MS, 28-30 March, Mumbai, India**, 2012**.

[12] Wray B., Bedford D., Leotaud L., and Hunter B., "The Application of High-Density Elastic Cements to Solve HP/HT Challenges in South Texas: The Success Story," SPE 122762-MS, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 4-7 October, **2009**.

[13] Khalaf F. and Cairo U., "Increasing Casing Collapse Resistance against Salt-induced Loads," SPE 13712-MS, 11-14 March, Bahrain, **1985**.

[14] "API Recommended Practice for Testing Well Cements," RP 10B API, Washington, **2010**.

[15] Nelson E., Guillot D., *Well Cementing*, 2nd Ed., Sugar Land, Tex.: Schlumberger, **2006**.

[16] Feder J., "Casing and Cementing," 3rd Ed., Austin, Texas: The University of Texas at Austin-Petroleum Extension Service, **2001.**

[17] Feder J., *Well Cementing (Oil and Gas Production)*, Austin, Texas: The University of Texas at Austin-Petroleum Extension services, **1983**.

[18] Rahman S. S., and Chilinggar G. V., "Casing Design: Theory and Practice," Amsterdam: Elsevier, **1995**.

[19] Ravi K., Bosma M., and Hunter L., "Optimizing the Cement Sheath Design in HPHT Shearwater Field," SPE 79905-MS**,** 19-21 February, Amsterdam, Netherlands, **2003**.