A NEW CEMENT ADDITIVE TO IMPROVE THE PHYSICAL PROPERTIES OF OIL WELL CEMENT AND TO ENHANCE ZONAL ISOLATION

Hamid Soltanian[1]*, Abdolrahim Khojastefar[2], and Ghorban Ali Sobhi[1]

[1] Exploration Department, Research Institute of Petroleum Industry (RIPI), West Blvd. of Azadi Sports Complex, Tehran, Iran.

[2] Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran.

ABSTRACT

The main purpose of cementing of the well is to provide effective zonal isolation for the entire life of wells. The standard cements cannot prevent loss of zonal isolation when the stress level in the well cement is severely fluctuated. Since elastic cements improve elastic properties, recently, a number of studies have been done in this area. For this purpose, a nanoparticle, named EX-RIPI, was designed as an additive to improve cement elasticity. A series of experiments were carried out to investigate the effects of this additive on the elastic properties of the cement. The experimental results showed that the addition of EX-RIPI to the cement slurries decreased Young's modulus from 2.86 GPa to 1.94 GPa but increased Poisson's ratio from 0.04 to 0.25. Consequently, EX-RIPI can be used as a suitable additive for improving the mechanical properties of cement used for a long time zonal isolation. To illustrate the performance of this additive, the properties of the cement stone was compared with one of available additives in the market (i.e., Flexstone).

Keywords: Elastic Cement, Young's Modulus, Poisson's Ratio, Compressive Strength, Cement Additive

INTRODUCTION

Casing is cemented in wellbore to provide casing support, to protect fresh water invasion from contamination, to prevent casing collapse which may be caused by formation creep to provide zonal isolation of producing zones, and to isolate casing from corrosive brines [1].

The main purpose of primary cementing is to provide an effective zonal isolation during the entire life of the well. This zonal isolation must be continued during the life of the well even after well abandonment. No fluid invasion must be occurred in the cement matrix, casing/ cement interface, and cement/formation interface [2]. The loss of zonal isolation in the absence of chemical attack can be due to either mechanical failure of the cement or debonding of casing from cement or debonding of cement from the formation [3]. In general, when wellbore temperature pressure changes in 2D cylindrical coordinate system, two principal stresses, which are called radial and tangential stresses, are imposed on the cement. Cement

*Corresponding author
Hamid Soltanian
Email: Soltanianh@ripi.ir
Tel: +98 21 4825 3426
Fax: +98 21 4473 9725

Article history
Received: January 15, 2012
Received in revised form: September 13, 2012
Accepted: September 19, 2012
Available online: April 30, 2013

failure type is determined by evaluating these stresses and divided into either tensile or shear failure. Tensile failure causes cracks while shear failure leads to cement plastic deformation [4]. The loss of zonal isolation can result in the following problems:

- Loss of gas reservoir;
- Unsafe operation;
- Production of premature gas or water;
- Well shutdown [5].

Neat and standard cements usually have a high compressive strength and show brittle behavior. This brittle behavior is determined by low tensile strength and cement toughness. On the other hand, the high Young's modulus and low Poisson's ratio of these cements reduce their deformation capacity. Such cements can be used where there is a small change in the cement stress level [6]. The formation of micro-annulus can be prevented by using expanding agents in the cement. New cement systems containing expanding agents and flexible additives lead to the reduction of cement Young's modulus in comparison with conventional cements [7]. As a result, these systems increase the cement elasticity. Poisson's ratio is another parameter which plays a key role in cement sheath integrity. A higher cement Poisson's ratio results in a more qualified sheath. Elastic cements have a higher Poisson's ratio usually greater than 0.2 [8]. In fact, a synergy exists between elastic cements and expanding agents. The expanding cements will move toward casing when these cements are more flexible than the formation [9]. Le-Roy Delage et al. investigated the effects of a flexible additive and its concentration on cement mechanical properties [3]. The results of their work can be summarized as follows; flexible cements have a lower Young's modulus and higher Poisson's ratio values in comparison with conventional cements. Moreover, using higher flexible agent concentrations improves the elasticity of cement. Walter Morris et al. used a polymeric fiber in cement to improve its mechanical properties [6]. Their study indicated that fiber reinforced cements had a high tensile strength, good elastic behavior, and improved toughness. Boukhelifa et al. developed a large scale laboratory test for sealants in annular geometry [7]. They used different cement systems in their work. This study showed that cement mechanical properties (elasticity, strength, and expansion) and rock properties were key parameters in maintaining the cement sheath integrity during the life of the well. They found that the expanding and flexible systems showed the best properties in the loading stage. Barry Wray et al. compared the integrity of two different cement sheaths during high pressure high temperature (HPHT) well operations [10]. These systems were standard cement, and flexible cement. In order to prepare elastic cement they used elastomer and fiber in the cement for improving elasticity and increasing tensile strength of the cement [11]. The results showed that the standard cement debonded from casing during well completion and stimulation. However, when elastic cement was used in the well, casing debonding from cement was not observed. Consequently this cement created a better zonal isolation in comparison with the standard cement [12,13].

The elastic properties of the cement stone can be improved by adding nano-sized particles in low volumetric fractions to the cement formulation. This study includes the laboratory examination of the effect of a nano-particle, named EX-RIPI, on the physical properties of heavy-weight oil well cement.

EXPERIMENTAL SET-UP

In order to design proper cement for using in oil/gas wells, a series of experiments were done. These tests were classified in two categories, namely preliminary and compressive strength tests. Preliminary tests were done to measure the routine cement slurry properties such as slurry weight, free water, rheology, fluid loss, and thickening time according to API RP 10B-2 [14]. Slurry weight was measured by mud balance. HPHT filter press apparatus was used to determine fluid loss. The rheological properties of slurry were measured by viscometer. Finally, pressure-temperature consistometer was used to determine the slurry thickening time [15]. An ultrasonic cement analyzer (UCA) was used to measure the compressive strength at well condition. The transit time of ultra-sonic wave through the cement sample is the basis of compressive strength measurement with UCA. American petroleum institute (API) compressive strength tester model 4207 was used to meas-ure the uniaxial compressive strength of the set cement [16]. In this test, axial and lateral strains can be determined at a specific stress by four dis-placement sensors. This apparatus provides stress-strain curve of the set cement. Cement Young's modulus and Poisson's ratio were determined from this curve. This apparatus yields the stress-strain curve through the follow-ing steps:

1. The cylindrical set cement sample is placed on the lower part of hydraulic press;
2. The loading rate is set by a control unit at 0.5 $MPa.sec^{-1}$;
3. The sample is engaged with the upper part of hydraulic press;
4. Three displacement sensors are set around the sample to measure the average diamet-ric strain;
5. A displacement sensor is set in axial direction to measure the axial strain;
6. Loading continues until the sample fails. Data during loading are analyzed by data processor unit and are then sent to a PC for plotting.

EX-RIPI Additive (Elastic Additive)

EX-RIPI is a nano-particle specifically designed to improve the tensile strength and elastic proper-ties of cement. Also, it allows cement sheath to withstand stresses imposed by varying condi-tions throughout the life of a well. EX-RIPI slurries provide enhanced mechanical properties This additive spreads point or non-uniform loads through the cement sheath and causes the cement sheath to experience uniform loads. The spreading effect of EX-RIPI prevents casing collapse in moving salt formation. The physical properties of this nanoparticle are shown in Table 1.

Table 1: Physical properties of EX-RIPI

Specific gravity	1.37
Additive form	Powder
Color	Dark brown
Applicable temperature	16 to 160 °C
Proper concentration	3 to 7% by weight of cement
Solubility in water	0.3 g/100ml H_2O, at 20 °C

EX-RIPI also can affect slurry properties. These effects can be itemized as slurry gelation, rapid initial set, expansion increase, viscosity increase due to high surface area of the particles constituting EX-RIPI, and density decrease due to its low specific gravity.

RESULTS AND DISCUSSION

In this study, a cement formulation for salt formation cementing was used and was modified. During the test Finally, EX-RIPI was added to the modified cement. The properties of the cement slurry and stone were compared with commercially available elastic cement. The formulations for these cement slurries are shown in Table 2. Table 3 shows the cement slurry properties measured during the prelim-nary tests. Compressive strength and its progression were determined with UCA.

Figures 1, 2, 3, and 4 show that the compressive strength is gradually increased in the cement samples. The ultimate compressive strengths of these cements are shown in Table 4.

Table 2: Cement formulation

	Cement class E (g)	Water (cc)	Retarder D13 (g)	Highdense (g)	Salt (g)	Dispersant (g)	EX-RIPI (g)	Flexstone (g)
Base cement	1000	545	3.1	964	203	-	-	-
Modified cement	1000	380	3.2	577	142	-	-	-
Elastic cement	1000	380	3.1	550	142	1	90	-
Flexstone cement	1000	385	3.1	552	141	-	-	90

Table 3: Cement slurry properties

Cement type	Plastic viscosity (Pa.s)	Yield point (kPa)	Density ($kg.m^{-3}$)	Free water (cc)	Thickening time (min)
Base cement	0.0615	4.55	2387.8	15	151
Modified cement	0.249	11.49	2387.8	1.5	136
Elastic cement	0.254	10.77	2339.7	0.5	125
Flexstone cement	0.239	12.02	2338.9	10	145

Table 4: Measured cement compressive strengths with UCA

Cement type	Compressive strength (MPa)
Base cement	14.87
Modified cement	25.50
Elastic cement	16.47
Flexstone cement	21.05

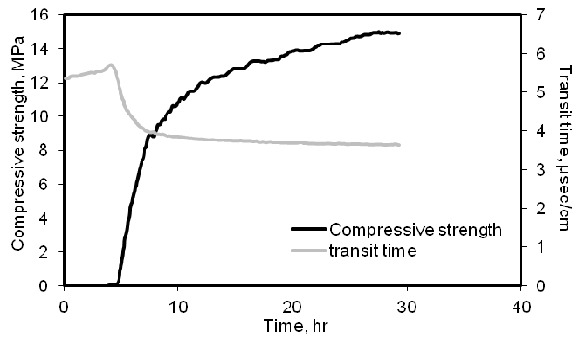

Figure 1: Compressive strength progression of the base cement

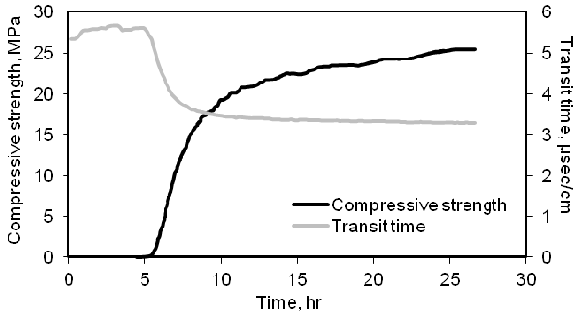

Figure 2: Compressive strength progression of the modified cement

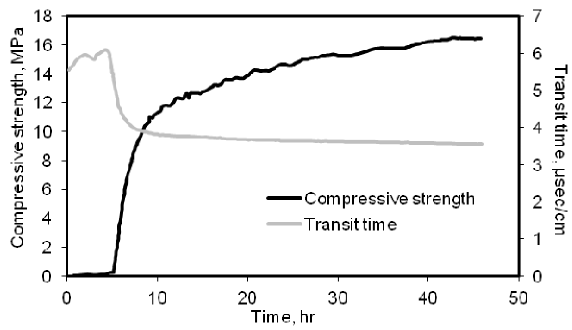

Figure 3: Compressive strength progression of the elastic cement

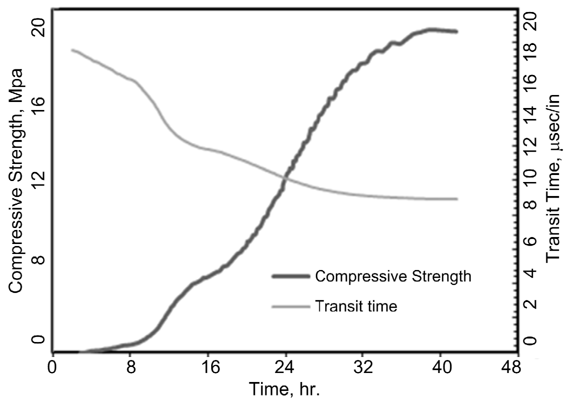

Figure 4: Compressive strength progression of the Flexstone cement

For measuring uniaxial compressive, the cement samples were cured at 210 °F and 10680 psi for 3 days; sample curing was done with a curing chamber. Uniaxial compressive strength, elastic (Young's) modulus, and Poisson's ratio were measured with API compressive strength tester, model 4207; the corresponding results are shown in Tables 5, 6, 7, and 8. Stress-strain curves are also indicated in Figures 5, 6, 7, and 8. The base cement formulation was modified due to its high free water and low yield point. The low yield point leads to the settlement of high density additives. In order to modify the cement formulation, the amounts of water, salt, and high density additive were decreased. When the water content of the slurry is decreased, the water cement ratio (WCR) is also reduced. WCR reduction causes the compressive strength, and therefore the Young's modulus, of the modified cement to become greater than that of the base cements. The stress-diametric strain curves of these two cements are approximately similar and lie near the stress axis (Figures 5 and 6). Since Poisson's ratio is the ratio of Young's modulus to the slope of the linear part of stress-diametric strain curve, it can be obvious that the Poisson's ratios of these two cements are very low and nearly equal to each other.

Table 5: Results of uniaxial compressive strength test for the base cement

Cement diameter (mm)	66.8
Cement height (mm)	166.4
Peak stress (MPa)	12.75
Failure type	Axial
Loading rate ($MPa.sec^{-1}$)	0.5
Young's modulus (GPa)	2.43
Poisson's ratio	0.03

Table 6: Results of uniaxial compressive strength test for the modified cement

Cement diameter (mm)	65.8
Cement height (mm)	168.4
Peak stress (MPa)	23.58
Failure type	Axial
Loading rate ($MPa.sec^{-1}$)	0.5
Young's modulus (GPa)	2.86
Poisson's ratio	0.04

The modified cement and cement containing EX-RIPI have the same WCR; therefore, it is beneficial to compare their mechanical properties. The cement containing EX-RIPI has a lower compressive strength and Young's modulus in comparison with the modified cement. Moreover, the stress-strain curve of this cement shows that the Poisson's ratio of the cement containing EX-RIPI is much higher than the modified cement (Figure 7). Such mechanical property changes indicate that EX-RIPI improves the cement elasticity. In addition, the EX-RIPI performs much better to improve the elastic properties of the cement stone than the commercially available additives.

Table 7: Results of uniaxial compressive strength test for the elastic cement

Cement diameter (mm)	65.5
Cement height (mm)	168
Peak stress (MPa)	13.07
Failure type	Axial
Loading rate ($MPa.sec^{-1}$)	0.5
Young's modulus (GPa)	1.94
Poisson's ratio	0.25

Table 8: Results of uniaxial compressive strength test for the Flexstone cement

Cement diameter (mm)	65.8
Cement height (mm)	167.4
Peak stress (MPa)	16.00
Failure type	Axial
Loading rate ($MPa.sec^{-1}$)	0.5
Young's modulus (GPa)	2.33
Poisson's ratio	0.18

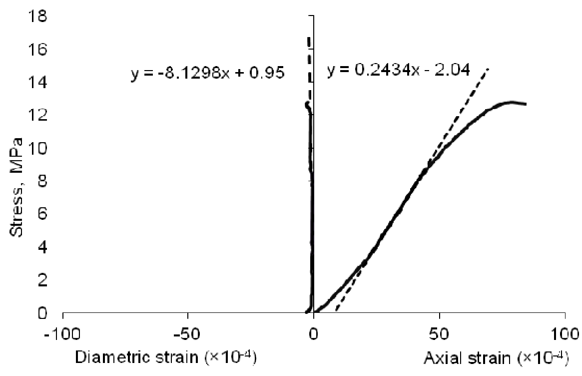

Figure 5: Stress-strain curve of the base cement

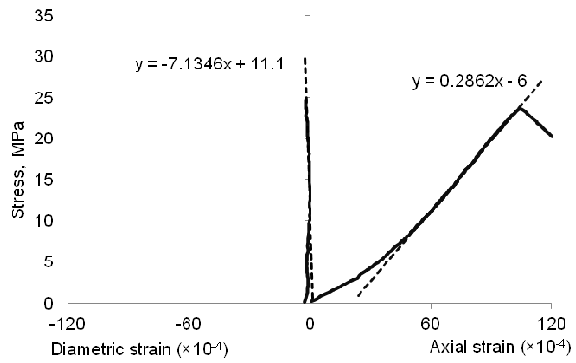

Figure 6: Stress-strain curve of the modified cement

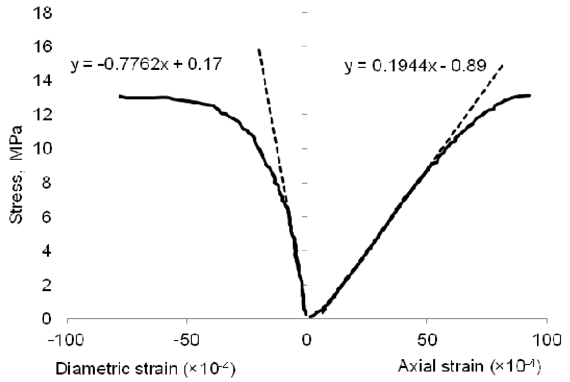

Figure 7: Stress-strain curve of the elastic cement

Using EX-RIPI nano-particles as an additive has significant effects on the compressive strength and elasticity properties of the cement stone because the compressive strength is primarily controlled by the total porosity. The nano-particles will fill the pores, which leads to increasing strength and improving the microstructure of the cement if they are uniformly dispersed. EX-RIPI has elastic properties and adding elastic additives to the cement composition can improve the elastic properties of the cement stone, which leads to an increase in Young's modulus and Poisson's ratio. The cement stone matrix consists of two elastic and rigid phases; under the exposed tensions, the rigid phase resists and the elastic phase deforms. By increasing the elastic phase the whole system tends to increase the overall elasticity. Thus, the elastic phase plays the principal role. The improvement of elasticity is also due to the formation of more hydrated products in the presence of nanoparticles.

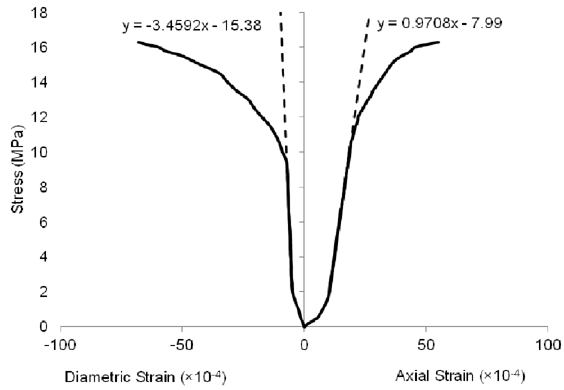

Figure 8: Stress-strain curve of the Flexstone cement

CONCLUSIONS

On the whole, the following conclusions can be deduced from the present study:

1. EX-RIPI reduces the compressive strength of cement in an appropriate range for casing support. Moreover, the addition of EX-RIPI to the cement slurries reduces the rate of compressive strength progression.
2. The Young's modulus of EX-RIPI cement is measured to be lower than the standard cements. This is due to the lower compressive strength.
3. EX-RIPI increases the axial and lateral strain of the cement when it is exposed to axial stress. But, the lateral strain increases more rapidly with respect to axial strain. Consequently, EX-RIPI increases the cement Poisson's ratio significantly.
4. The EX-RIPI-added cement is an elastic cement due to a low Young's modulus and a Poisson's ratio greater than 0.2.
5. EX-RIPI performs much better than the commercially available additives in the market.

ACKNOWLEDGMENT

The authors would like to thank Research Institute of Petroleum Industry (RIPI) for continuous help during conducting experiments and IOOC for the financial support of this work.

NOMENCLATURE

API : American petroleum institute
BHST : Bottom hole static temperature
BWOC : By weight of cement
E : Young's modulus (MPa)
FW : Free water (cc)
HPHT : High pressure high temperature
PV : Plastic viscosity ($kg.m^{-1}.s^{-1}$)
TT : Thickening time (s)
UCA : Ultra-sonic cement analyzer
UCS : Uniaxial compressive strength (MPa)
WCR : Water cement ratio
YP : Yield point (MPa)
v : Poisson's ratio
ρ : Density ($kg.m^{-3}$)

REFERENCES

[1] Mack J., Dillenbeck L. R., BJ Services Company, "Cement: How Tough is Tough Enough? A Laboratory and Field Study." SPE 78712-MS, SPE Eastern Regional Meeting, **2002,** Lexington, Kentucky, U.S.A., 23-26 October.

[2] Lullo G., Phil Rae, BJ Services Company. "Cements for Long Term Isolation Design Optimization by Computer Modeling and Prediction." SPE 62745-MS, IADC/SPE Asia Pacific Drilling Technology, Kuala Lumpur, Malaysia . **2000**, 11-13 September.

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

[4] Mueller D. T., BJ Services Company, "Producing Stress-Resistant High-Temperature/High-Pressure Cement Formulations through Microstructural Optimization". SPE 84562-MS, SPE Annual Technical Conference and Exhibition, **2003**, Denver, Colorado, U.S.A., 5-8 October.

[5] Ravi K., Halliburton; Bosma M., Shell International E & P; Gastebled O., TNO Building and Construction Research, "Safe and Economic Gas Wells through Cement Design for Life of the Well." SPE 75700-MS, SPE Gas Technology Symposium, **2002** Calgary, Alberta, Canada, 30 April-2 May.

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

[7] Feder, J., "Casing and Cementing" 3rd Edition, *Petroleum Extension Service, University of Texas*, **2001**, p. 99.

[8] Boukhelifa L., Schlumberger; Moroni N., ENI SpA; James S. G., Le Roy-Delage S., Thiercelin M. J, Schlumberger, Lemaire G., INSA. Toulouse. "Evaluation of Cement Systems for Oil and Gas Well Zonal Isolation in a Full-Scale Annular Geometry." *SPE 87195-MS, IADC/SPE Drilling Conference*, **2004**, Dallas, Texas, U.S.A., 2-4 March.

[9] El-Hassan H., Sultan M., and Saeed A. A., ADCO, and Johnson C., SPE, Belmahi A., and Rishmani L., Schlumberger . "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*, **2005**, Bahrain., 12-15 March.

[10] Wray B., Cimarex Energy, Bedford D., Leotaud L., and Hunter B., Halliburton . "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, **2009,** New Orleans, Louisiana, U.S.A, 4-7 October.

[11] The University of Texas at Austin-Petroleum Extension services, "Well Cementing (Oil and Gas production)", *The University of Texas at Austin-Petroleum Extension Service*, **1983**, p. 345.

[12] Montgomery C P., "Oil Well Cementing Practices Materials", *Halliburton Oil Well Cementing Co*, **1959**, p. 149.

[13] Marlow S R., "Effect of Temperature/ Pressure Cycling on Cement Bonding Characteristics in Gas Injection/Withdrawal Wells", *Southwest Research Institute*, **1987**, p. 202.

[14] Jacqueline and Cartalos Ulysses “Cementing Technology”, *Editions Technip*, **1994**, p. 116.

[15] Smith, K. D., “Cementing”, *Henry L. Doherty Memorial Fund of AIME*, **1987**, p. 189.

[16] Nelson E., D., “Well Cementing”, 2nd Edition, *Schlumberger*, **2006**, p. 301.