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# Using an Elastic, Expandable Sealant System for Zonal Isolation of Maroon Wells: a Laboratory Study

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## ABSTRACT

An oil and gas well cementing in Gachsaran formation, where sustained annular pressure has been reported in many wells, presents a big challenge in Maroon field. The main challenges are preventing gas migration and achieving zonal isolation using a competent cement sealant system which is able to withstand downhole stresses and high temperatures during production cycles. Unlike conventional cement systems, properties, such as, high Poisson's ratio and low Young's modulus compared to that of the rock were optimized in the new system to achieve mechanical resistance and durability. The use of elastic-expandable additives to solve 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 an elastic-expandable additive on the physical properties of a new cement sealant system. In the research process, a candidate well was selected and the properties of the used cement slurry in a problematic section of the well were evaluated in the laboratory. Then, the elastic-expandable additive was added as an elastic agent and the improvements in the cement slurry and stone properties were studied. This article discusses the problems associated with the conventional cement used in the candidate well and gives the detail of the improvements in cement properties obtained by adding the elastic-expandable additive to the cement slurry formulation as an elastic agent. The elastic-expandable additive increases the Poisson's ratio and expansion set cement, but it decreases the Young's modulus and fluid loss of the cement slurry. In addition, to prevent gas migration and achieve zonal isolation, there is an optimum concentration of the elastic-expandable additive at which the maximum compressive strength is reached. The results of this study can be used to optimize the cement slurry design in any given set of conditions.

**Keywords:** Expandable Additive, Compressive Strength, Rheological Properties, Young's Modulus, Poisson's Ratio

## INTRODUCTION

Interzonal communication in a wellbore may lead to loss of reserves, the contamination of zones, the production of unwanted fluids, or safety and environmental issues. Remedial solutions are available to solve the problems, but for technical or economic reasons, the well may be shut in or abandoned To improve the lifetime of the well, the

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cement sheath must be chemically and mechanically durable [1-2]. Sealants resistant to aggressive formation fluids are designed when required. In the same way, sealants should be designed to withstand the stresses experienced during production and well operations for instance casing pressure tests, stimulation treatments or temperature changes during production cycles-throughout the well life. To achieve this, a better understanding of the mechanical behavior of different sealants under downhole conditions is required to design fit-for-purpose materials [3-5].

Several papers have been written on the subject. According to Thiercelin et al., three changes in downhole conditions can cause mechanical damage to the cemented annulus (mechanical failure or the creation of microannuli) that may lead to a loss of zonal isolation [6]. The key conclusion of that paper was that, instead of considering the strength of the sealant as the primary property, one should rather look at the complete mechanical system formed by the steel casing, the cemented annulus, and the formation. Indeed, the increase of pressure and/or temperature in the wellbore initially expands the inner steel casing, which instantly imposes this deformation on the neighboring cement sheath [7-8]. As a consequence, imposed displacements rather than imposed stresses are applied to the cement inner diameter (ID). At a greater time scale (the lifetime of the well), the cement sheath must withstand multiple displacement cycles. Numerical models have been proposed by several authors to simulate the sealant mechanical behavior and predict the initiation of failures, according to known mechanical properties of the complete system (steel, cement, and rock) [9-10]. In the past, the perception for judging the mechanical properties of cement was to look at the compressive strength of the set cement. However, the recent lessons learned from the wells experiencing sustained annular pressure showed the limitation of this traditional approach [11]. Changes in downhole conditions in terms of temperature and pressure can induce sufficient stresses to destroy the integrity of the cement sheath, which will cause long term gas migration and sustained annular pressure. Hence, the set cement mechanical properties have to be carefully designed in order to withstand the downhole stresses. Cement mechanical failure is caused by stresses induced by variations in downhole conditions such as [12-13]:

- Change in mud weight after cement placement;
- Pressure increase due to gas production;
- Pressure integrity test;
- Stimulation treatments;
- Temperature Changes;

Two scenarios need to be distinguished; the above stresses can cause cement failure either in traction or compression depending on downhole conditions [14-15]. Traction or compression failure is caused by the pressure or temperature increment. If the cement is placed across a soft formation and subjected to a tangential stress which exceeds the cement tensile strength, this will cause radial cracks, and thereby cement traction failure. Cement compression failure may occur if the cement is placed between the two casings or across a hard formation and the radial stresses exceed the cement rupture strength [16]. Another important cause of the loss of zonal isolation is the formation of microannulus, which is caused by temperature or/and pressure decrement. This paper summarizes the implementation and evaluation of a new sealant system designed to overcome this problem by preventing the formation of a microannulus across the gas zone [17-18].

## Elastic, Expandable Sealant Cement System

The unique performance factors of this new sealant cement system are the mechanical parameters of the set cement. These are controlled by the system design and may be affected by the bottom hole static temperature. The mechanical parameters can be controlled independently of slurry density and properties. Based on the optimized, tri-modal, particle-composition theory, it encompasses all the advantages of an engineered particle-size distribution blend and the additional benefits of specific particles which can adjust the flexible properties and expansion capabilities of the set cement [19]. During the production life of a well, the cement sheath is exposed to varying stress fields as pressure and temperature fluctuate in the wellbore. These stresses can compromise the integrity of the cement sheath and affect its ability to maintain hydraulic isolation. Studies have shown that cement with a low Young's modulus and good expansion properties during the hardening phase is best for mechanical durability and resistance to stresses [20-21].

This system is adaptable to pressure and temperature changes, and the ability to expand improves sealing at the casing/formation interface. The addition of flexible material to the optimized blend plays an important role in increasing the flexibility of the set cement by decreasing the Young's modulus. The system applications focus on the need for zonal isolation in wells with severe changes in the downhole temperature and pressure, gas wells, high-pressure and high- temperature wells, plug-and abandon-applications, multilateral wells, and tectonically active environments or areas, where subsidence or compaction causes casing failure. There are four key cement mechanical parameters that must be determined to allow modeling the cement sheath behavior. These parameters are as follows:

- Compressive strength;
- Young's modulus;
- Poisson's ratio;
- Expansion capability;

## EXPERIMENTAL PROCEDURES

This study is based on laboratory testing of the improvements in the cement slurry and stone by using an elastic-expandable additive. Figure 1 shows the SEM images of the elastic-expandable additive. The specifications of the elastic-expandable additive are presented in Table 1. This section provides a detailed description of the key sample preparation and testing methods required for the determination of the mechanical behavior of the set cement.

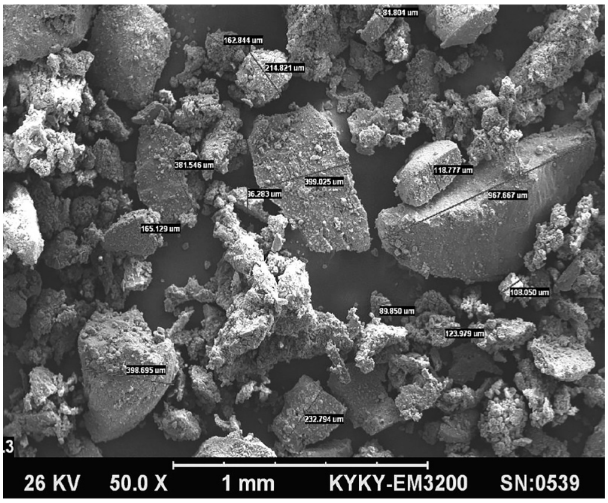

**Figure 1: SEM images of the elastic-expandable additive.**

**Table 1: Physical and chemical properties the elastic-expandable additive.**

| Physical and Chemical Properties | | | | |
|---|---|---|---|---|
| **Size (micron)** | **Specific Gravity** | **Humidity (%)** | **Color** | **Phase** |
| 75 | 1.1 | 4-5 | dark brown | solid |

## Sample Preparation

It is very important to prepare samples that are representative of the systems which are to be pumped. The systems must have zero free-fluid, which show no settling, and be free of air bubbles. The systems should be cured under downhole conditions. In many cases this is the bottomhole static temperature in the zone of interest, but in some cases, e.g. for steam injection wells, the curing may be done in two steps and at two different temperatures to simulate the parameters before and after steam injection. Ideally, a pressurized curing chamber should be used. However, if one is not available, then the slurry should be degassed under vacuum prior to cure to ensure that no air can enter through the sample. The curing period should be sufficiently long to enable the system to attain equilibrium. The systems to be tested are cured in molds of an appropriate size to allow correctly-sized samples to be prepared (Figure 2). For compressive strength, Young's modulus, and Poisson's ratio, cylindrical samples are required with a length to diameter ratio greater than 2.5. This length to the diameter ratio provides uniaxial compression conditions. For samples with smaller length to diameter ratios, the ultrasonic cement analyzer (UCA) would be overestimated, and correction factors are required. For length to diameter ratios of 1 (e.g., cube samples), the UCA can be overestimated by 15%. Typically, the samples which their diameters are equal to 68 mm, and their length is equal to 210 mm (length/diameter=3) have been used.

For tensile test measurements (Brazilian test), a length to the diameter ratio of 0.5 is required. Samples are first cured, and then the ends are cut perpendicular to the cylinder length using a rotating saw. In both operations, a continuous stream of tap water is used to cool the cutting surfaces and remove debris. The saw has two parallel blades and a special core holder which ensures that the ends are both parallel to each other and perpendicular to the cylinder axis. Throughout the preparation process, the samples must be kept saturated with water to avoid cracking related to drying shrinkage.

**Figure 2: Cylindrical rubber mold ready for placement in a pressure curing chamber.**

**Figure 3: Cement samples ready for the test.**

## Equipment

The main requirement for the measurements is a load frame, with controllable load and displacement rates, equipped with a force transducer. The press that was used in the current work was a computer-controlled electromechanical press which can be fitted with different load cells depending on the strength and the geometry of the materials to be tested. The axial and radial displacements were measured with linear variable-displacement transducers (LVDT) and a strain gauge cantilever respectively (Figure 4). The LVDT's directly measure the displacement of the loading platens to eliminate deformation of the load frame assembly, which may occur at high loads. The cantilever is placed at the middle of the sample height under test and measures the radial displacement in three directions. The output from the 3 LVDT's is averaged to give the radial displacement, and the output from the cantilever is axial displacement. The LVDT's and cantilever were calibrated against the displacement of the press crosshead which was calibrated annually against a standard displacement transducer. The amount of the set cement expansion can only be measured after being cured in special rectangular cylinders called expansion cell under downhole conditions (Figure 6), and it is then tested in an expansion apparatus (see Figure 7).

## Study Method of the New Cement System

The key advantage of the new cement is its ability to provide elasticity that can be adapted based on the well conditions. Another important advantage of the new system is its ability to provide flexibility characteristics along with the expansion. This study is based on taking the laboratory tests of the improvements in the cement slurry and stone by using the elastic-expandable additive at five concentrations. The conventional and new cement system 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 a uniaxial compressive strength tester equipped with axial and radial strain gauges (Figure 4). The elastic properties of the cement stone are determined based on the ISRM (International Society for Rock Mechanics) and ASTM (American Society for Testing and Materials) 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 (Figure 5). After the ends of the sample are cut flat, they are cooled down and kept saturated by immersing in the saturated water, and the loading rate is 4000 psi/min, which is the maximum loading rate of the available equipment. Table 2 shows the conventional cement recipe and 4 other recipes modified by different amounts of the elastic-expandable additive. The elastic-expandable additive is added to the cement slurry composition at four different concentrations (3.3, 6.6, 9.9, and 13.2% by weight of cement). Tables 3 and 4 show the measured properties of the cement slurries and stones, according to API RP 10B-2. Table 5 shows the elastic properties measured for the 5 samples.

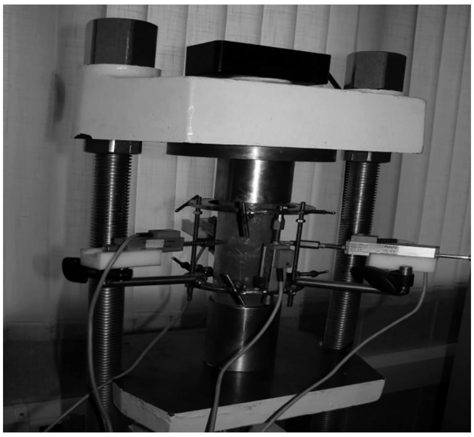

**Figure 4: Detailed view showing the LVDT's and cantilever.**

**Figure 5: API Cement pressure curing chamber.**

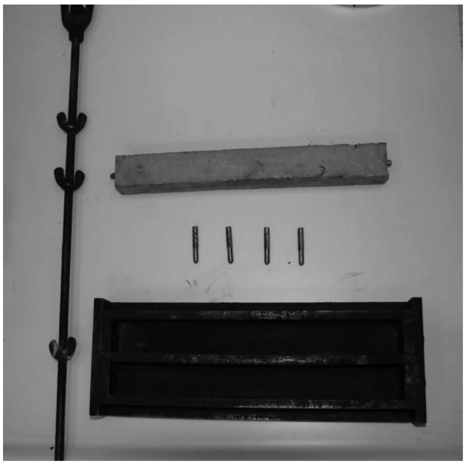

**Figure 6: Cement expansion cell.**

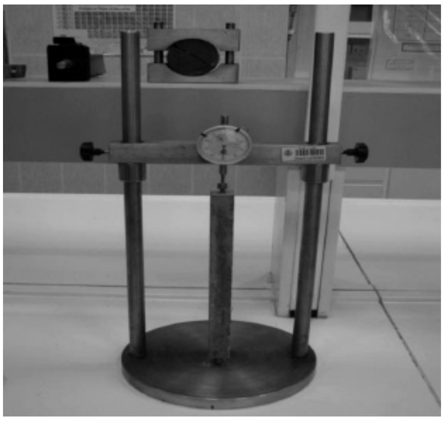

**Figure7: Cement expansion equipment.**

## Expansion Capability

Expansion is an increase in the bulk volume of the initial hardened cement. One of the main causes of the loss of zonal isolation is the formation of microannuli. An inner microannulus between the casing and the cement can be created, for instance, by the radial displacement of the casing, resulting from wellbore temperature or/and pressure decrement, especially when the wellbore pressure is decreased (change in drilling fluid density for example), once the cement has set. An outer microannulus between the cement and the casing can be generated by cement bulk shrinkage (the bulk volume shrinkage of conventional cement system is 3 to 4% of total volume). The formation of microannuli can be avoided by the use of expanding cement systems, which have been specifically designed to compensate for the inward radial displacement of the casing. This problem has been overcome after adding an expansion agent to the new cement system to seal off possible microannuli and tighten the cement against the casing and the formation. Bonding between the cement/formation and cement/casing increases with time due to the fact that expansion occurs after the cement has set. The concentration of the expansion additive required for a certain value depends on several factors. These include bottomhole static temperature (BHST), the nature of the surrounding formation, cement type, and slurry additives. Table 6 shows the expansion measurements made at 210°F for 5 samples.

## New Cement Properties

The new cement system was designed to be gastight to prevent gas migration, which could ultimately lead to an undesired sustained annular pressure. The fluid migration analyzer (FMA) test was performed to measure the tightness of cement slurry to gas or fluid migration during its transition from liquid to solid under downhole conditions. Figures 8 and 9 show the results of the gas migration test through the cement column (Slurry No. 5). The data from the static gel strength test has been used to calculate the pattern of cement slurry pore pressure changes, which was the input into the calculations used in the fluid migration analyzer apparatus. All realistic conditions in a wellbore; such as, curing cement slurry at downhole condition, fluid loss, slurry pore pressure decline, and finally the formation fluid migration through the cement column have been simulated in this apparatus. While the cement pore pressure declines (the (a) curve) and becomes close to gas-bearing formation pressure (Figure 8), the process of injecting gas to the cement is started. gradually eliminated due to the compressive and gel strength development in the slurry. In this test, the total gas volume migrated through cement has been equal to 80 ml per 5 hrs test period (Figure 9, (b) curve); thus the gas migration rate was nearly 2.67 cc/min. In accordance with the literature, the maximum gas migration rate should not exceed the 30 ml/min limit.

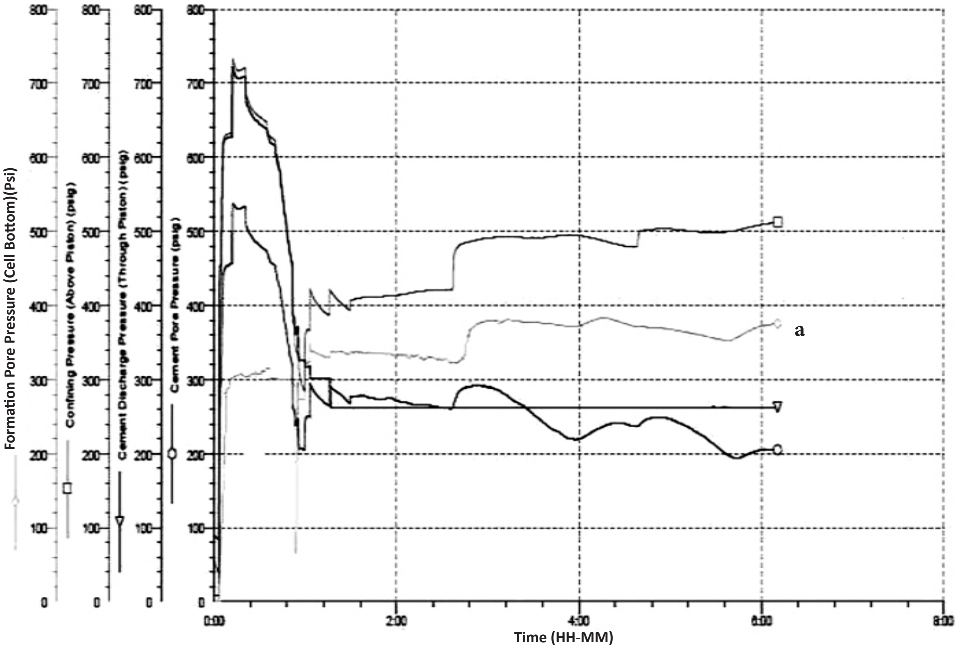

**Figure 8: The fluid migration test shows that there is no indication of gas migration in cement slurry No. 5.**

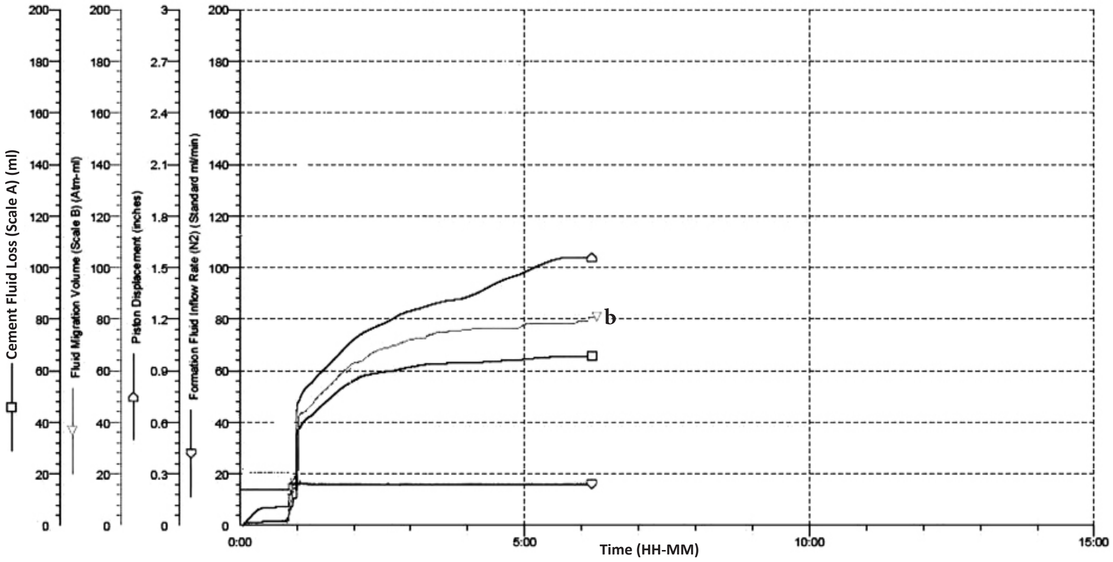

Figure 9: The fluid migration volume and cement fluid loss changes in cement slurry No. 5.

**Table 2: Cement slurry compositions.**

| Component | Unit | Slurry 1 | Slurry 2 | Slurry 3 | Slurry 4 | Slurry 5 |
|---|---|---|---|---|---|---|
| **Cement class E** | **lb.** | 110 | 110 | 110 | 110 | 110 |
| **Elastic-expandable 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 3: Cement slurry 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 hrs(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 |

**Table 4: cement slurries rheological properties.**

| Slurry number | $(\theta_{600})$ | $(\theta_{300})$ | $(\theta_{200})$ | $(\theta_{100})$ | $(\theta_6)$ | $(\theta_3)$ | 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 |

**Table 5: 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 |

**Table 6: Expansion set cement stones.**

| Sample | Expansion (%) | |
|---|---|---|
| | 24 hr | 3 Day |
| **1** | 0.0 | 0.0 |
| **2** | 0.04 | 0.09 |
| **3** | 0.10 | 0.19 |
| **4** | 0.15 | 0.25 |
| **5** | 0.16 | 0.30 |

## CONCLUSIONS

The stresses induced in the cement matrix through the deformation of the cemented casing can cause damage due to the variations in the downhole conditions. Appropriate mechanical properties of cement can reduce potential cement failure and debonding. High compressive cement is not always the best solution; however, the elastic cement is the appropriate approach. The new cement system has been examined in the lab and the following conclusions have been obtained:

- The new cement system is more ductile than the regular cement. As a result, the new cement system enhances cement resistance to stress cycling.
- The new cement system expands after placement in order to enhance the bonding between the casing and the formation.
- The new cement system has a low fluid loss, free water, and compressive strength compared to conventional systems.
- Increasing the concentration of elastic-expandable material in the new cement system reduces Young's modulus.
- The new cement system prevents gas migration and achieves zonal isolation.
- Increasing the concentration of the elastic-expandable material in the new cement system increases the Poisson's ratio and the expansion of the set cement.
- The lifetime of a well may be greatly improved by the selection of the most appropriate sealant.
- The key advantage of the new cement is its ability to provide the elasticity which can be adapted based on the well conditions.
- Another important advantage of the new system is its ability to provide flexibility characteristics along with the expansion.

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