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Self-healing efficiency of EVA-modified cement for hydraulic fracturing wells

Bin Yuan [a,*], Yuanguang Yang [a], Yongqing Wang [a,*], Kaimin Zhang [b]

[a] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China*
[b] *Cementing Branch Company of SINOPEC, Southwest Petroleum Engineering Corporation Limited, Deyang, Sichuan 618000, China*

HIGHLIGHTS

- EVA was used as self-healing agent to improve repair efficiency of oil well cement.
- Multiple evaluation methods were used to evaluate self-healing efficiency.
- EVA can improve the self-healing efficiency by mechanical and chemical reactions.
- The EVA-modified cement has excellent repetitive self-healing properties.

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ABSTRACT

During hydraulic fracturing, the cement sheath of oil wells experiences a huge pressure and alternating stress, and may crack due to its hard and brittleness. The cracks could lead to the transmission of formation fluids behind the casing and before the formation. A new emerging science on the self-healing cement provides solutions to the problem. In this work, the ethylene-vinyl acetate (EVA) copolymer was used as the self-healing agent to improve the self-healing efficiency of cement for hydraulic fracturing wells, and different methods were considered for evaluating the self-healing efficiency. The experimental results show that mixing EVA into oil well cement significantly decreases the fracture permeability and flow channels by melting flow-out and blocking, and markedly improves the broken bonding strength by mechanical and chemical bonding. The EVA-modified cement has excellent repetitive self-healing properties. When the EVA-modified cement is used, the working temperature should be higher than the softening temperature of EVA. The effect of pressure on self-healing effect is very small, and the self-healing observably increases with the increase in the temperature before 110 °C.

1. Introduction

Hydraulic fracturing is one of the effective measures for enhancing production in low-permeability reservoirs [1]. During the hydraulic fracturing process, however, enormous pressure and alternating stress cause make failure and affect the long-term integrity of cement sheaths because of the hard and brittleness of the sheaths [2]. Cracks and micro-annuluses are generated to provide channels for formation fluids [3]. In addition, the cement sheaths will lose the capability of protecting the casing strings and providing the intended zonal isolation [4], which will cause many serious problems, such as sustained casing pressure (SCP) and interzonal communication that could reduce the work life of wells [5,6]. Squeezing the cement and altering the mechanical properties of the cement compositions enable us to overcome these problems [6], but the cost and the technologies limit the advancements of these measures. Recently, another novel approach has been used to design cement compositions that are capable of self-healing when a cement sheath fails due to development of cracks or micro-annuluses [7–9].

The self-healing capability of the cement is achieved by several methods and by using self-healing agents, such as hollow fibers [10], microcapsules [11], expansive agents [12–15]and bacteria [16]. However, these methods and only the expansive self-healing agents are suitable for oil well cement because the working environment of a cement sheath usually has a high temperature and high pressure. Moreover, the drawback of these self-healing agents is that they cannot achieve repeated healing. Therefore, new agents need to be developed to improve the healing capacity of cement sheaths.

* Corresponding authors.
E-mail addresses: yuanbin19880118@126.com (B. Yuan), swpiwyq@163.com (Y. Wang).

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According to the previous research studies on polymer materials [10,17]. The ethylene-vinyl acetate (EVA) copolymer has the potential to improve the self-healing properties of cement sheaths because of its hot-melting property and expansibility in an alkaline environment. Especially, its hot-melting property is the key to the repetitive healing of cement sheath. Repetitive healing can repair cracks that are generated during construction after the completion of wells. Research studies have found that EVA improves the flexibility, deformability [18], flexural strength, and bond strength of cement sheath [19–21]. Therefore, EVA is superior to other materials in improving the self-healing properties of cement sheaths. However, it has never been reported as an agent for improving the self-healing properties of cement sheaths in oil wells.

To verify the self-healing efficiency of the EVA-modified cement, laboratory evaluation is required prior to field application. A variety of methods for evaluating the self-healing efficiency of including the permeability method, chloride diffusion method, bonding strength and compressive strength test, and conductivity test are found in the literature. The permeability method [22] tests the self-healing efficiency of a sample by measuring the change in the permeability of cement stone at different curing times. The chloride diffusion method [23,24] evaluates the efficiency of self-healing by testing the change in a sample during chloride diffusion. The bonding strength and compressive strength [25] method evaluates the self-healing efficiency by measuring the regained mechanical properties of a sample and comparing it with the original. The conductivity test [26] can nondestructively and continuously evaluate the self-healing efficiency by testing conductivity of an electrolyte solution in a through-hole.

The objective of this study is to evaluate the self-healing efficiency of the EVA-modified cement under the working conditions of oil wells. In this work, the fracture permeability, broken bonding strength, and conductivity tests were used to evaluate the self-healing efficiency of the EVA-modified cement; the microstructure of the cement was observed by using a scanning electron microscope (SEM); and the Fourier-transform infrared spectroscopy (FT-IR) and energy disperse spectroscopy (EDS) were used to analyze the self-healing mechanism of EVA. All of these mixing methods are based on the API standards [27].

2. Experimental details

2.1. Materials

The materials include API Class G oil well cement (Jiajiang, China), drag reducer (Chengdu, China), EVA LD 712.QE (ExxonMobil, Belgium), defoamer (Chuanfeng, China), filtrate reducer BSL100L (Chenhong, China), retarder (Chenhong, China), and water. The chemical properties of the cement and the characteristics of the EVA polymer are presented in Table 1 and Table 2, respectively. There are four types of cores—shale, siltstone, gritstone and mudstone—representing the four types of formations, and their size is 25.4 mm × 50 mm. The casing string is simulated by using steel columns (25.4 mm × 50 mm).

2.2. Samples preparation

Cement slurries were mixed according to the API standards [27] with a water–cement ratio of 0.44. The components of the cement slurry are presented in Table 3. Five cement samples were papered for each test. To mimic the working condition of cement sheaths in oil and gas wells, all the cement samples were cured in water at 90 °C and 20 MPa for 28 days by using a high-temperature and high-pressure kettle. Compressive strengths of the samples are presented in Table 3. The samples are cured for 28 days to reduce the effect of self-healing because of the hydration of the cement sample [28], as far as possible.

Table 2
Characteristics of EVA polymer powder.

Properties	Values
Vinyl acetate content (%)	9.70
Density (g/cm^3)	0.95
Tensile strength (MPa)	34.10
Elongation (%)	650.00
Particle diameter (mm)	0.91∼1.20
Vicat softening temperature (°C)	84.00

2.3. Experimental methods

For the permeability test, penetrating axial cracks were developed on the samples (25.4 mm × 50 mm) by using an electro-hydraulic testing machine, and the cracks divided the samples into two parts (Fig. 1). The permeability of the samples was tested by using a gas at a confining pressure of 3 MPa and a differential displacement pressure of 0.6 MPa. First, the initial fracture permeability of the samples was tested. Then the samples were cured sequentially in water at 90 °C and 20 MPa, and their fracture permeability was tested every three days.

The conductivity test [26] was chosen to evaluate the self-healing efficiency because it is accurate, nondestructive, and continuous during the test process. The schematic of the conductivity test device is shown in Fig. 2. To simulate a crack a through-hole was made on the sample by a mini glass bar before the cement slurry condensed. Then the sample was cured sequentially to 28 days. The sample was soaked in an electrolyte solution and taken out after 15 min. Then the conductivity of the through-hole was tested. After testing the original conductivity, sample was sequentially cured in water at 90 °C and 20 MPa, and the conductivity was tested every three days. The change in the conductivity reflects the change in the diameter of the through-hole. The conductivity becomes zero, when the hole is completely healed.

We developed a schematic of the device, as shown in Fig. 3, to evaluate the healing efficiency of cement–casing, and cement–formations and the efficiency of repetitive healing. We defined the tensile strength of the samples as broken bonding strength. First, the samples were made, and the cores and steel columns were butted with cement samples (25.4 mm × 25 mm). The samples were vertically placed in water at 90 °C and 20 MPa. Second, the samples were fixed in a core holder, and the test temperature was set at 90 °C. When the temperature reaches the temperature setting, the test starts. During the test, the motor rotates at 3 rpm/s, and the tensile strength was recorded and communicated to a computer by a pressure sensor. When the tensile strength becomes 0 MPa, the test will stop automatically.

To study the effect of the temperature and pressure on the self-healing efficiency of the EVA-modified cement, the curing temperature and pressure were set at 80–120 °C and 10–30 MPa, respec-

Table 1
Chemical composition of Jiajiang Class G oil well cement.

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	P_2O_5	TiO_2	K_2O	Na_2O	Loss on Ingnition
Content (wt%)	65.4	21.8	3.2	4.4	1.1	1.4	0.1	0.3	0.2	0.5	1.6