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Short Communication

An enhanced oil recovery polymer promoted microbial growth and accelerated microbiologically influenced corrosion against carbon steel

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ABSTRACT

Enhanced oil recovery typically relies on injection of seawater mixed with chemicals to increase reservoir pressure. A polymer such as partially hydrolyzed polyacrylamide (HPAM) is often added to increase viscosity. In this work, an oilfield biofilm consortium was found to utilize a commercial HPAM-based polymer. The polymer at 1000 ppm (w/w) promoted the growth of planktonic cells and sulfate reducing bacteria sessile cells in an artificial seawater medium during a 30-day incubation period in anaerobic vials. The polymer utilization led to 34.5% viscosity loss and more severe microbiologically influenced corrosion weight loss and pitting against C1018 carbon steel.

1. Introduction

After many years in operation, a reservoir's pressure dwindles. Enhanced oil recovery (EOR) is needed to continue oil production [1]. Seawater is typically injected along with other oilfield chemicals [2]. Water flooding brings microbes, nutrients and oxidants (e.g., sulfate) to the downhole environment, causing microbes to flourish [3]. In nature, microbes often live in communities and form biofilms to protect themselves against harmful environmental factors [4]. They can cause corrosion or accelerate the corrosion caused by other corrosive agents in the oil and gas industry and many other industries [5–10]. This is known as microbiologically influenced corrosion (MIC) [11–15]. There is a growing awareness of MIC after the 2006 Trans-Alaska Pipeline leak [16]. Without contamination, an oil reservoir is strictly anaerobic because the organic matters downhole consumed all the oxygen since geological times [17]. Oxygen is typically removed in the injection fluid to avoid oxygen corrosion of downhole tubing and downstream transport pipelines. In such an anaerobic environment, anaerobic microbes, such as sulfate reducing bacteria (SRB) flourish because seawater contains sulfate [18]. Other microbes such as fermentative microbes can also grow [19]. SRB generate biogenic H_2S, which causes reservoir souring [20]. Since EOR uses polymers which are organic molecules, it is necessary to investigate whether they can be utilized by downhole microbes and thus contribute to increased MIC.

Polymer flooding is one of the most efficient EOR technologies that started as early as the late 1950 s [21]. Adding polymers increases the viscosity of the injected fluid downhole, which helps to push out viscous crude oil for better oil recovery [21]. Xanthan gum is a polysaccharide [22]. It was a popular EOR polymer in the past, but this polymer is more readily utilized by downhole microbes [23], which is not surprising because it is widely used as a food additive. Partially hydrolyzed polyacrylamide (HPAM) is gaining popularity in EOR because it can tolerate high mechanical forces during water flooding [24,25]. In addition, HPAM is inexpensive [25]. However, HPAM also has a potential to be utilized by downhole microbes as nitrogen and carbon sources, which is a major concern to field operators [24]. Ma et al. found that a sulfate reducing bacterium utilized HPAM as a carbon source by hydrolyzing the amide group to carboxyl group, leading to loss of viscosity [26]. Bao et al. found that *Bacillus* spp. degraded HPAM. Their results showed that bacteria such as *Bacillus cereus* can utilize the amide group of HPAM as their nitrogen source, and the HPAM carbon backbone can be metabolized as an organic carbon source [27]. It is expected that a biofilm consortium can degrade HPAM more easily than pure-strain microbes because there are multiple microbial species in a consortium [28]. Li et al. found that HPAM was degraded to lower molecular weight fragments by a biofilm consortium containing diverse bacterial groups [24]. So far, there is a lack of literature data discussing the impact of the utilization of HPAM on MIC due to enhanced microbial growth.

In this work, a commercial HPAM-based polymer was tested to see whether it could be biodegraded by an oilfield biofilm consortium during a 30-day incubation period. Corrosion analyses and electrochemical measurements were performed to check its effects on the MIC of C1018 carbon steel. This is the first systematic study on the impact of

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microbial utilization of an EOR polymer on MIC.

2. Materials and methods

2.1. Microbes, culture medium, metal and chemicals

A corrosive oilfield biofilm consortium labeled as Consortium II was tested in this work. Its metagenomics data were disclosed previously, which indicated that the consortium contained SRB, biodegradation microbes and fermentative microbes [19]. The consortium was cultured anaerobically in 125 mL anaerobic vials (Wheaton Industries Inc., Millville, NJ, USA). An artificial seawater medium was used as the culture medium to grow the consortium [29]. Its composition (g/L) was: Na_2SO_4 3.917, NaCl 23.476, Na_2SO_4 3.917, KCl 0.664, $NaHCO_3$ 0.192, KBr 0.096, $MgCl_2{\cdot}6H_2O$ 10.61, H_3BO_3 0.026, $SrCl_2{\cdot}6H_2O$ 0.040, $MgSO_4{\cdot}H_2O$ 0.4, $CaCl_2{\cdot}2H_2O$ 1.469, tri-sodium citrate 0.5, CaSO4 0.1, K_2HPO_4 0.050, NH_4Cl 0.1, $Fe(NH_4)_2(SO_4)_2$ 0.1. Square coupons used in this work were cut from a C1018 carbon steel (AISI G10180) rod. The mass percentage composition of the carbon steel was: P 0.017, C 0.200, S 0.012, Mn 0.900, Si 0.044, Cr 0.061, Ni 0.044, Mo 0.018, and Fe balance [30]. Only the top surface area of 1 cm^2 was exposed on each coupon. The other surfaces were coated with an inert Teflon paint. Coupons were polished and cleaned before use according to previously reported procedures [31]. A commercial HPAM-based polymer (labelled as cHPAM in this work) was provided by Petronas. Other chemicals were purchased from Fisher Scientific (Pittsburgh, PA, USA) or Sigma-Aldrich (St Louis, MO, USA).

2.2. The impact of cHPAM on microbial growth

The culture medium and lab tools were sterilized in an autoclave at 121 °C for 20 min. The culture medium and stock solutions of other chemicals were sparged with filter-sterilized nitrogen (N_2) for at least 1 h to remove dissolved oxygen. The culture medium was supplemented with 100 ppm (w/w) L-cysteine as an oxygen scavenger to mitigate any possible oxygen ingress. cHPAM was added to the culture medium to reach a concentration of 1000 ppm as requested by Petronas. Five replicate coupons, 100 mL culture medium, and 1 mL seed culture were added to each 125 mL anaerobic vial in an anaerobic chamber. The initial pH of the culture medium was adjusted to 7.0 before inoculation. The biofilm seed culture was grown in the artificial seawater medium enriched with 3.5 g/L sodium lactate and 1 g/L yeast extract. It should be noted that a very small amount of organic carbon was introduced to each vial by the 1 mL seed culture upon inoculation. After inoculation, the initial planktonic cell amount in each vial was 10^6 cells/mL. The anaerobic vials were sealed and incubated at 37 °C without shaking. During the 30-day incubation period, a 0.3 mL broth was withdrawn each time from each vial to measure the planktonic cell count with a hemocytometer under an optical microscope at 400X magnification [32]. After 7, 14, 21 and 30 days of incubation, coupons were taken out for SRB sessile cell count using most probable number (MPN) method. Once a vial was opened, its incubation was terminated. The MPN method used the modified Postgate's B medium (Biotechnology Solutions, Houston, TX, USA) for SRB. The detailed procedure for the sessile cell enumeration was described before [4]. The viscosity was measured using a falling ball viscometer at 23 °C according to the reference [33]. After the 30-day incubation, scanning electron microscopy (SEM) (Model JSM-6390, JEOL, Tokyo, Japan) was used to observe biofilm morphology [31]. Confocal laser scanning microscopy (CLSM) (Model LSM 510, Carl Zeiss, Jena, Germany) was used to visualize live and dead cells in the biofilm on a coupon surface [34].

2.3. Corrosion analyses

Weight loss was measured using at least 6 coupons for every data point. The corrosion products and biofilms on coupons were removed

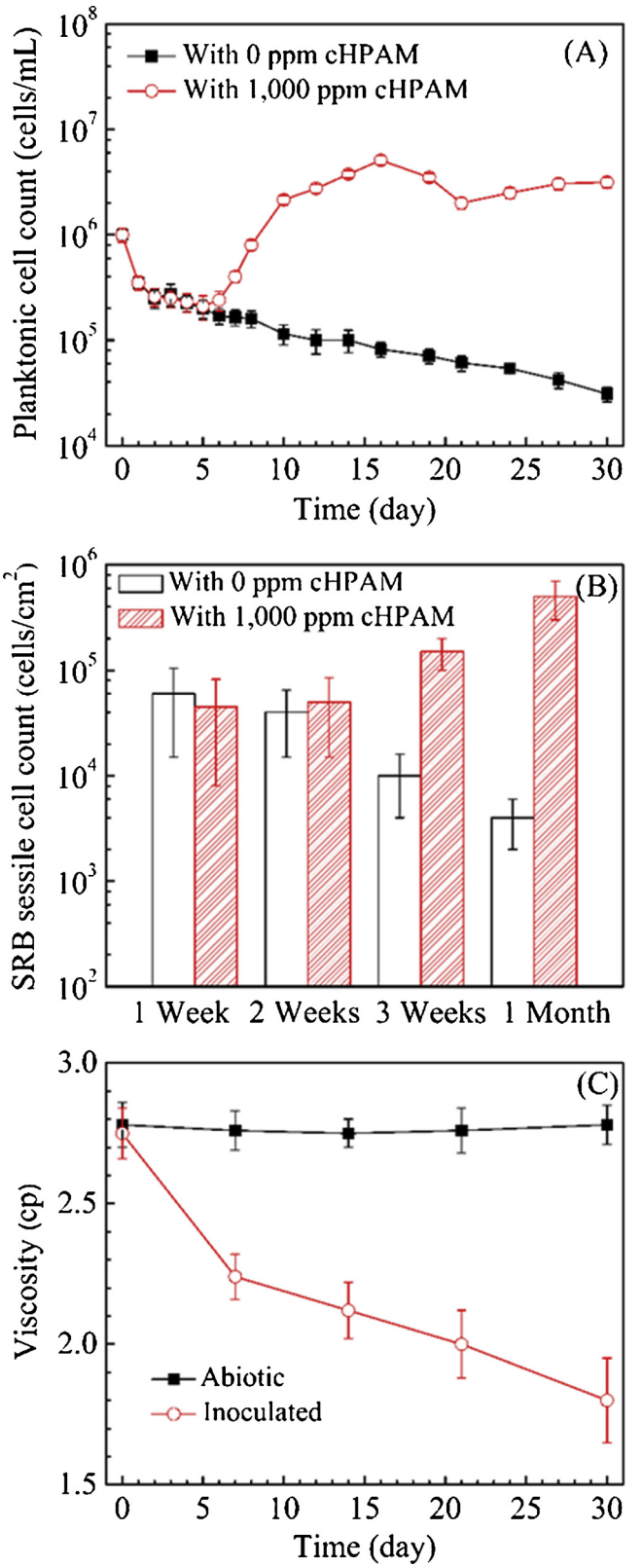

Fig. 1. Planktonic cell counts (A) and SRB sessile cell counts (B) in inoculated artificial seawater medium with and without cHPAM. (Error bars represent standard deviations from 4 independent samples.) Viscosities of the abiotic artificial seawater medium and inoculated artificial seawater medium, both with 1000 ppm cHPAM (C). (Error bars represent standard deviations from 3 independent samples.).