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Design of a novel alkaliphilic bacterial system for triggering biopolymer gels

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The use of microorganisms to trigger a delayed gelling reaction with curdlan biopolymer gelant was evaluated. The gel-triggering bacteria were strict alkaliphiles isolated from a soda lake. Using the alkaliphilic isolates to trigger gel formation, gelation time was inversely proportional to inoculum concentration and could be delayed up to 12 days after inoculation. The microbially triggered polymer system was injected into cores and then gelled *in situ*. Treatment of cores with the system decreased brine permeability by two to four orders of magnitude. Individual strains of the alkaliphiles had distinct effects on the polymer system, with respect to both gelling time and permanence of the polymer gel. These strain-specific traits may be exploited to design gelled polymer systems with desirable performance properties. *Journal of Industrial Microbiology & Biotechnology* (2000) **24,** 389–395.

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Introduction

Gelled polymers are widely used in oil production for permeability modification. Hydrated polymer gels are able to physically block fluid flow through permeable media such as reservoir rock or sand, and thereby reduce permeability of treated zones to reservoir fluids. Near-wellbore treatments of polymer gels can be used in production wells with high water cut for water shutoff [14,17] and in wells with a gas cap as a method of gas shutoff [4]. In-depth placement of gelling systems can be used to block water channels in waterflooded reservoirs and improve drive fluid sweep efficiency [10]. These types of gels also impart preferential relative permeability of the porous media to oil [8,15].

Application of a typical gelled polymer system involves injection of a low-viscosity gelant into the target zone of a reservoir, followed by some delayed reaction which initiates the formation of a high-viscosity phase or gel. Delaying the gelation reaction until after the desired placement gives these systems a unique advantage for in-depth penetration. In-depth placement of these low-viscosity gelant solutions can result in effective permeability modification after gelation [2]. Polymers used in this type of process must therefore be interconvertible, through a delayed reaction, between a low-viscosity gelant form and a high-viscosity gelled form.

Curdlan-type biopolymers, described first by Harada *et al.* [5], exhibit a pH-dependent transition between a gel and a soluble state. Curdlan is a pH-sensitive glucan biopolymer produced by the soil bacterium *Alcaligenes faecalis* var. *myxogenes*. Many characteristics of curdlan-type biopolymers make them desirable for permeability modification. Curdlan is water-soluble and can be mixed as a low-viscosity gelant in alkaline solutions of pH greater than 10. At pH levels below ca. 9, curdlan forms an insoluble gel. Gelled curdlan is a very strong gel and is stable in neutral or acidic solutions. These gels are insoluble to most organic solvents, and stable to heating to 90°C [11]. Curdlan-type biopolymers are injectable in alkaline solutions as low-viscosity gelants, and form rigid gels upon neutralization. Despite these inherent advantages, the delayed pH shift required to initiate gel formation poses some technical challenges for accurate placement and gelation in a reservoir.

Gelation of curdlan-type biopolymers can be triggered by neutralizing the alkaline gelant [3]. Neutralization was achieved in coreflood experiments using a layered process of injecting alternating slugs of alkaline-solubilized polymer gelant and an acid [18]. Injecting both acid and alkaline-solubilized polymer gelant into a porous medium results in gelation of the polymer at any point where mixing occurs. This layered process, when applied for in-depth gel placement in a reservoir, would be a major challenge. The ability to control the propagation of two or more slugs through the formation in close proximity without co-mingling, followed by mixing the slugs at the critical predetermined location in the reservoir is highly unlikely. The lack of thorough knowledge of the down-hole differential flow of the two components renders this process too complex to control.

Controlling the application and performance of these curdlan-type polymer gels, as well as other gelled polymer systems, can be improved substantially by engineering a novel internal triggering mechanism. Incorporating an internal trigger into these systems enables the process to be designed such that all components can be mixed together above-ground and injected as a single slug without having to rely on complex *in situ* mixing of components.

The pH-dependent transition that curdlan-type polymers exhibit when they go from a soluble state to a gel state makes this polymer gelant especially amenable to gelation by acid-producing bacteria. The strong alkaline conditions (pH >10) required to solubilize curdlan-type biopolymers is outside the growth range of most bacteria and imposes that only extreme alkaliphiles could be suitable for triggering the reaction. This report describes the development of a microbially driven gelled polymer system that uses alkaliphilic bacteria as an internal biological trigger to cause formation of a polymer gel. Placing the gelling reaction under the

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control of acid-producing bacteria created a reliable internal triggering mechanism. Bottle tests showed that varying inoculum concentration could control gelation delay time. The microbially triggered gelled polymer system was injectable into porous media and caused effective permeability modification after delayed gelation. It was further found that after gelation, the polymer gel could be removed slowly using a specific degrader strain, which can allow the design of polymer gel systems with a controlled lifetime.

Materials and methods

Bacteria and culture conditions

Acid-producing alkaliphilic bacteria used in this study were enriched from sediment samples collected in a dry alkaline lakebed in the Soda Mountains of the Mojave Desert, California. Enrichment cultures were incubated anaerobically at 30°C in trypticase soy broth (TSB) with 5% NaCl and pH 11.5 using procedures described by Hungate [6]. Hungate tubes were sealed with butyl rubber septa and headspace gas was replaced with O_2-free N_2. Alkaliphilic isolates were picked from streak plates of the enrichment cultures on pH-adjusted (pH 11.5) tryptic soy agar (TSA) with 5% NaCl added. Plates were incubated anaerobically at 30°C in an atmosphere of 5% CO_2, 10% H_2, and 85% N_2.

Strains SL-1A and SL-2A were chosen for further study because they grew more rapidly under the culture conditions than other strains. Briefly, strain SL-1A was a Gram-positive, facultative coccobacillus with complex nutritional requirements. Growth of strain SL-1A occurred from pH 7.5 to 11.5 and was optimal between pH 8.5 and 10.5. Strain SL-2A was a Gram-variable, anaerobic, spore-forming bacillus. Growth of strain SL-2A occurred from pH 7.5 to 11.0 and was optimal between pH 8.5 and 10.5. Both strains were mesophilic and halotolerant. Anaerobically both strains grew using glucose as a sole carbon and energy source and produced acidic fermentation products which lowered medium pH to near neutral when the organisms were grown in batch cultures. Gas production was not detected from glucose fermentation in liquid or solid (agar) medium.

Preparation of polymer gelant

Polymer gelant was prepared by dissolving 0.5% curdlan biopolymer (Wako Chemical USA, Richmond, VA) into deionized water with 0.1 N KOH and 24 mM Na_2CO_3. Microbial nutrients were added per 100 ml: Hutner's mineral base [16], 2 ml; $K_2HPO_4{\cdot}3H_2O$, 0.3 g; glucose, 1.5 g; soytone, 0.5 g; NaCl, 3.0 g. The final pH of the gelant was adjusted to 11.2–11.5 with concentrated KOH or concentrated HCl. Viscosity of the polymer gelant was measured on a Brookfield viscometer, Model LVDV-11 +CP, using CP-42 cone and plate. The gelant viscosity was 5.6 cP at 22°C.

Gelation assay

Bottle tests were conducted to determine if acid-producing alkaliphilic microorganisms can cause delayed gelation of alkaline-soluble curdlan biopolymer. Polymer gelant samples of 5 ml were aliquoted into Hungate tubes. Gelant samples were inoculated with a dilution series made from 48-h stock cultures of each strain. All polymer gelant samples received a total inoculum of 50 μl from a dilution series of alkaliphilic strain SL-1A, SL-2A, or SL-1A/SL-2A in combination; samples were prepared in duplicate. Polymer samples were incubated at 25°C and time of gelation was recorded when a firm gel formed in each sample. Bottle tests were maintained at 25±5°C for 2 years and long-term stability of the microbially gelled polymer was monitored visually.

During experimentation using alkaliphilic bacteria with curdlan biopolymer, some microbially gelled polymer samples softened or liquefied after long-term incubation. To determine if the agent which caused liquefaction was a diffusible product, dialysis tubing was used to separate polymer samples from the gel-triggering bacteria. Approximately 75 ml polymer gelant was placed in a 125-ml bottle as the bulk phase. Dialysis tubing was prepared according to Sambrook *et al.* [13] and a 10-ml aliquot of polymer gelant was loaded into the tubing (6–8 kDa mol. wt. cutoff, Spectra/Por (Los Angeles, CA)). In duplicate test bottles, the bulk phase was inoculated with strain SL-1A or strain SL-2A from 48-h stock cultures. Dialysis tubing containing gelant was placed into bulk phase gelant after inoculation. One negative control test bottle was prepared without inoculum. Test bottles were incubated anaerobically at 30°C and polymer samples were monitored visually for gelation and polymer liquefaction for 8 months. At the end of the monitoring period the dialysis tubing was removed from each sample bottle, cut open, and the polymer gel was removed. The firmness of all polymer samples, from both the bulk phase and inside the dialysis tubing, was recorded.

Permeability modification

Packed columns: Clear PVC pipe was cut into lengths of approximately 30 cm and fitted with solid PVC pistons which sealed against the inside of the pipe with recessed O-rings. Pistons were line drilled, tapped for connections on the back side, and covered with 250-mesh steel screen on the face. Columns were packed with glass oxide beads or unwashed river sand, and pistons were confined in the columns with mechanical clamps. Columns were evacuated and then saturated with 0.5% NaCl brine. Saturated columns were mounted horizontally and brine was made to flow through the column using a hydraulic head gradient maintained from a 5-l tank elevated above the packed column. The pressure head gradient across the packed column was measured directly from manometers connected to inlet and outlet ports of the column. Two pore volumes (PV) of brine was flowed through each column from a constant hydraulic head of approximately 1.2 m. Initial brine permeability of each column was measured prior to treatment using Darcy's law:

$$k = \frac{q\mu L}{A\Delta P} \qquad (1)$$

where k is permeability, q is the rate of fluid flow, μ is fluid viscosity, L is length of the flow path, A is cross sectional area of the flow path, and ΔP is the pressure drop across L.

Columns were preconditioned prior to treatment injection. The pH of the interstitial fluid was stabilized by preflushing the column with thymolphthalein-tagged (thymolphthalein; colorless↔blue at pH 9.4↔10.6) 0.02 M CO_3^{2-} buffer, 3% NaCl, at pH 11.5. Inoculum for the gelant solution was 2.0 ml each of SL-1A and SL-2A from 24- to 48-h stock cultures per 100 ml gelant. One PV inoculated gelant solution was injected into each column at 5.0 ml/min. Samples of both uninoculated and inoculated polymer gelant were collected and sealed in Hungate tubes concurrent with polymer injection into columns. Columns and accompanying gelant samples in Hungate tubes were incubated at 23°C. Gelation of the polymer system was monitored in Hungate tubes during the

incubation period. After gelant in all accompanying Hungate tubes formed firm gel, a hydraulic head gradient was restored to the column and posttreatment permeability was measured with 0.5% NaCl brine using Equation 1. Effluent pH was measured to assess the pH shift by the microbial trigger.

Berea sandstone cores: Berea sandstone blocks (Cleveland Quarries, Amherst, OH) were cut into cylindrical cores approximately 3.8 cm diameter by 26.6 cm length. Cores were evacuated (74 cm Hg) for 2 h, then flushed with degassed 0.5% NaCl. Brine-saturated cores were encased in neoprene sleeves and placed inside stainless steel Hassler-type coreholders. After loading cores into coreholders, 2 PV brine was pumped through each core at 2.0 ml/min. Fluid was driven at a constant rate with an Isco syringe pump. All pressure measurements were recorded on a chart recorder using a Validyne Model DP15 pressure transducer and a Validyne Model CD15 carrier demodulator. Initial permeability of each core was measured with 0.5% NaCl brine using Equation 1.

Berea cores were preconditioned by preflushing them with 2 PV thymolphthalein-tagged 0.02 M CO_3^{2-} buffer at pH 11.5 prior to treatment. Polymer gelant solution was inoculated with 1.0 ml each SL-1A and SL-2A per 100 ml gelant from stationary phase stock cultures. One PV inoculated polymer gelant solution was injected into each core at 2.5 ml/min. Cores were shut in for 7 and 10 days after polymer gelant injections for cores C-01 and C-02, respectively, and incubated at 27°C. Samples of both uninoculated and inoculated polymer gelant were collected and sealed in Hungate tubes concurrent with polymer injection. Headspace gas was replaced with N_2 and samples were incubated beside the cores. Shut-in pressure of the cores and gel formation in accompanying Hungate tubes were monitored during the incubation period.

After the incubation period, flow was established through each core with 1 PV brine and posttreatment permeability was measured. The residual resistance factor, F_{RR}, was calculated for each core using the equation:

$$F_{RR} = \frac{\left(\frac{q}{\Delta P}\right)\text{pre} - \text{treatment}}{\left(\frac{q}{\Delta P}\right)\text{post} - \text{treatment}} \quad (2)$$

where q and ΔP are steady-state effluent rates and pressure drop across the core, respectively. Core effluent pH was monitored during preflush and polymer injection, and during displacement of the first PV during posttreatment flow to assess the pH shift by the microbial trigger. Samples of core effluent were examined by phase contrast microscopy for viable bacteria and subcultured in TSB. Polymer samples in Hungate tubes were monitored visually for 2 months. Cores were shut in and stored at 23–28°C for approximately 1 year following polymer gel treatment to assess

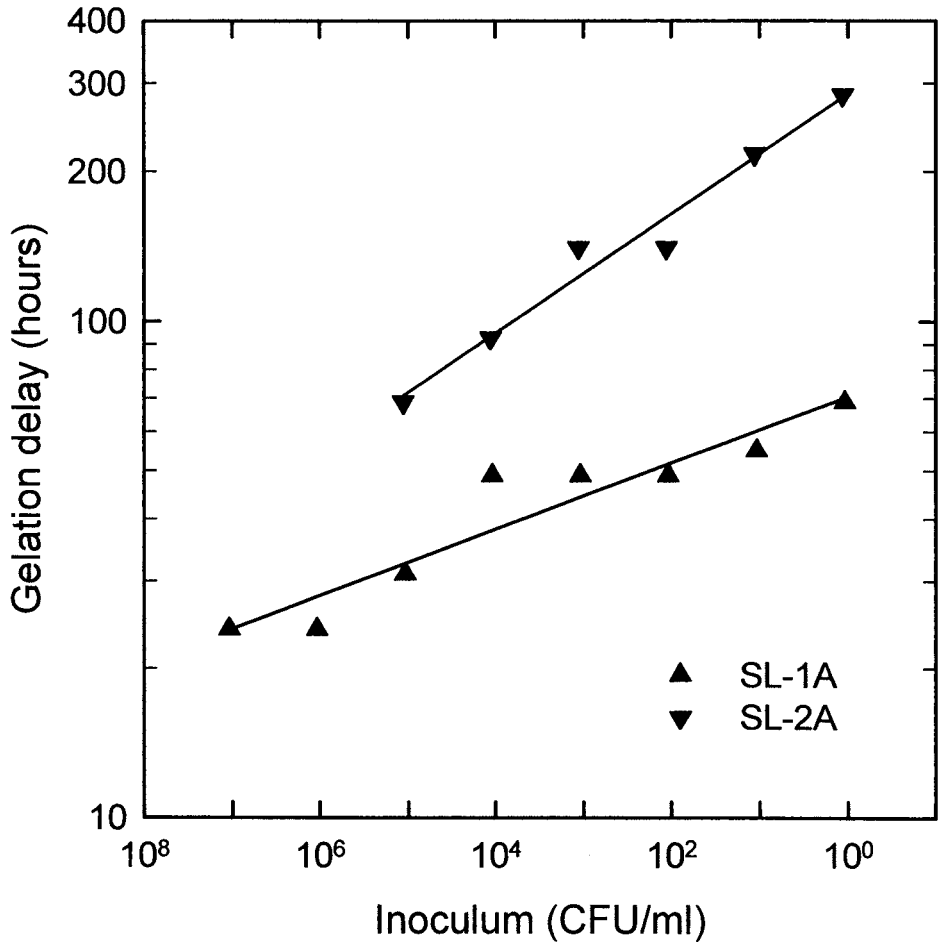

Figure 1 Gelation delay time of the polymer gelant system as a function of inoculum concentration. Samples were incubated anaerobically at 25°C. Time recorded was when firm gel formed.

Table 1 Permeability modification in porous media by microbially gelled 0.5% curdlan biopolymer

Core	Media type	Dimensions (cm)		Porosity (%)	Permeability (mD)	
		Length	Diameter		Initial	Post-treatment
B-01	Glass beads	28.9	1.5	35.0	33,900	7.7
B-02	Glass beads	28.9	1.5	39.9	19,200	174.1
N-09	Sand	20.8	5.2	37.5	19,100	24.4
N-10	Sand	15.0	5.2	37.8	5,910	3.5
N-11	Sand	17.5	5.2	32.2	3,680	2.5
C-01	Berea sandstone	26.6	3.8	23.0	852	3.0
C-02	Berea sandstone	26.7	3.8	22.8	904	4.9

long-term stability of the microbially gelled polymer in sandstone cores. Long-term brine permeability measurements were made of core C-01 at 77 and 384 days posttreatment, and of core C-02 at 404 days posttreatment.

Results

Gelation assay

Curdlan biopolymer gelant was initially transparent with an amber color. The first visual sign of gelation after inoculation was a noticeable increase in viscosity without a color change. In this "soft" gel stage the gelant remained transparent. The soft gel flowed in the culture tubes as they were inverted. The final stage of gelation involved a loss of transparency and a color change from amber to white. At this "firm" gel stage the polymer maintained rigid form and would not flow when the culture tube was inverted.

The time after inoculation that firm gel formed in each sample tube with SL-1A or SL-2A is shown in Figure 1. Gelation occurred at almost exactly the same times for samples co-inoculated with SL-1A/SL-2A as for samples inoculated with SL-1A only (data for co-inoculated samples not shown). The maximum gelation delay of samples inoculated with strain SL-1A was 69 h at a calculated initial cell concentration of approximately 1 CFU/ml. Gelation delay time

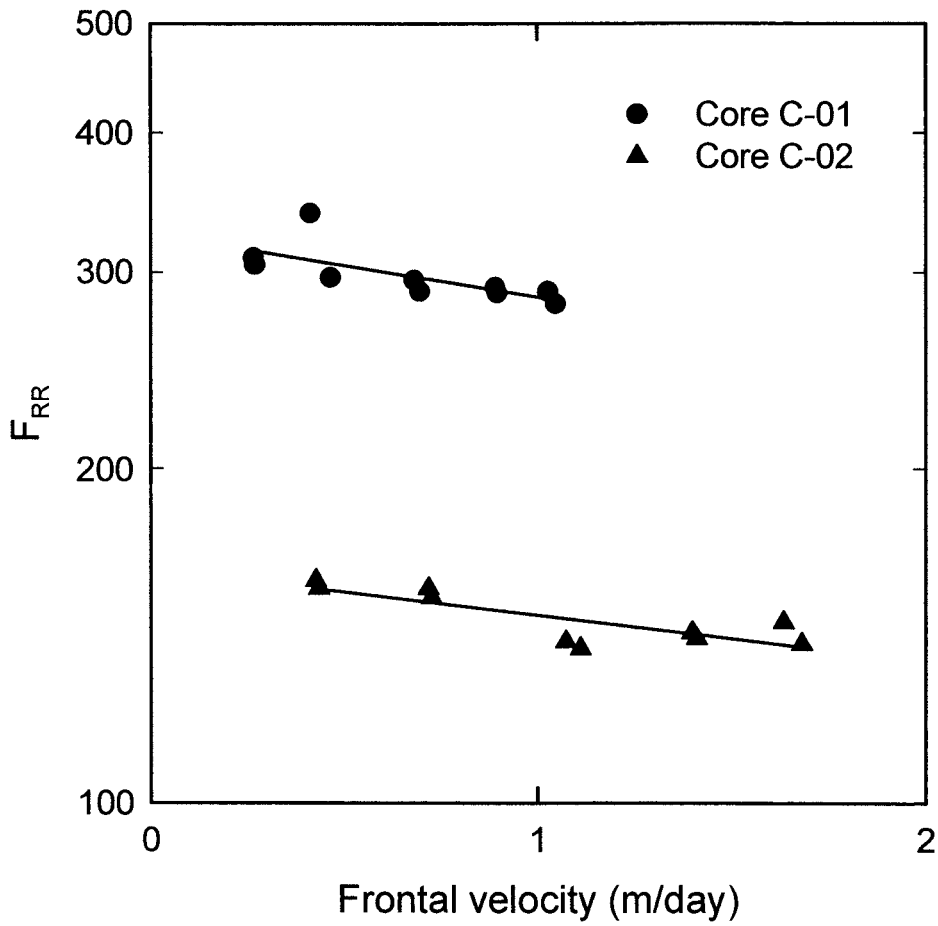

Figure 2 Permeability modification in Berea sandstone cores after treatment with microbially gelled 0.5% curdlan biopolymer. The residual resistance factors (F_{RR}) (ratio of flow before and after treatment) decrease slightly as the frontal velocity increases, indicating that the gelled polymer exhibits slight shear thinning.

for samples inoculated with strain SL-2A extended to 285 h at a calculated initial cell concentration of 1 CFU/ml. Polymer gelant control samples, which received no inoculum, formed soft gel after approximately 35 days. Gelant samples receiving inoculum beyond extinction in the dilution series (calculated zero cells in the inoculum) also formed soft gel after 28–40 days. The samples receiving no cells, both control and dilution beyond extinction, did not progress to the firm gel stage even after 2 years.

Stability of the gelled polymer samples was monitored for 2 years. After approximately 3 months incubation, samples receiving inoculum containing strain SL-1A began to soften and liquefy. The liquefaction was nonuniform within individual samples, and large globules of firm gel remained in most liquefied samples. Liquefaction was limited exclusively to samples that had formed firm gel after receiving inoculum containing strain SL-1A. No liquefaction was observed within 2 years in any samples inoculated with strain SL-2A only. No syneresis was observed in the gelled polymer samples over the 2-year period.

When dialysis tubing was used to separate gel-triggering bacteria from samples of the gelant, inoculated samples formed firm gel after 2 to 3 days incubation. The uninoculated control sample did not form firm gel. After 10–15 days of incubation, the bulk phase of samples inoculated with strain SL-1A liquefied. After 8 months incubation, all samples were examined. In bottles inoculated with strain SL-1A, the bulk phase which had received the inoculum was liquefied, but the polymer inside the dialysis tubing remained firm, indicating that the agent causing gel softening was dialyzable (i.e., an enzyme). Liquefaction did not occur in samples inoculated with strain SL-2A only.

Permeability modification

Packed columns: Physical parameters of the packed columns are shown in Table 1. Effluent pH from columns B-01 and B-02 climbed to 11.3 after injection of 1.0 PV of thymolphthalein-tagged carbonate buffer, indicating that there was not significant buffering in the glass-bead-packed columns. Sand-packed column N-09 also had little buffering capacity; the effluent was clear and pH stabilized at >10 after injecting approximately 1.5 PV preflush. By contrast, effluent from sand-packed columns N-10 and N-11 acquired a dark amber tint after injection of approximately 0.8 PV preflush, which we concluded was caused by soluble organic material in the sand. Cores N-10 and N-11 also had much greater buffering capacity, and approximately 4.5 to 5.0 PV preflush was injected into cores N-10 and N-11, respectively, before effluent pH reached 10. All inoculated gelant samples collected in Hungate tubes during column injections formed firm gel in 2–3 days incubation. When flow was restored through columns after treatment, column effluent from B-01 and B-02 was approxi-

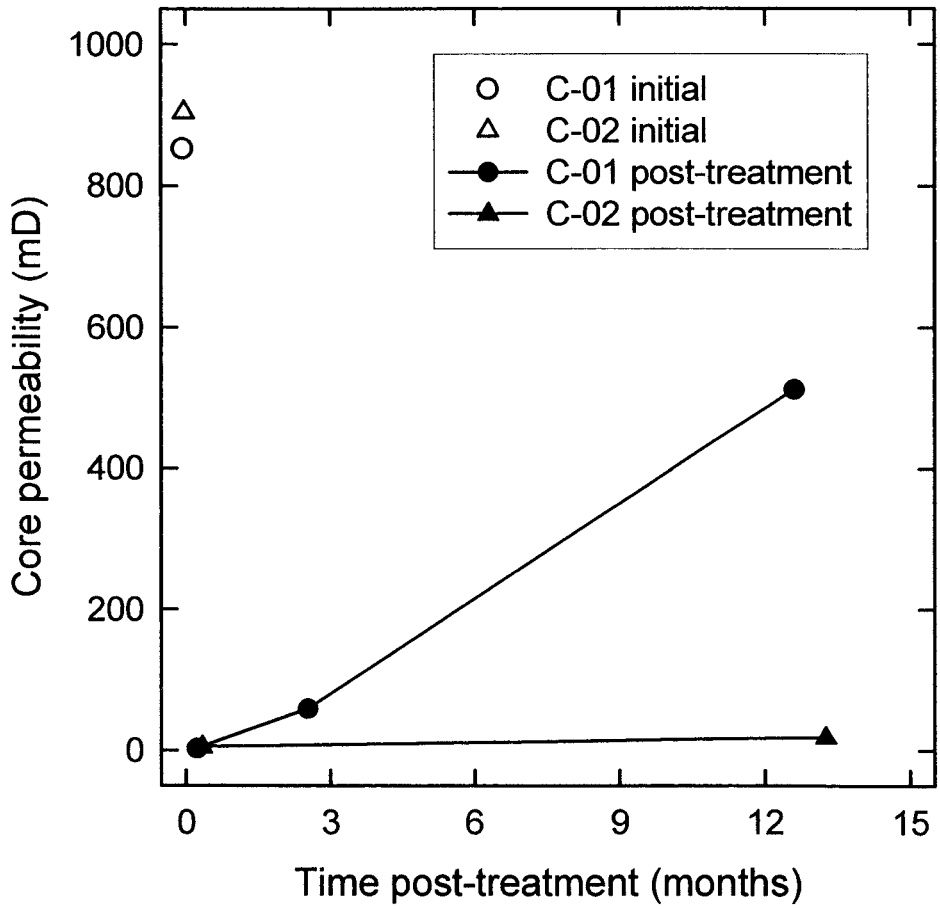

Figure 3 Permeability measurements of cores C-01 and C-02 were repeated periodically after treatment to assess the long-term stability of the microbially gelled polymer system in Berea sandstone cores. Strain SL-1A, which caused slow degradation of the polymer gel in other experiments, could not be cultured from fluids from core C-02.

mately pH 6.0, indicating the microbial trigger had lowered the pH of the gelant by more than 5 pH units. Effluent from columns N-09, N-10, and N-11 was pH 7.8, 8.8, and 9.2, respectively. Pre- and posttreatment permeability of the columns are shown in Table 1.

Berea sandstone cores: Physical parameters of the cores are shown in Table 1. During preflush the effluent pH of cores C-01 and C-02 reached 11.4–11.5 after displacement of approximately 2 PV. The pH of core interstitial fluid was stable at 11.4–11.5 during polymer gelant injection and until the cores were shut in. All inoculated polymer gelant samples in Hungate tubes accompanying core C-01 gelled after 2 days of incubation. Gelation of polymer samples accompanying core C-02 occurred more slowly than with core C-01, with gelation delay times of 5–12 days. Uninoculated control polymer samples did not form a firm gel during 2 months incubation.

Shut-in pressure for both cores was 5 to 10 psi at the end of the incubation period. Since the isolates did not produce noticeable gaseous fermentation products in culture, the source of the pressure buildup is not known. Small amounts of gas may have been produced by fermentation or CO_2 may have been formed from carbonate as a result of the pH shift. When the cores were opened after incubation, fluid pressure of 25–35 psi ΔP was necessary to initiate flow through them. The pH of core effluent samples was measured in the first PV of flow after incubation to assess pH modification by the microbial trigger. Cores had an initial pH of 11.4–11.5 at the time they were shut in. In core C-01, effluent from the core was decreased to pH 7–8 after microbial gelation. Effluent pH after treatment of core C-02 was decreased to around 8.4. Permeability of the cores was decreased by more than 99% after treatment with microbially gelled polymer (Table 1). When F_{RR} values (Equation 2) are plotted against frontal velocity of the fluid flow, Figure 2 shows that microbially gelled curdlan exhibits slight shear thinning. Nonetheless, F_{RR} range from near 150 to 300 at frontal velocities up to 1–2 m/day.

The microbial trigger took longer than expected for core C-02 and gelant samples were examined for inoculum viability. Gelant and core effluent samples were examined by microscopy and enrichment culturing. All samples examined showed that strain SL-1A was not viable in the gelant used in coreflood C-02. The gelled polymer in Hungate tubes accompanying core C-01 remained a firm gel for approximately 1 month and then began to soften and liquefy. A sample of the solubilized polymer was viewed by phase contrast microscopy and found to have high-density growth of a strain resembling SL-1A. Hungate tubes accompanying core C-02 were incubated under similar conditions for 2 months and showed no visible signs of polymer degradation. Long-term stability of microbially gelled polymer in the cores is shown in Figure 3. The permeability of core C-01 increased to over 60% of the initial pretreatment value after 1 year of incubation. Core C-02, which did not contain viable cells of strain SL-1A, did not show a similar increase in permeability during long-term incubation. Brine permeability of core C-02 increased to only 2.0% of the initial pretreatment value over 1 year.

Discussion

Gelled polymer systems currently available rely on a delayed chemical process or *in situ* mixing of reactants to cause *in situ* gelation of an injectable polymer gelant. This study examined creating an internal triggering mechanism for a gelled polymer system by placing the gelation reaction under the control of acid-producing bacteria. The microbially driven gelling system offers some distinct advantages over many of the other gelled polymer models. Gelation of curdlan-type biopolymers is controlled by a pH shift and requires addition or production of an acid. McCool *et al.* [12] reported that [uninoculated] gelant samples injected into sandpacks, Berea sandstone, Baker dolomite, or J-Alpha grainstone, failed to gel after incubation of up to 60 days. We have also observed in independent polymer adsorption studies with glass beads, sand, and crushed Berea sandstone, that interactions with core matrix material do not cause gelation without the gel-triggering microorganisms. In this study, acid-producing microorganisms provided a direct mechanism to drive the gelling reaction. The triggering microorganisms were mixed with the gelant before injection, which simplifies injection and placement. Also, the rate of acid production by a growing culture of microorganisms begins slowly and then increases exponentially as the culture grows. Therefore, gelation can be delayed a number of hours or days during placement and then rapidly triggered to form a gel.

The gelation assay demonstrated that gelation time can be controlled with a microbial trigger, and delayed considerably by starting with a light inoculum. The strain-specific rate of acid production also influences gelation time, as shown in Figure 1. Strain SL-1A produced acid at a faster rate than strain SL-2A, which caused shorter gelation times in samples inoculated with strain SL-1A. Under the conditions of the gelation assay, the gelation delay ranged from less than one day to more than 11 days. It is reasonable to expect that gelation could be delayed even longer by increasing the buffering capacity of the gelant solution. More buffering capacity in the gelant would increase gelation times by requiring that more acid be produced before the triggering pH-shift occurred. Buffering capacity of the reservoir rock or soil in which the polymer system is injected could be a significant contributor in controlling the final gelation time as well. Other factors which may exert significant influence on the rate of the triggering reaction include the type of fermentable substrate, and environmental factors, such as salinity and temperature of treatment zone, that influence rates of microbial growth or metabolism. Actual gelation times should be evaluated on a site-specific basis to account for differences in environmental conditions. The microbial trigger appears to provide a direct and controllable mechanism to drive the gelation reaction under a variety of environmental conditions.

We observed that strain SL-1A caused polymer degradation in the gelation assay. Although gelled curdlan biopolymer is resistant to biodegradation by most bacteria, some *Bacillus* spp. have been described which have β-1,3 glucanase activity and can degrade the gelled polymer [1,7]. Also, β-1,3-D-glucanase activity can be polymer specific. For example, a glucanase produced by the fungus *Ganoderma tsugae* was active against laminarin, an extracellular β-1,3-D-glucan produced by fungi, but had no activity against the bacteria product β-1,3-D-glucan, curdlan [9]. The slow and/or incomplete degradation of the gelled curdlan polymer by alkaliphilic strain SL-1A indicates that enzymes produced by this bacterium may have limited catalytic activity on gelled curdlan. The slow degradation of the polymer gel may be desirable for some applications in designing gel polymer systems with a finite lifetime in the environment.

All of the packed columns and corefloods demonstrated that the microbially gelled polymer system was effective in reducing permeability and blocking fluid flow. Treatment with the microbial polymer system consistently decreased permeability by two to four orders of magnitude. The pressure gradient required to initiate flow through Berea sandstone cores, approximately 100 to 130 psi/m, indicates that the polymer formed a rigid gel *in situ* that effectively sealed the matrix from fluid flow. The long-term stability of the Berea sandstone cores indicate that the individual alkaliphilic strains cause quite different effects with the polymer system. These differences can be exploited to engineer polymer systems for specific applications. Strain SL-1A caused more rapid gelation and slow removal of the polymer gel. Applications requiring temporary permeability modification and having short injection times might be suited for triggering with strain SL-1A. Triggering the gelation reaction with strain SL-2A produced a longer delay before gelation and no noticeable degradation of the polymer after gelation. Strain SL-2A is well suited for applications where a long delay is needed for deep placement in a formation, or applications where long-term stability of the gel is desired. In addition, spores formed by strain SL-2A should transport well in porous media and survive brief exposure to hostile conditions, such as shearing, heat extremes, and nutrient starvation, that may accompany deep injections in petroleum reservoirs.

The use of gelled polymer systems has increased significantly in the last decade in the petroleum industry as oil production from depleted reservoirs declines and costs of disposing of produced water increase. Development of a bacterial trigger for a gelled polymer system advances biotechnology into a new area in petroleum production, the science of gelled polymer systems. The microbially gelled polymer system explored in this study represents the first polymer system to use microbial metabolism as a triggering agent for a polymer gelant. This novel system is environmentally friendly and offers significant technical advantages over existing gelled polymer systems. This study demonstrated that microbial systems can be designed as *in situ* triggers for gelled polymer systems.

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