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Review

Shallow penetration conformance sealants (SPCS) based on organically cross-linked polymer and particle gels—An overview

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Abstract: This review summarizes some of the recent advances related to shallow penetration conformance sealants (SPCS) based on cross-linked polymer nanocomposite gels. The cross-linked polymer nanocomposite gels formed a three-dimensional (3D) gel structure upon contact with either water or oil when placed at the downhole. Therefore, the cross-linked polymer nanocomposite gels offer a total or partial water shutoff. Numerous polymeric gels and their nanocomposites prepared using various techniques have been explored to address the conformance problems. Nevertheless, their instability at high temperature, high pressure, and high salinity down-hole conditions (HT-HP-HS) often makes the treatments unsuccessful. Incorporating inert particles into the cross-linked polymer nanocomposite gel matrices improves stability under harsh down-hole conditions. This review discusses potential polymeric nanocomposite gels and their successful application in conformance control.

Keywords: shallow penetration conformance sealants; water shutoff; cross-linked polymer gels; silica nanoparticles; particle gels; conformance control

1. Introduction

Hydrocarbon extraction from reservoirs is always accompanied by excessive water production, which is one of the most severe issues in the industry to date [1–6]. Such water production significantly impacts the oil wells' economic life and causes other potential problems of sand production, scaling, and corrosion of the pipelines [7,8]. The problems include leaks in the casing, water coning, and direct communication from the injector to the producer through fractures [9–15]. Numerous techniques have been exploited to address the water production issue successfully, and each of the methods has its own merits and drawbacks [16–19]. One such method was to squeeze cement into the formation and shut off the water production of the wellbore. Squeezing the cement operation was an efficient treatment in many cases, but there were significant limitations, too. One such drawback was that it required complete drilling out of the cement left in the wellbore, and this process could be time-consuming and costly [20]. Also, the cement in the formations can be damaged during the drilling-out process; hence, the seal over the offending zones is conceded, allowing the water to continue flowing into the wellbore [21,22].

The other treatment type involves using polymer gel sealants to plug the offending zone [23–25]. During the last two decades, polymer gel systems have been the most effective tools to control excessive water production. During the last decade, organically cross-linked polymer (OCP) gel and their nanocomposite systems were among the most successful treatment systems for water shutoff [8,26–29]. These potential sealant systems offer various advantages, including easy pumping into the wellbore and the rock matrix. After the squeeze of the formulation into the formation, the fluid becomes a 3D gel that plugs the treated zone [30]. More importantly, the sealant system can be used effectively for several years, but the only drawback is that the treated zone should be isolated from the productive zones [31,32]. Also, if the sealants enter the production zone, it could potentially damage either the permeability or completely shut off the hydrocarbon zone [33]. Therefore, it is essential to use the isolation technique, which sometimes is not feasible because of the configuration of the wellbore or can be costly [34]. Nevertheless, it is crucial to control excessive water production, and this should be achieved by any means. Polymers and their nanocomposites are found to be promising candidates for various industrial applications [6,10–12,35–68]. This review paper discusses a method that uses polymer gel sealants with fluid-loss control additives and non-cement particulates that can limit leakage into the formation [69]. A typical sealant is composed of (1) an organically cross-linked polymer, (2) a fluid-loss control polymer, and (3) non-cement inert particulates to provide leak-off control. Once the filtrate, the porosity fill-sealant, is inside the rock matrix, the system is thermally activated, forming a 3D gel structure that efficiently seals the targeted formation [70–72]. After the sealant formulation is squeezed, the bore-well conditions activate the polymeric formulations to crosslink. **Figure 1** shows the cased hole and perforated wellbore producing at high water cut from multiple zones [8]. Once the SPCS system arrives at perforations, a squeeze pressure is applied so that the sealing polymer filtrate leaks off into the matrix with a controlled, shallow penetration. After the system is set up, the excess SPCS system in the wellbore is washed/jetted out.

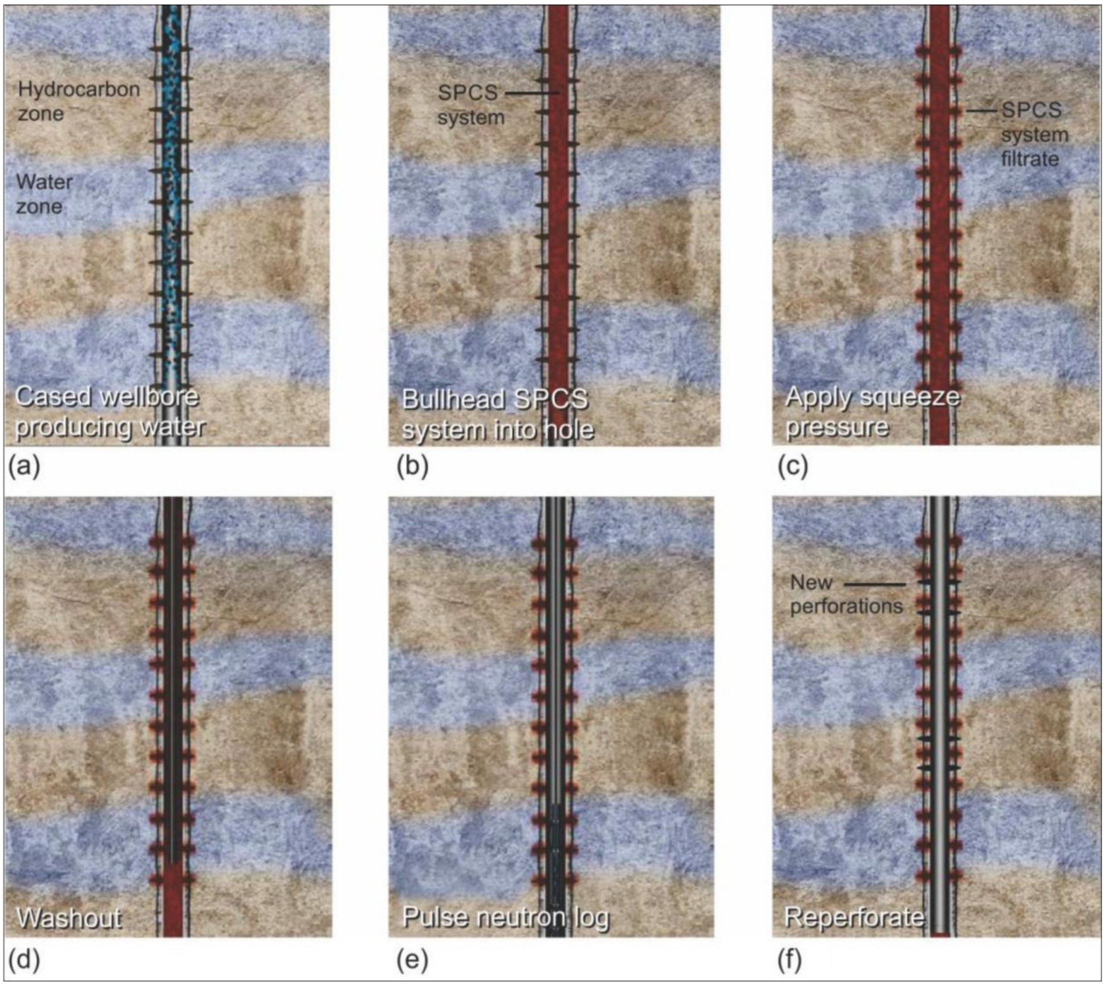


Figure 1. A typical sealant system (shallow penetration conformance sealant, SPCS) application. **(a)** cased hole and perforated wellbore producing at high water cut from multiple zones; **(b)** the SPCS system is bull-headed across all perforations; **(c)** once the SPCS system arrives at perforations, a squeeze pressure is applied so that the sealing polymer filtrate leaks off into the matrix with a controlled, shallow penetration; **(d)** after allowing the system to set up, excess SPCS system in the wellbore is washed/jetted out; **(e)** pay zones with economic hydrocarbon potential are identified with additional diagnostic tools (i.e., pulsed neutron logging tool); **(f)** new perforations are added with conventional perforation guns in the identified hydrocarbon-producing zones, bypassing SPCS [8].

2. Organically cross-linked porosity fill sealants

The sealant system is conventionally either polyacrylamide (PAM) or a copolymer of acrylamide (poly(acrylamide-co-t-butyl acrylate, PAtBA)), cross-linked with organic cross-linkers such as polyethyleneimine (PEI) [25,70,73–75]. The system's temperature range is from 40 to 400 °F (**Figures 2–5**) [76]. The borewell's temperature initiates the crosslinking process of the sealant formulation [77,78]. The cross-linking rate of the polymeric formulations depends on various factors, including the well's temperature, salinity, pH, polymer, cross-linker, and concentrations [79]. The significant advantages of the sealant systems are as follows:

- Due to the low viscosity of the polymeric formulation (20 to 30 cP), the solution can be easily injected deep into the formation without hydrolysis or precipitation. However, the chrome-based system tends to hydrolyze and precipitate at higher pH and elevated temperatures [80].

- Sufficient pumping times are required to properly place the polymeric formulations at high-temperature wells before the system forms a 3D-gel structure.
- Effective water and unwanted gas shutoffs depend on the gel's strength to resist drawdown pressure inside the formations to stop water and gas flow. The PAM-PEI systems provide sufficient strength to withstand differential pressures of at least 2600 psi.
- The overall thermal stability of the PAM-PEI gels is up to 400 °F (204 ℃).
- Moreover, the PAM-PEI sealant systems are not sensitive to formation fluids, lithology, and heavy metals. This system has been used globally in various applications, and Vasquez et al. summarized laboratory data and several case histories for both water and gas shutoffs [81].

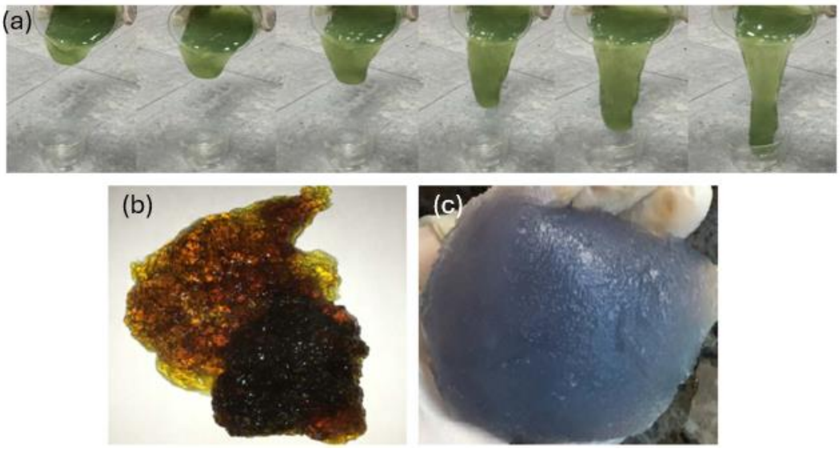


Figure 2. (a) Pre-crosslinked polyacrylamide gel; **(b)** and **(c)** cross-linked polymer gels with PEI at 150 ℃ [82].

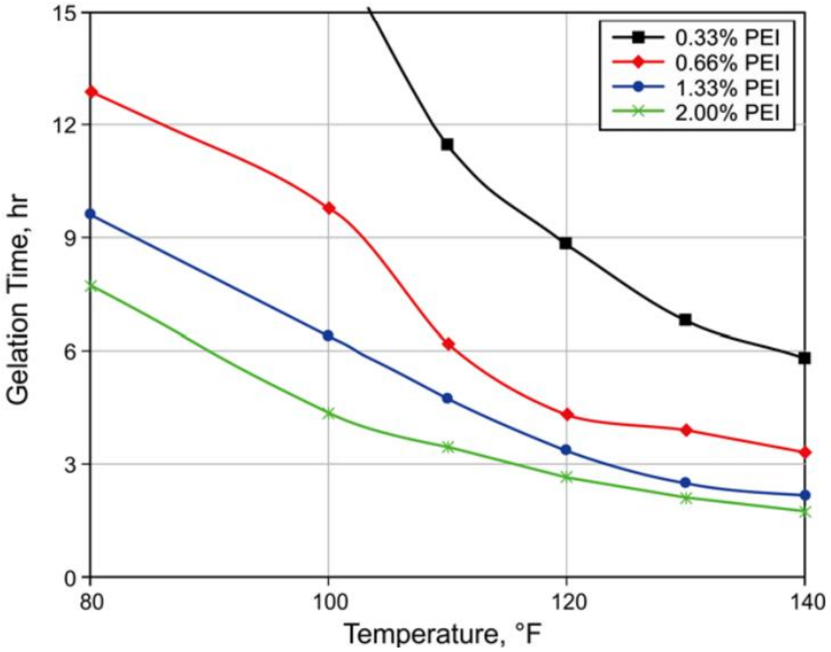


Figure 3. Gelation time of 5 wt.% of polyacrylamide in 2.0 wt.% of KCl with different PEI concentrations [81].

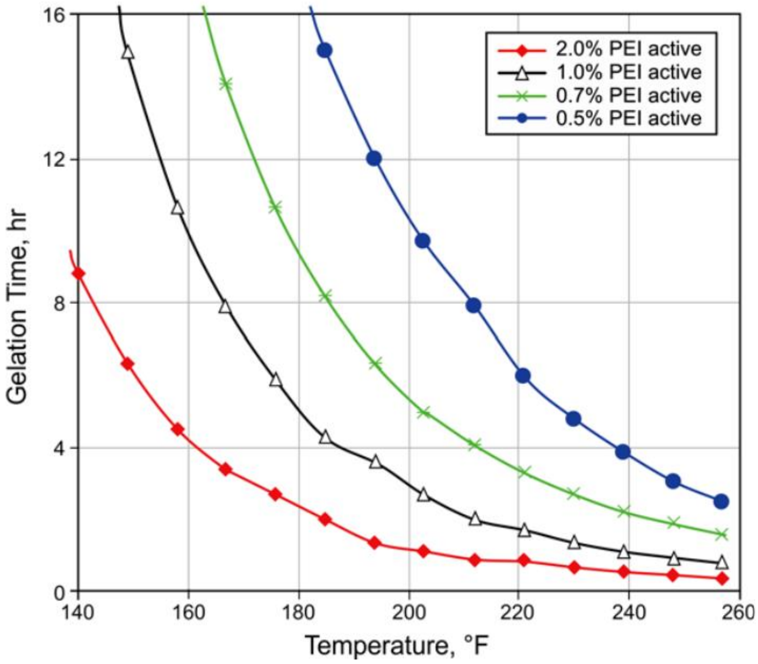


Figure 4. Gelation time of 7.0 wt.% of PAtBA in 2.0 wt.% of KCl with different PEI concentrations [81].

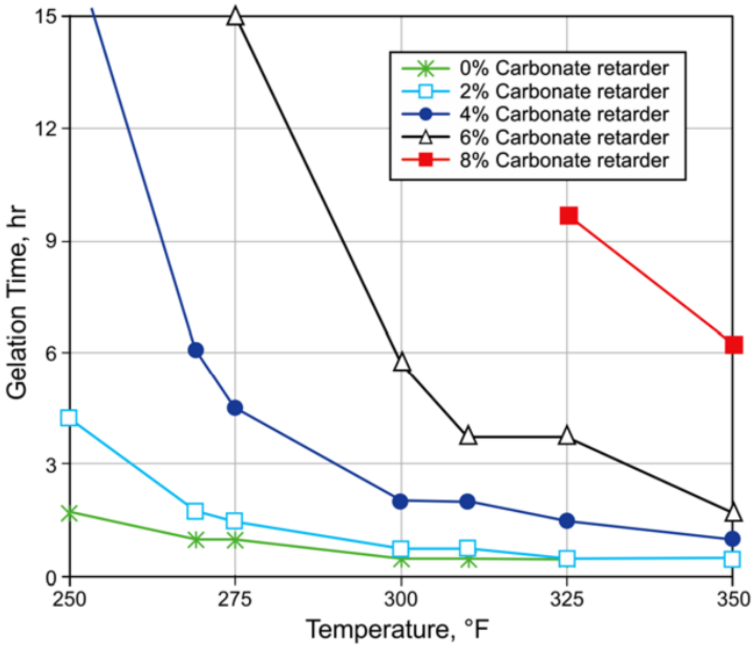


Figure 5. Gelation time of 7.0 wt.% of PAtBA with 0.66 wt.% of PEI and 2.0 wt.% of KCl with varied carbonate retarder concentrations [81].

2.1. Fluid loss control polymer

Polysaccharide-based biopolymers and their cross-linked gels (**Figures 6–9**) are usually added to the system for leak-off control to obtain a controlled, shallow penetration into the rock matrix [83–87]. Additionally, this polymer adds suspension properties to the inert solids present in the SPCS system formulation [88,89].

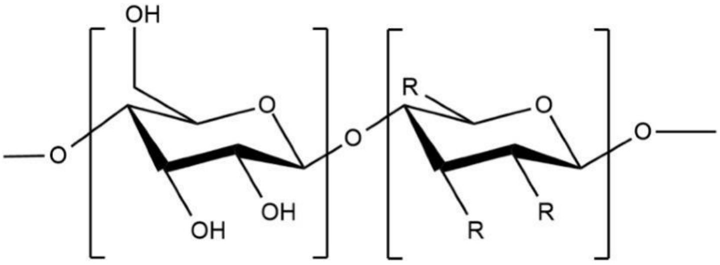


Figure 6. Chemical structure of Polysaccharide [84].

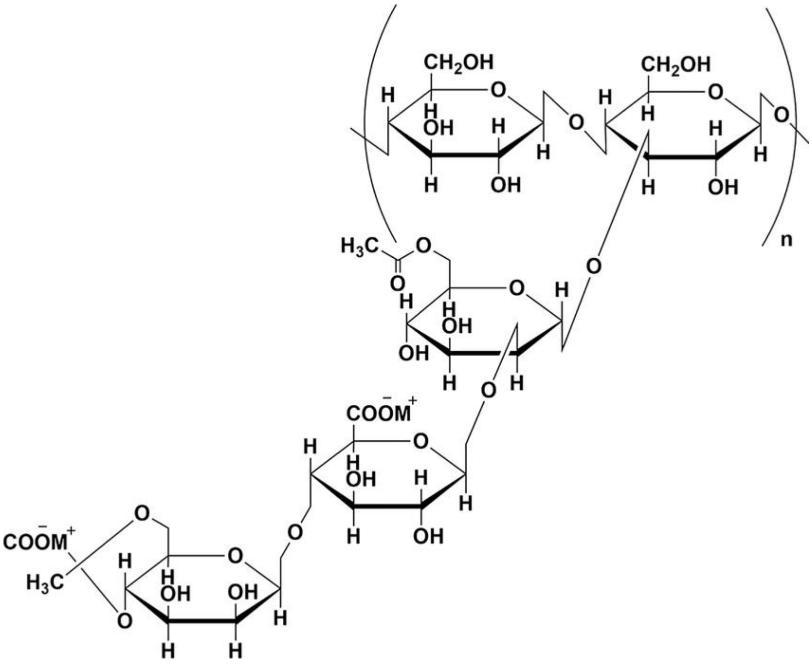
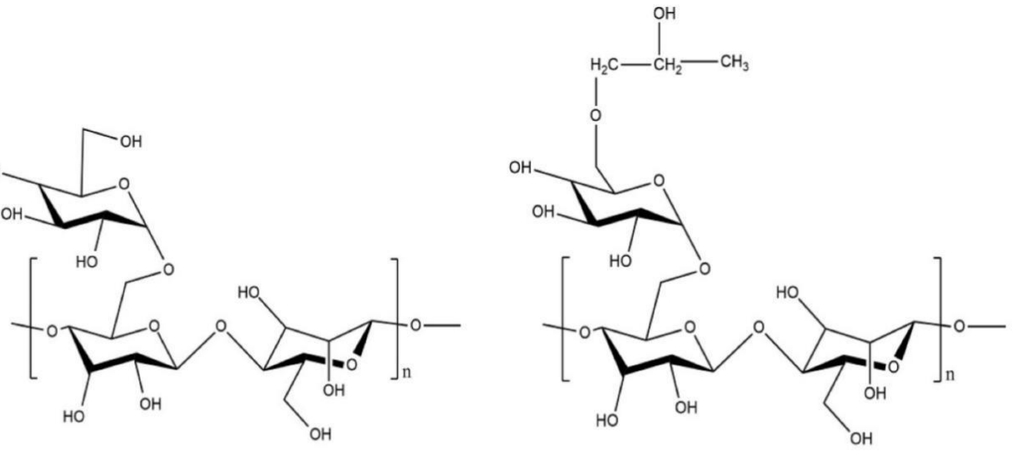
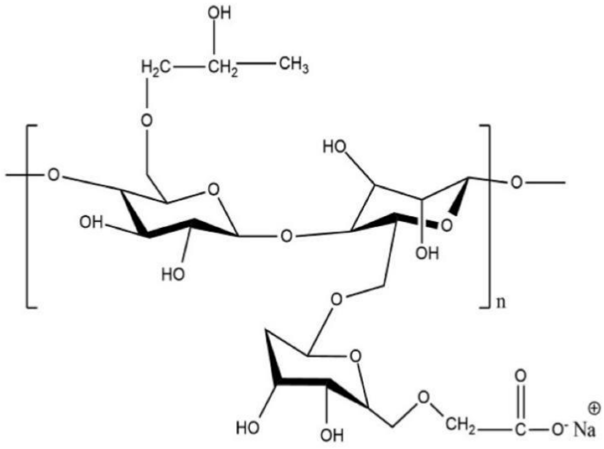


Figure 7. Chemical structure of Xanthan Gum [90].

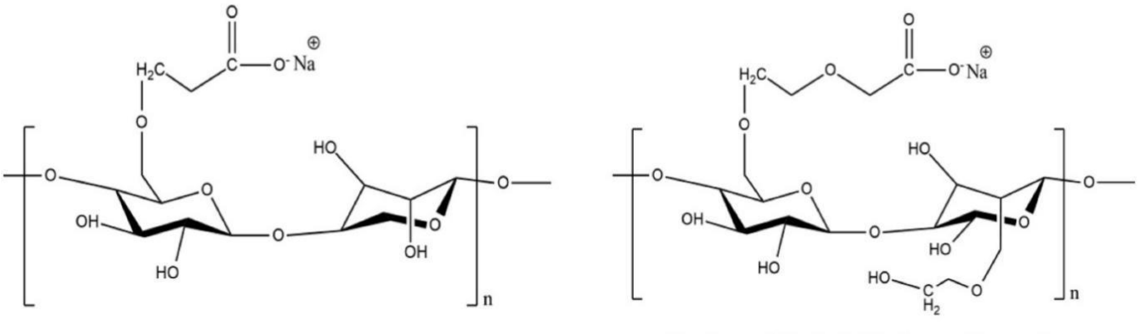


Guar

HydroxyPropyl Guar Gum (HPG)



CarboxyMethyl HydroxyPropyl Guar (CMHPG)



CarboxyMethyl Cellulose (CMC)

CarboxyMethyl HydroxyPropyl Cellulose (CMHEC)

Figure 8. Chemical structures of Guar and Guar derivatives [84].

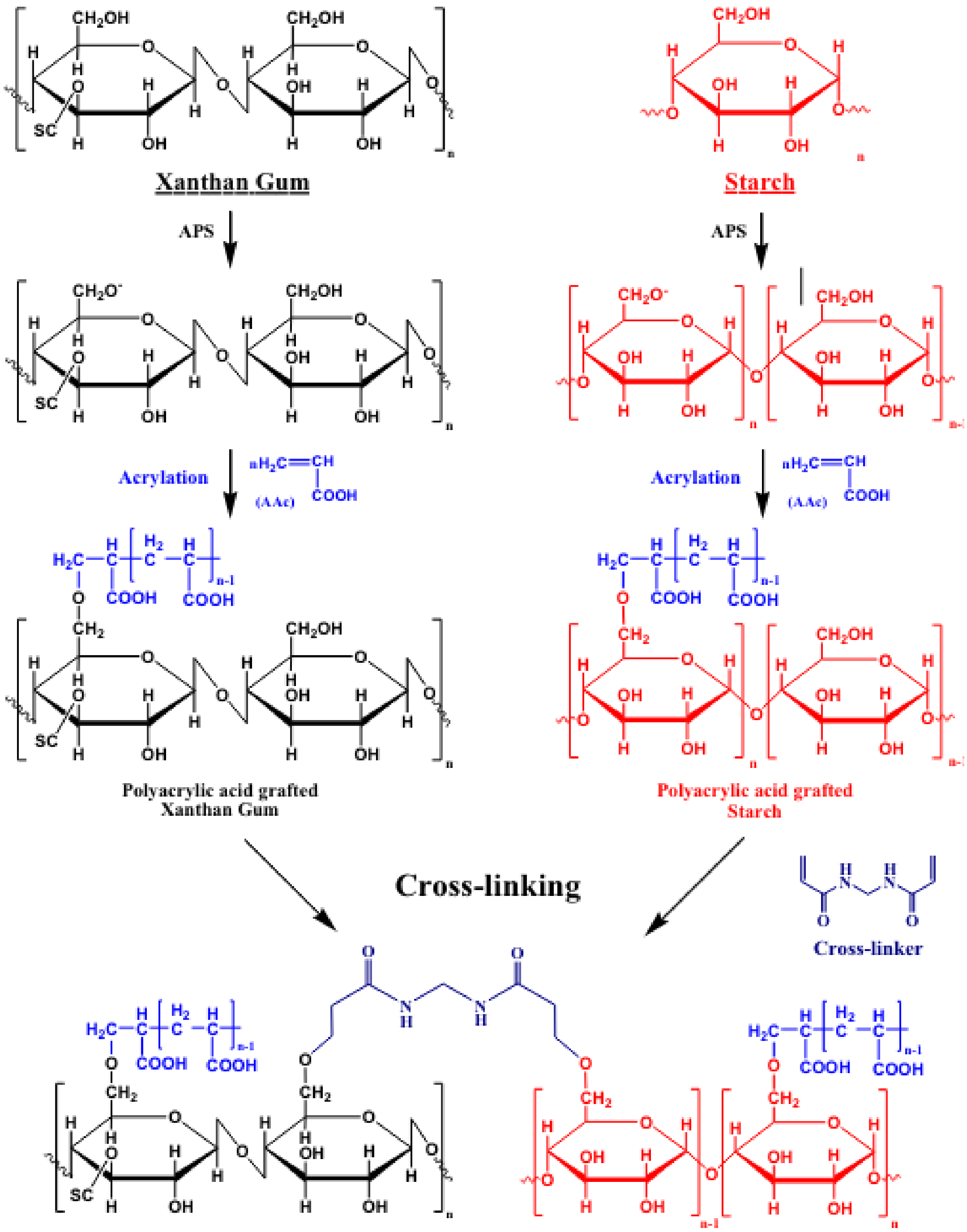


Figure 9. Chemical structures of Xanthun gum and starch and their respective cross-linking reactions [91].

2.2. Inert particulates

Inert particulates are added to the SPCS system for fluid-loss control [92,93]. These particulates synergize with the polysaccharide-based biopolymer to provide improved leak-off control. Various inert particulates, such as silica nanoparticles or cross-linked polymer gel-modified particulates, have been extensively employed to control fluid loss without changing the activation time of the sealant system. For most applications, silica flour [94] is used as the inert particulate (**Figures 10** and **11**); however, in some cases, nanosized calcium carbonate particulates [95] have been used (**Figure 12**) [96]. The major design criteria for the potential sealant systems are the gelation kinetics of the polymeric formulation for given down-hole conditions, such as temperature, salinity, and the squeezing time of the polymeric formulation before it gets completely gelled.

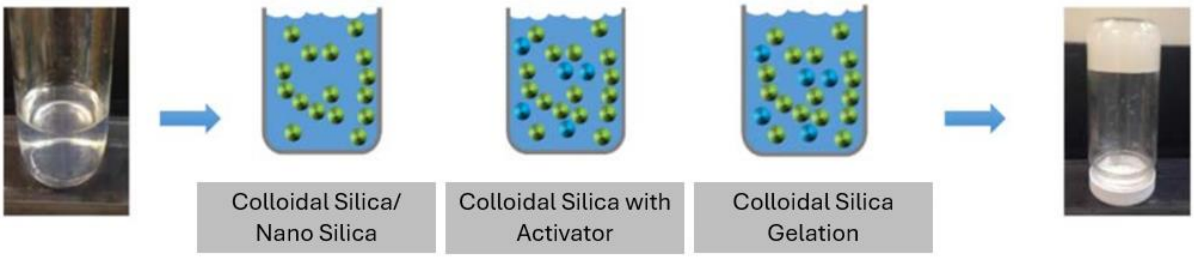


Figure 10. Schematic illustration of gelation of nano silica system [94].

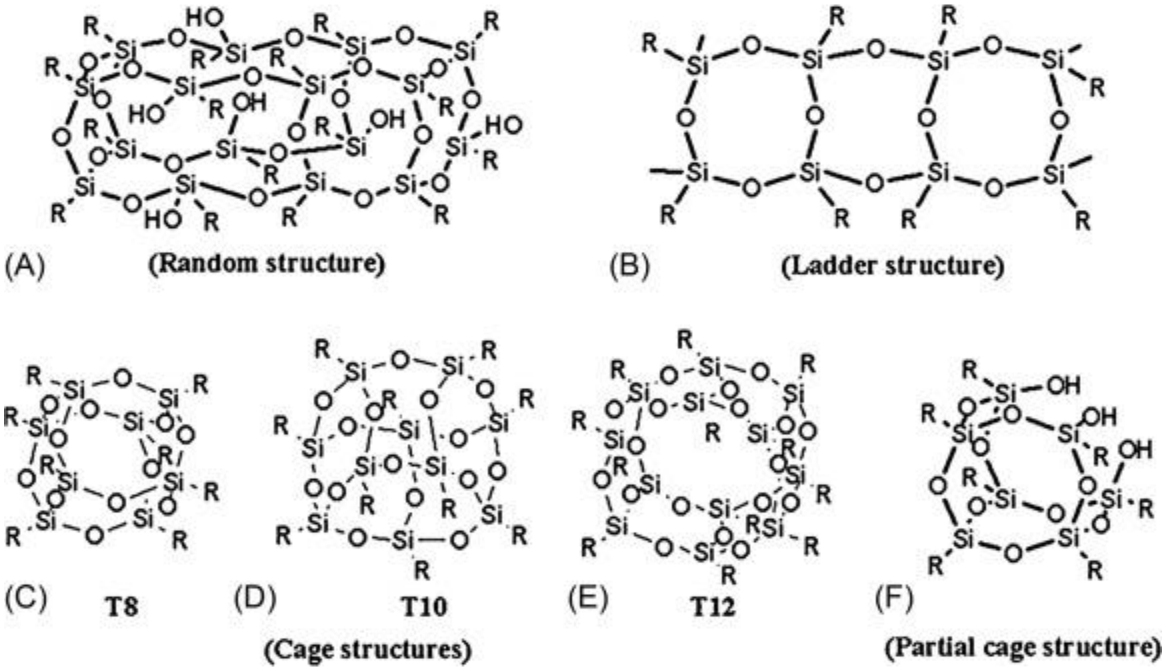


Figure 11. Chemical structures of silica nanoparticles [97].

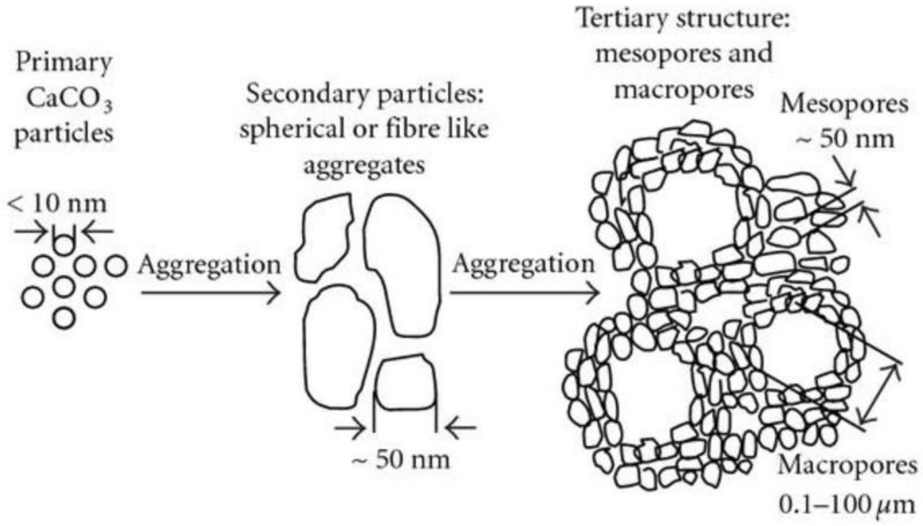


Figure 12. Schematic representation of gelation of calcium carbonate particles [96].

3. Summary and outlook

The general design for successful SPCS treatments is very similar to squeezing cement into a downhole in many aspects. Sufficient polymeric formulation is poured to cover all perforations, and approximately 10%–20% more is needed, considering the possible leak-off of the formulations into the perforations. After successfully filling all open perforations using the fluid, a squeeze operation is executed so that the polymeric formulations penetrate deep into the rock matrix. The squeezing operation is performed at a pressure just below the formation-parting pressure. The SPCS system provides an alternative to conventional cement squeeze treatments, offering the following advantages:

- There is no need for zonal isolation as with standard polymer gel sealant; the slurry can be bullheaded into all open perforations.
- Shallow penetration of the SPCS filtrate allows future reperforation of the hydrocarbon-producing zone(s), if applicable.
- Unlike cement, the SPCS slurry left inside the wellbore does not have to be drilled or milled out but can be easily jetted out the jointed pipe.
- Moreover, the SPCS formulation can be tailored and optimized for wellbore completion.

Based on prior experience, it is recommended to employ a sealant formulation with a cross-linking time similar to or comparable to the time required for the squeezing operation. This kind of sealant treatment provides a better and more complete sealing option. At the same time, premature gelation is considered a significant risk in these sealant formulations. After the SPCS plug is squeezed, the well is shut in to allow the base fluid to crosslink. Then, the set SPCS remaining in the wellbore is washed or jetted out to reperforate pay intervals. In these cases, preformed particle gels can be employed as a potential alternative to achieve a complete sealing solution, as shown in **Figure 13**.

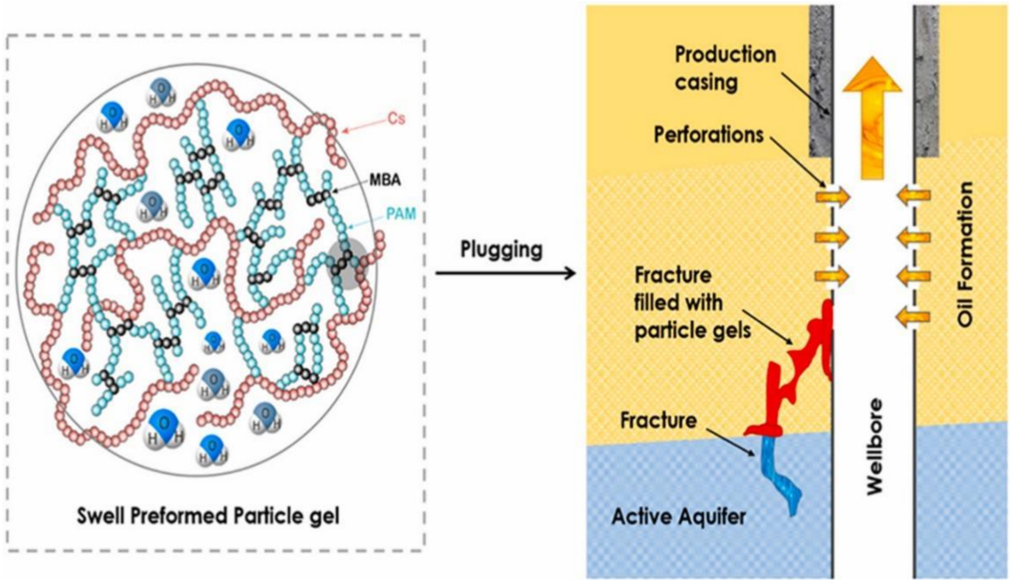


Figure 13. Preformed particle gel based on chitosan-g-polyacrylamide for conformance control in high-temperature, high-salinity (HT-HS) reservoirs [98].

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Conflict of interest: The authors declare no conflict of interest.

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