ABSTRACT

This study explores the potential of different cross-linked gel systems as a technology for addressing two critical challenges in subsurface engineering: excessive water production and mitigating the risk of CO_2 leakage. Different cross-linked fluid systems (FS) were formulated by using sulfonated hydrolyzed polyacrylamide polymer (HPAM-S'/SHPAM) along with different types of inorganic (Chromium acetate, CrAc) and organic crosslinking agents (Hydroquinone, HQ; Hexamethylenetetramine, HMTA; and Polyethyleneimine, PEI). The formulated FS underwent quantitative rheological analysis coupled with the Time-Temperature Superposition (TTS) approach to predict the gelation behavior in the temperature range of 90°C–150°C. Based on the TTS approach, the term 'gelation time' was defined as the time required to reach a pre-specified viscosity to transit from the liquid-like state to the solid-like state. The gelation time decreases with increasing temperatures. Further, an underlying mechanism based on polymer hydrolysis was utilized to explain the evolution of distinct viscous and viscoelastic properties as a function of temperature. The formulated FS demonstrated a significant reduction in permeability (>99%) for water shutoff applications.

To further investigate the in-situ gelation mechanism, conventional bottle testing method as well as high-temperature rheological experiments were performed under a pressurized CO_2 environment using a pressure cell assembly. The viscosity evolution with time demonstrated three distinct regimes: an induction period ($d\mu/dt$ = 15-50 mPa·s h^{-1}), a nonlinear transition zone ($d\mu/dt$: 60-90 mPa·s h^{-1}), and a rapid crosslinking period ($d\mu/dt \geq 350$ mPa·s h^{-1}). The gelation time, corresponding to the onset of the rapid crosslinking regime, was successfully modeled using first-order kinetics as a function of polymer concentration. The results obtained from bottle testing and oscillatory rheological measurements were in close agreement (±5%).

Comparative analyses of inorganic (SHPAM/CrAc) and organic (SHPAM/PEI and SHPAM/HQ/HMTA) gel systems demonstrated distinct gel strength. The key inferences obtained from the conventional bottle method and rheological evaluation indicate that an inorganic gel system (SHPAM/CrAc) exhibited thermal stability up to 90 °C, while an organic gel system (SHPAM/PEI) maintained thermal stability up to an aging temperature of 110 °C. In contrast, the SHPAM/HQ/HMTA organic gel system demonstrated thermal stability across all tested aging temperatures (90°C to 130°C). The sealing efficiency of these gels was further validated by core-flooding experiments conducted under sub-critical and super-critical CO_2 conditions at 110°C.The SHPAM/HQ/HMTA gel system has the highest permeability reduction, over 98% in both conditions, while the SHPAM/PEI (44.2-74.5%) and SHPAM/CrAc (<10%) gel systems demonstrated a moderate to low permeability reduction. Reactive flow simulation (i.e., CMG-STARS) results indicate that the SHPAM/HQ/HMTA gel system can effectively block CO_2 leakage from high-permeable layer with a water resistance factor (i.e., permeability reduction factor) ranging from 60 to 98, signifying moderate to strong plugging in the leakage zone.

KEY WORDS: Time-Temperature Superposition, Degree of hydrolysis, CO_2 leakage mitigation, Sub-C_{CO2} phase, Super-C_{CO2} phase, Peclet number.