Rheological Properties of New Polymer Compositions for Sand Consolidation and Water Shutoff in Oil Wells

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ABSTRACT: The rheological properties of some newly developed polymer compositions have been investigated with and without crosslinking. These polymer compositions were developed as a water shutoff and sand consolidation treatment agents for producing oil and gas wells. The effects of several variables on the rheology of the compositions were evaluated over a wide range of temperatures (25–110°C), shear rates (0–500 s^{-1}), brine percentages (0–15%), crosslinker types and concentrations (0–3%), and polymer concentrations (6–50%). It was found that increasing the shear rate from 0 s^{-1} to 100 s^{-1} caused shear thinning and reduction of the viscosity of the dilute solutions (6–13%) from 25 cP to ∼ 3 cP at 80°C. In contrast, for the concentrated solutions (20–50%), the viscosity dropped slightly in the shear rate range 0–10 s^{-1}, and subsequently decreased more slowly up to shear rates of 500 s^{-1}. The viscosities of all polymer solutions dropped by a factor of 2 as the brine concentration increased from 0% to 15%. Finally, aging time coupled with shear rates and higher percentages of crosslinkers accelerate the buildup of viscosity and gelation time of the polymer compositions. For concentrated solutions, shear rates ranging within 0–200 s^{-1} accelerated gelation time from 9.75 h to 2–3 h, when they were sheared at 80°C. The polymeric solutions exhibited Newtonian, shear-thinning (pseudo-plastic), and shear-thickening (dilatant) behavior, depending on the concentration, shear rate, and other constituents. In most cases, the rheological behavior could be described by the power law. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 104: 2076–2087, 2007

Key words: polymer; rheology; crosslinkers; viscosity; gelation time; water shutoff

INTRODUCTION

Normally, when oil reservoirs become mature, oil wells produce more water than oil. They also produce loose inorganic particulates such as sand and silt. The production of water, sand, and silt causes many problems, which could lead to closure of the oil wells. Some of these problems, like excessive water production, increase the cost of water separation from the produced hydrocarbons. This cost could rise from ∼ 0.5 $/bbl, when the water cut is ∼ 20%, to ∼ 3.0 $/bbl, when the water cut reaches ∼ 80–90%. Moreover, the production of sand and silt tends to plug filters and causes erosion of some expensive equipment such as electrical submerged pumps (ESPs). Consequently, the cost of operating such oil wells becomes very uneconomical and leads to their closure, resulting in large economic losses.

Many techniques have been developed and used to alleviate and overcome the above-mentioned problems. Polymers have been heavily researched and employed as water shutoff and sand consolidation materials. Limited successes were reported because of the many stringent requirements that these polymeric systems have to meet. These requirements include high injectivity and ease of flow through oil-producing formations, high thermal stability, high shear stability, tolerance to reservoir water salinity, high-pressure stability, and aging durability, among others. To meet these stringent requirements, knowledge of the flow behavior of these polymers in porous media becomes of paramount importance. Therefore, the rheology of some recently developed polymeric systems in our laboratories was investigated under a wide range of conditions of temperature (25–110°C), shear rates (0–500 s^{-1}), salinity (0–15% of 3% KCl), and aging durability (at 80°C for > 4 h under high shear rates), and for various polymer concentrations (6–50 g/mL).

The flow of polymer solutions and suspensions in porous media has been the subject of research for many years. Emphasis has been on the elastic and inelastic responses of these materials. Viscosity has been the most important single parameter studied, since it signifies the energy dissipated by a fluid in

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motion as it resists an applied shearing force. The polymer compositions that have been investigated and reported in the present work range from dilute solutions (6–13 g/mL) to concentrated solutions (18–50 g/mL). They were noncrosslinked solutions or crosslinked solutions by using organic and inorganic crosslinkers. Therefore, they are expected to behave differently where their coiling and uncoiling chains are ever-changing under various conditions of flow. Depending on shear rate, the length of time at a given shear rate, solution concentration, solvent, temperature, pressure, and salinity, these polymeric solutions may behave as Newtonian and non-Newtonian fluids.

BACKGROUND

Knowledge of the rheology of polymer systems used to control water production in oil wells is important in evaluating the injectivity and depth of penetration of the polymer system in porous media, such as subterranean formations under various conditions. Some of the important variables include temperature, pressure, formation permeability, compatibility of the fluids, brine salinity, the level of water cut in the fluid, and the size of the inorganic matter, like sand and silt. Thus, a substantial amount of related research has been carried out over the past few decades. A brief review of relevant research on the rheology and the mechanism of polymer flow in porous media, such as subterranean formations, is given below.

Rheology of polymers and transport in porous media

Rousseau et al.[1] studied the rheology of new water soluble microgels with various crosslinker densities and dissolved in 6% brine. These systems were specifically designed for water shutoff control. The relative viscosities, which refer to the solution-to-solvent viscosity ratio, were measured at various shear rates (from 0.1 s^{-1} to 70 s^{-1}) and at constant temperature (30°C), ranged from 3 to 30. It was observed that the soft microgels exhibited Newtonian behavior at low shear rate, indicating that the microgel conformation is unaffected by shear stress in the corresponding range. As the shear rate increased, viscosity was found to decrease. Thus, Rousseau et al.[1] found that such microgel solutions behave as shear thinning fluids in porous media. This pseudo-plasticity facilitates the injectivity of these systems in field operations.

The rheological behavior of Xanthan was studied in terms of aqueous phase mobility both with and without oil content in Berea and Bentheimer sandstone cores. Also the influence of temperature and Xanthan concentration on the viscosity yield curves (using the rheometer) and apparent viscosity yield curves (pore space) was studied. It was found that the rheological parameters of Xanthan in the porous medium (power-law index) increase with increasing permeability and show the highest values in rheometric measurements.[2]

Mechanism of polymer flow in subterranean formations

As a polymer solution is injected into the subterranean formation, it tends to flow preferably into the higher permeability water-producing zone. This results in reduction of water flow, but it does not affect the flow of oil appreciably. White et al.[3] and Sparlin and Hagen[4] attributed the residual resistance to brine flow to the following factors: (1) the polymer may be adsorbed or attached to the pore walls; (2) it may also become entrapped in the capillaries and voids of the formation matrix; and (1) it might form a slug and lead to physical plugging of the pores and pathways, resulting in complete blockage of fluid flow, including oil. In oil-producing wells, sometimes there are separate zones that are rich in oil and produce oil, while other zones are rich in water and, hence, produce water. However, there are other zones where oil and water are produced simultaneously. It is recommended that polymer treatments be used in oil or gas wells, where distinct and separate zones of oil and water exist.[4]

An ideal polymer system for subterranean sand consolidation and water shutoff would be one that would have affinity to both water and oil-coated grains of sand. Field tests show that a large reduction in permeability to brine occurs, even though only small amounts of polymer may be retained by the formation core.[3] This means that the process is selective, where oil flow is not impaired, even though the flow of brine is significantly reduced. Usually, the reduction in oil flow does not exceed 15%.

Injectivity, penetration depth, and polymer viscosity

Another requirement for an effective sand consolidation polymer system is that these systems should be able to penetrate the weak formation, where sand consolidation is required, to a reasonable depth before they become immobile. It is reported that a penetration depth of 1–2 feet (30.48–60.96 cm) or ½–1 foot (15.24–3048 cm) or even deep penetration of 40–75 feet (1242.1–2286 cm) is needed for effective consolidation.[3,5–7] Other investigators suggest that penetration of 1–5 feet (30.48–152.4 cm) might be necessary to have an effective consolidation.[4] Penetration of the polymeric fluid system in the formation depends on its viscosity during the injection stage and on the flow of the polymer into the formation matrix. This is referred to as ''injectivity.'' It is reported that polymers with initial viscosities of

1–5 cP for an amino-aldehyde system,[8] or 54 cP for a 5% concentration polyacrylamide pre-gel system,[9] and 1–2 cP for a sodium silicate/HCl system,[10] are ideal for deeper radial penetration into a sand-producing zone. Two sodium silicate solutions (35% w/w and 70% w/w) in 3% KCl brine were used. Their viscosities were 93 cP and 11.6 cP, respectively, at 20°C, and 40 cP and 3.3 cP, respectively, at 60°C. Commercial furanic resins (50% w/w in butyl acetate) were also used as sand consolidation and water shutoff materials. They have viscosities of 33.8 cP and 9.3 cP at 20°C and 60°C, respectively.[11]

Polymer thermal and shear stability

Another requirement for polymer treatments is that they should not be prone to thermal degradation, at least to ~ 150°C. Most polymeric systems are susceptible to thermal degradation. It was reported that polyacrylamide gels undergo syneresis or shrinkage by 20% volume of the gel, due to the hydrolysis of the amide groups followed by additional crosslinking with the divalent cations present in the brine.[12] This syneresis is reported to be critical at temperatures greater than 90°C. Another requirement for a successful sand consolidation treatment is that the polymer system not be shearing sensitive. This problem is normally encountered during the injection step of high-molecular-weight polymers, such as polyacrylamides.

The viscosities of the various treatments used vary widely. It was reported that 300–400 cP at 80°C for the furfuryl alcohol formulation was used,[13] while others reported 6 cP at 60°C for their epoxy resin.[14] Friedman and Surles[15,16] and Shotts et al.[17] reported viscosities of 33.8 cP at 20°C and 9.3 cP at 60°C for their furanic resin treatments.

EXPERIMENTAL

Materials

The materials used to prepare the various polymer compositions were mixtures of amino-aldehyde resins, with water-soluble resins plus other additives, such as dispersants and organic and inorganic crosslinkers (e.g., acetic acid, ammonium sulfate, boric acid, borax, and hydrochloric acid). The water-soluble resin that was used in the mixture was a 87–89% hydrolyzed polyvinyl alcohol with an average molecular weight of 13,000–23,000, purchased from Aldrich Chemical Company (Milwaukee, WI). The dispersant used was sulfonated melamine formaldehyde, prepared according to a procedure developed and reported by Lahalih.[18] Finally urea–formaldehyde was also prepared according to a procedure developed by Lahalih et al.[19] The molecular weight

and molecular weight distribution for these compositions were reported in the above-mentioned references. Different polymer compositions were prepared from these polymers by varying the various ratios of these compositions and are reported according to the composition final concentration as shown in Table I. The impact of KCl brine or acetic acid on the rheology of the various compositions is affected by the ratios of the various components in the final polymer composition tested, as reflected by the percentage concentration of various formulations.

The above mixtures were tested with and without 3% KCl brine. Various polymer solutions were prepared with different concentrations, ranging from 6% to 50%. These polymer solutions were prepared with different brine percentages (0–15%) and were tested at different temperatures (25–80°C) over broad ranges of shear rates (0 s^{-1}–500 s^{-1}).

Procedure

The Haake Rotational Viscometer RT-20 (Thermo Electrone Corp., Karlsruhe, Germany) was used to measure the dynamic viscosity of the various formulations within the range of 2–200,000 cP, using the cone and plate spindle (DIN 53018). The rheometer operates within a shear rate range of 0–1000 s^{-1} and temperature range of −10–150°C. Rheo-cal software was employed in an attached computer to obtain all the needed calculations and viscosity plots.

RESULTS AND DISCUSSION

As pointed out earlier, knowledge of the rheology of polymer formulations is essential to determine their flow behavior in porous media. Rheology determines the degree of injectivity and depth of penetration in oil-producing formation or other porous media. However, rheology of polymers is governed by many variables. The effects of some of the key variables on the rheology and gelation time will be presented and discussed below.

Effect of temperature

Table I shows the viscosities at 100 s^{-1} of some polymer compositions without crosslinker, within the temperatures range 40–80°C. Table I also shows the viscosities at 90°C and 110°C, predicted by curve fitting and extrapolation. The polymer formulations shown in Table I are designed for use either as water shutoff or as sand consolidation materials. The viscosities of the various solutions varied between 6 cP and > 1700 cP at 40°C and between 3 cP and 438 cP at 80°C. It is usually recommended that the viscosities of polymer formulations used for water

TABLE I
Rheological Properties of Some Prepared Polymer Formulations

Polymer composition no.	Crosslinker (AA) (%)	Conc (%)	Measured viscosity @100 s^{-1} (cP)			Predicted viscosity @ 100 s^{-1} (cP)	
			40°C	60°C	80°C	90°C	110°C
1	0.0	23.0	287.7	147.2	94	88.1	47.3
1—1	0.0	17.95	130.2	73.4	44.0	37.8	27.2
	2.0		—	—	53.2		
	3.0		133	82.0	55.4		
1—2	0.0	10.72	26.2	15.6	10.3	8.9	6.7
1—3	0.0	6.04	6	4.6	4.1	3.9	3.7
11	0.0	32.0	340	152.5	117.75	97.3	81.2
11c	0.0	24.0	42	32	24	19.2	16.6
	0.05		88.8	47.6	—	27.9	21.3
	0.11		116.7	72.5	68	59.67	54.2
11c—1	0.0	17.65	37.0	22.8	15.56		
	2.0		—	—	14.37		
	3.0		25.0	17.0	15.2		
11c—2	0.0	10.65	7.4	5.5	4.5	3.9	3.3
11c—3	0.0	6.32	4.8	3.9	3.2	3.4	3.2
12	0.0	22.68	2105	1089	418.5	339.9	163.44
12d	0.0	20.2	800.6	252.8	97	87.8	30.37
	0.11	20.2	1717	570.5	437.7	254.8	159.29
12d—1	0.0	18.25	672.4	221.9	88.6	45.7	15.6
	2.0		—	—	231		
	3.0		800	458	404		
12d—2		9.24	35.2	15.8	9.4	7.4	5.1
12d—3		6.25	9.8	6.5	4.9	4.4	3.6
62 (2)		47.0	33.9	22.29	14.13	11.25	7.14

AA, acetic acid.

shutoff or sand consolidation be < 100 cP at reservoir conditions, or preferably lower by a factor of 2–3.

Figure 1(a–c) shows the viscosities, at 100 s^{-1} and different temperatures, of the various polymer compositions, considered for both sand consolidation and water shutoff at different temperatures. Figure 1(a) shows that solutions #11c and #62(2) have the lowest viscosities compared with the other polymer compositions.

Figure 1(b) shows the viscosities of the diluted polymer compositions of #1. The viscosities of the corresponding compositions were reduced by factors of 5–10 for polymer concentrations near 10%. The viscosities of polymer compositions with concentrations of ∼ 6% were reduced by factors of 10–25. Figure 1(c) shows that the diluted polymer composition #11c has the lowest viscosities compared with the other two polymer compositions (1 and 12d).

Effect of shear rate

Figure 2(a) plots the viscosities of the four main concentrated polymer compositions (i.e., #1, #11c, #11, and #12d) as a function of shear rate. The data at 80°C show a relatively steep drop in viscosity initially, followed by a leveling of or slower decrease of viscosity as shear rate increases to 500 s^{-1}. This may imply that the materials exhibit a yield stress at low shear rates, but a more detailed analysis would be

required to explain this behavior. The same behavior was also observed for solution #12, when viscosity was measured at various temperatures of 40–80°C, as shown in Figure 2(b). The overall drop in viscosity as shear rate increases is more pronounced at lower temperatures, compared with the drop at high temperature, as can be seen in Figure 2(b). This is due to the fact that polymer solutions generally exhibit larger deviation from Newtonian behavior at lower temperatures.

Figure 2(c) shows the viscosity as a function of shear rate for the dilute versions of the main polymer compositions (i.e., #1, #11c, and #12d). Again, the same behavior was observed, where the solution exhibit non-Newtonian shear thinning characteristics.

Effect of crosslinker and polymer concentrations

Figure 3(a) shows the effect of adding of 0.11% acetic acid as a crosslinker on the viscosity of polymer compositions #12d. The effect of polymer concentration on the viscosity is also shown in Figure 3(a). Figure 3(b) displays similar results for polymer compositions #11 and #11c. As expected, viscosity of polymer solutions increases with increasing concentration and with the addition of a crosslinker like acetic acid. As shown earlier, the viscosity decreases as temperature of the solution increases. Figure 3(c) shows the effect of concentration on the viscosity
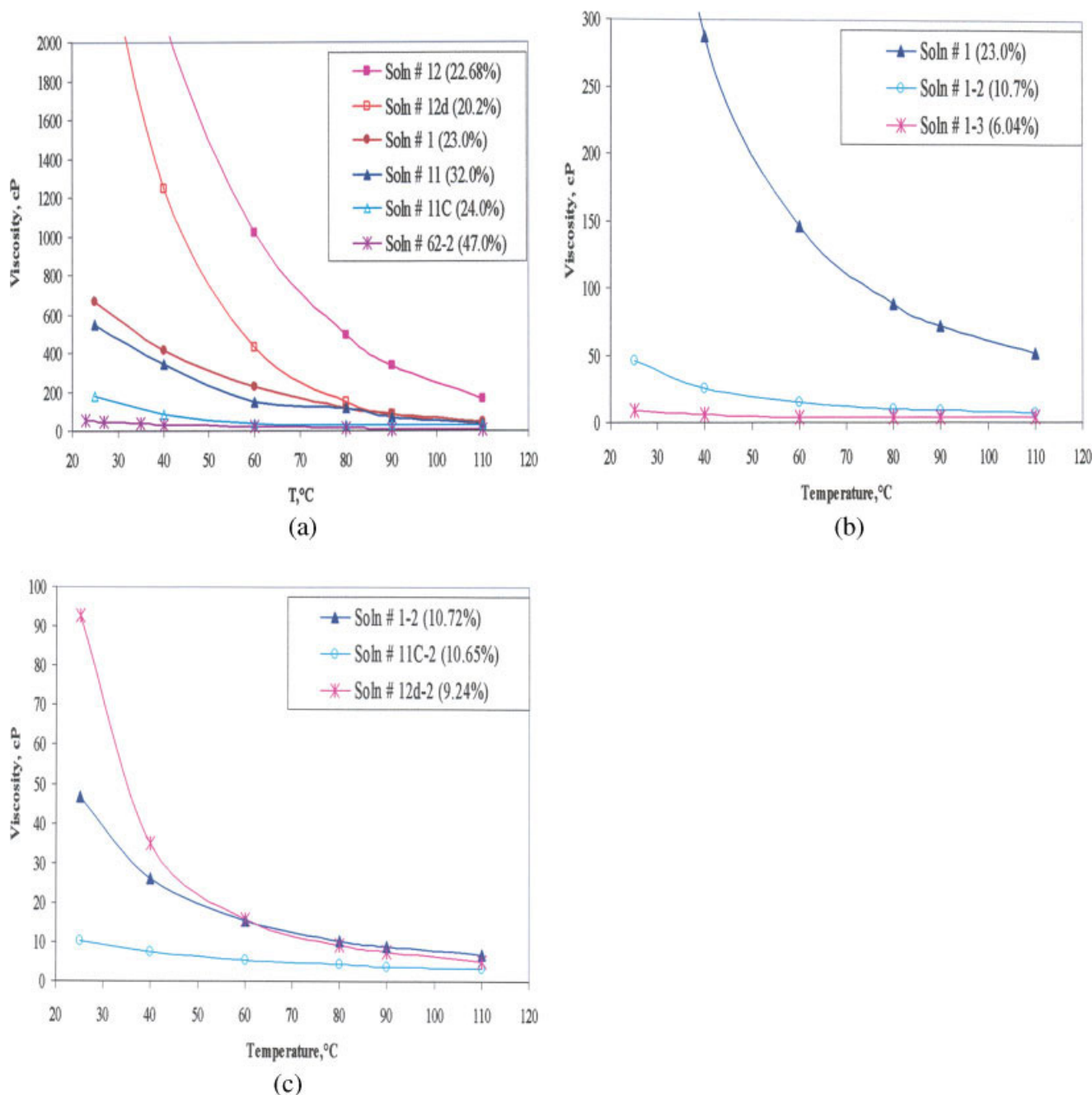
Figure 1 (a) Viscosities at 100 s^{-1} and different temperatures of various polymer formulations. (b) Viscosities at 100 s^{-1} and different temperatures of different concentrations of polymer formulation #1. (c) Viscosities at 100 s^{-1} and different temperatures for different dilute polymer formulations ($\sim 10\%$). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

buildup of polymer composition #11c at various temperatures. As can be seen, polymer concentration has a profound effect on the viscosity and, hence, on gelation time.

Effect of aging time coupled with different shear rates on the viscosity and gelation time

Figure 4(a) displays the viscosities of various polymeric solutions upon aging at 80°C. The viscosities

were measured using the Haake rotational viscometer at a shear rate of 100 s^{-1}. The samples were placed in the viscometer for different periods of time, and they were sheared as time elapsed. The data in Figure 4(a) show the effect of aging at 80°C plus the effect of shear rate on the viscosity buildup. It is observed that shear accelerates crosslinking substantially. For example, from Figure 4(a), solution #11 appears to approach gelation at ~ 4–5 h under shear, while the established gelation time for this solution at zero shear rate is 7.0 h at
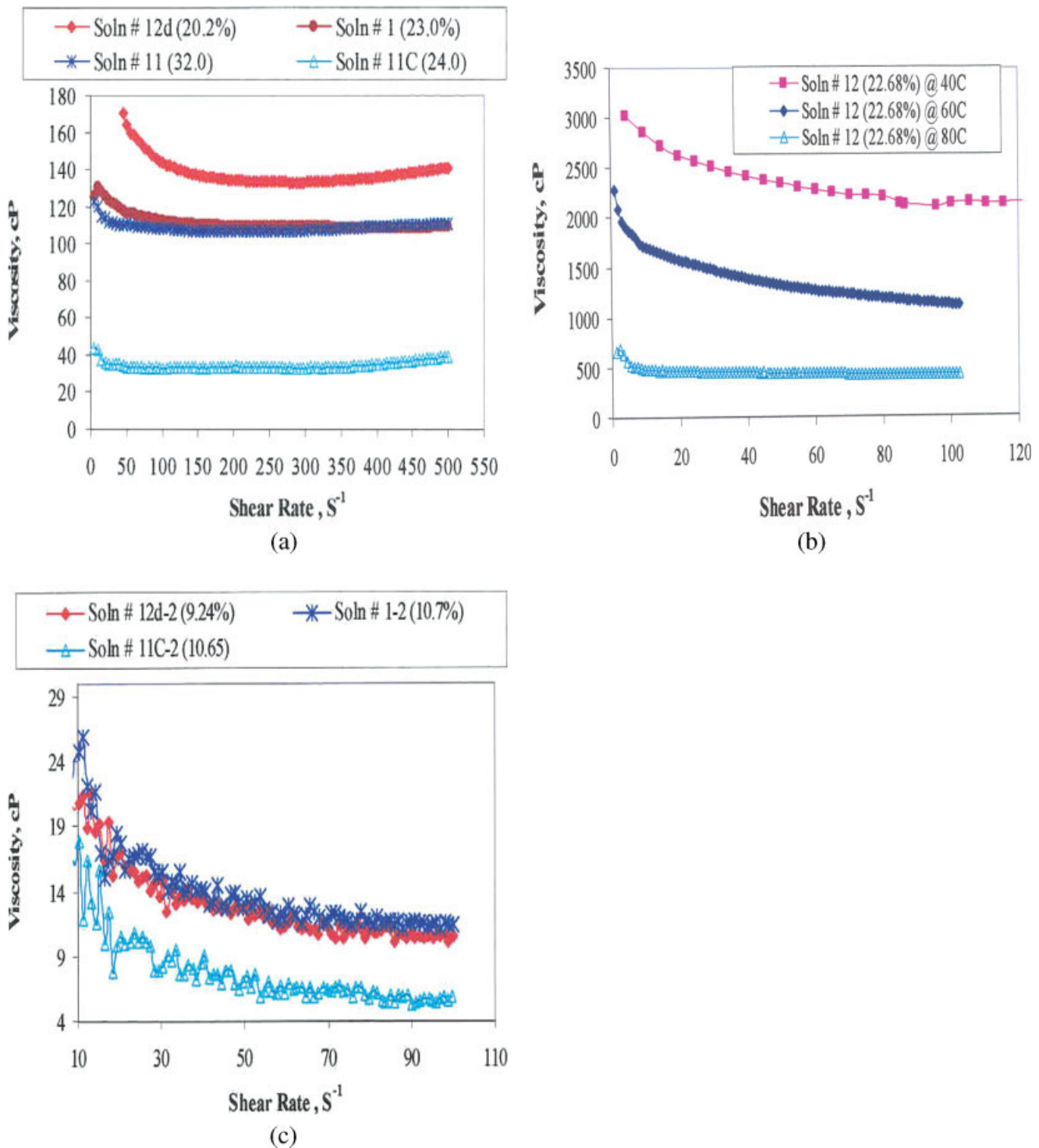
Figure 2 (a) Viscosities versus shear rate at 80°C of various polymer formulations. (b) Viscosities versus shear rates at different temperatures for polymer formulation #12. (c) Viscosities versus shear rates at 80°C for various dilute polymer formulations (10%). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

80°C. Similar behavior was observed for other solutions. For example, solutions #12d and #1 appear to have gelation times under shear of 8–9 h compared with 15 h and 9.75 h., respectively, at zero shear rate. It can therefore be concluded that shear accelerates gelation of these polymeric formulations.

Figure 4(b) shows the effect of aging time on the viscosity at 80°C and different shear rates of polymer solution #11c with different crosslinker concentrations. The data show that the concentrated polymer solution 11c + 0.11%A.A (24% conc) has higher viscosity at 200 s^{-1} shear rate than at 100 s^{-1} shear rate,
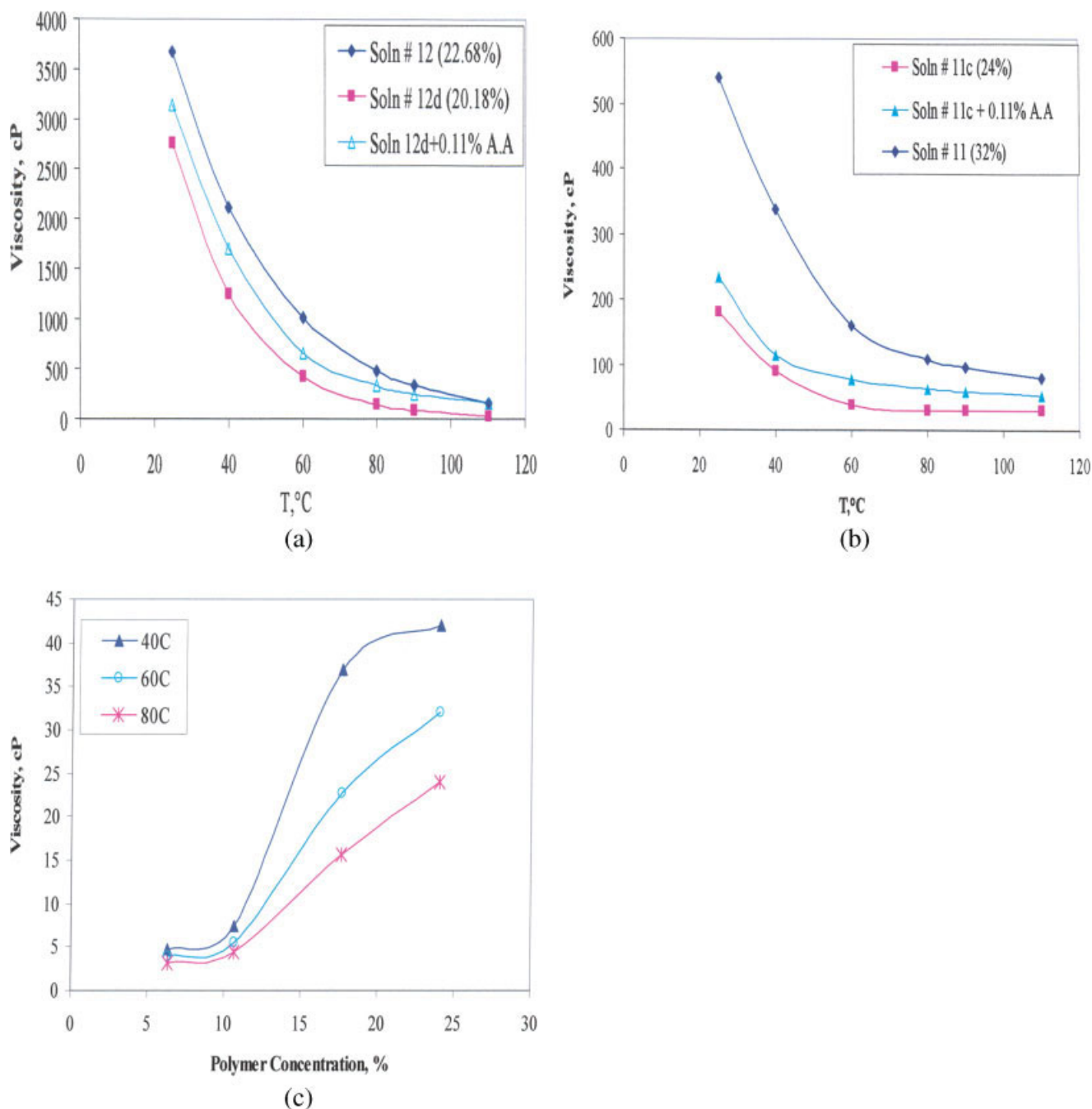
Figure 3 (a) Effect of acetic acid crosslinker on the viscosity of polymer composition #12d at various temperatures. (b) Effect of acetic acid crosslinker on the viscosity of polymer composition #11 at various temperatures. (c) Effect of concentration of polymer composition #11c on its viscosity at various temperatures. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

indicating accelerated crosslinking upon shear, hence faster gelation time. The same behavior was also observed for the dilute versions of this polymer solution (18% conc), represented by (11c-1) + 2%A.A and (11c-1) + 3%A.A. The viscosity increased faster at 200 s^{-1} than at 100 s^{-1} for both solutions. However, the effect of shear rate was more pronounced for the concentrated solution, compared with the dilute solution.

Figure 4(c) shows the case for concentrated polymer solution #12d (20.18% conc) and the dilute version 12d-1 (18.25% conc). Again solutions 12d + 0.11%A.A and (12d-1) + 2%A.A exhibit higher viscosity at 200 s^{-1} than at 100 s^{-1}.

Finally, Figure 4(d) shows the effect of aging time on the viscosity of polymer composition #1. Again for higher initial viscosity solutions like #1 and #(1-1) + 3%A.A, the high shear rate of 200 s^{-1}
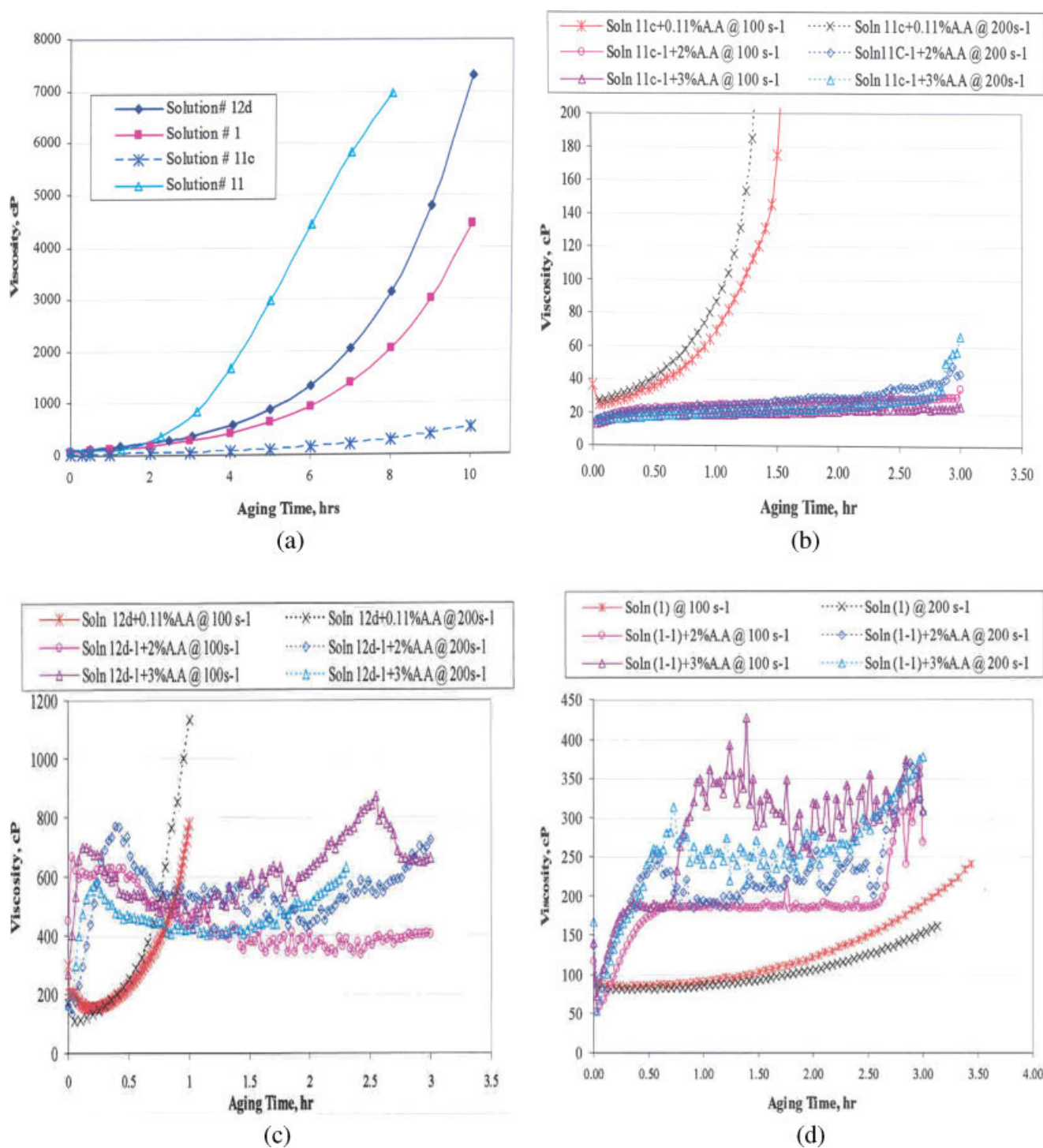
Figure 4 (a) Effect of aging time on the viscosity of different polymer solutions at 80°C and 100 s^{-1} using the Haake rotational viscometer. (b) Effect of aging time on the viscosity of concentrated polymer composition #11c and dilute composition #11c-1 with different concentrations of crosslinker acetic acid and at two different shear rates (100 s^{-1} and 200 s^{-1}) at 80°C. (c) Effect of aging time at 80°C on the viscosity of concentrated polymer composition #12d and dilute composition #12d-1 with different percentages of crosslinker concentration and at two different shear rates (100 s^{-1} and 200 s^{-1}). (d) Effect of aging time at 80°C on the viscosity of concentrated polymer composition #1 and dilute composition #1-1 with different percentages of crosslinker concentration and at two different shear rates (100 s^{-1} and 200 s^{-1}). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

causes shear thinning fluid and for lower initial viscosity solutions like (1-1) + 2%A.A, compared with the other two solutions, the higher shear rate

causes shear thickening and accelerates crosslinking and gelation time compared with lower shear rates.

TABLE II
Summary of Viscosities of Different Polymer Compositions at Different Brine
Concentrations upon Aging at 80°C

Polymer composition no.	Polymer conc (wt %)	Viscosity at 80°C and 100 s^{-1} for different brine %, (cP)			
		0%	5%	10%	15%
1	23.00	94	90.1	72.8	59.4
1−1	17.95	44.0	—	—	—
1−2	10.72	10.3	9.2	7.9	7.3
1−3	6.02	4.1	4.1	4	4.1
11	32.10	117.5	80.6	67.3	58.4
11c	24.07	31.70	24.80	21.40	19.70
11c + 0.11% AA	24.07	68.0	39.2	27.2	22.9
11c−1	17.65	15.56	—	—	—
11c−2	10.65	4.5	4.6	4.7	4.4
11c−3	6.32	4.7	3.9	3.4	3.5
12	22.68	418.5	261.9	186.7	149.7
12d	20.18	125.9	107.4	82.6	71
12d + 0.11% AA	20.18	667.4[a]	260.0[a]	218.6[a]	178.7[a]
12d−1	18.25	88.6	—	—	—
12d−2	9.25	9.4	8.4	7.2	6.6
12d−3	6.25	4.9	4.5	4.1	4.0
62	47.00	—	—	—	—
62 (2)	51.51	14.13	—	—	—

[a] Viscosities of solution 12d + 0.11% AA were measured at 60°C.

It can be concluded from Figure 4(b–d) that for polymer solutions with high viscosity initially, the higher shear rates cause shear thinning behavior. In contrast, dilute solutions with low initial viscosity exhibit shear thickening at the higher shear rates, which accelerates crosslinking and reduce gelation time.

Effect of brine on the rheology of some polymer compositions

The viscosities, upon aging, of various polymer solutions with different brine (3% KCl) concentrations were measured with the Haake rotational viscometer at 80°C and 100s^{-1} shear rate. The results are summarized in Table II and Figure 5. Brine concentrations ranging from 0.0% to 15% by weight of the polymer solutions were added to various polymer compositions to determine their effects on the viscosity of these compositions. Table II shows that, as the concentration of brine increases from 0.0% to 15%, the viscosity of various polymer compositions drops by a factor of 2. Figure 5 shows the effect of aging time on the viscosity of polymer solution #1, with and without brine, at 80°C and at 100 s^{-1} shear rate. In all cases, increase of brine in the polymer composition reduces the viscosity for all the polymer compositions that were tested. Figure 6(a,b) shows the viscosities of the concentrated polymer compositions with different brine concentrations at shear rate of 100 s^{-1}, after 0.5 h and 4.0 h of aging at 80°C,

respectively. Figure 6(a, b) shows that the brine percentage has a substantial effect on the viscosity reduction. Figure 6(c) shows the viscosities of the dilute versions of the polymer compositions as a
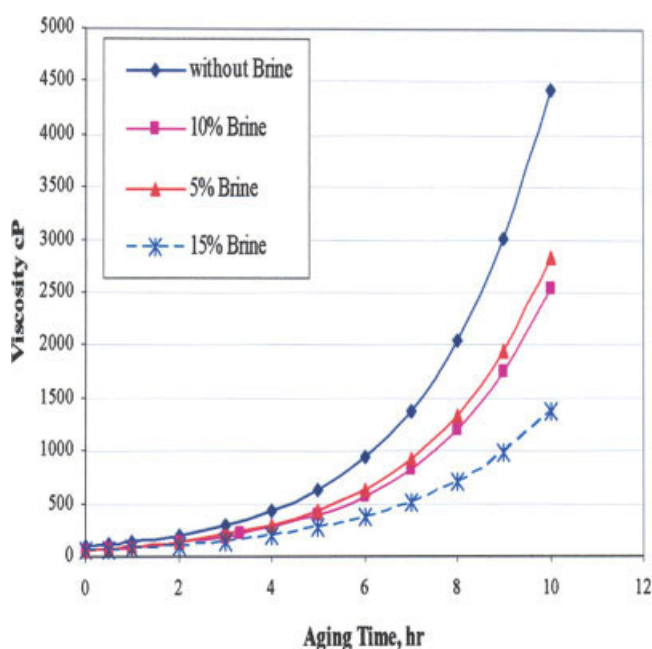

Figure 5 Effect of aging time on the viscosity of polymer solution #1 with and without brine at 80°C and 100 s^{-1} using Haake rotational viscometer. [Color figure can be viewed in the online issue, which is available at www. interscience.wiley.com.]
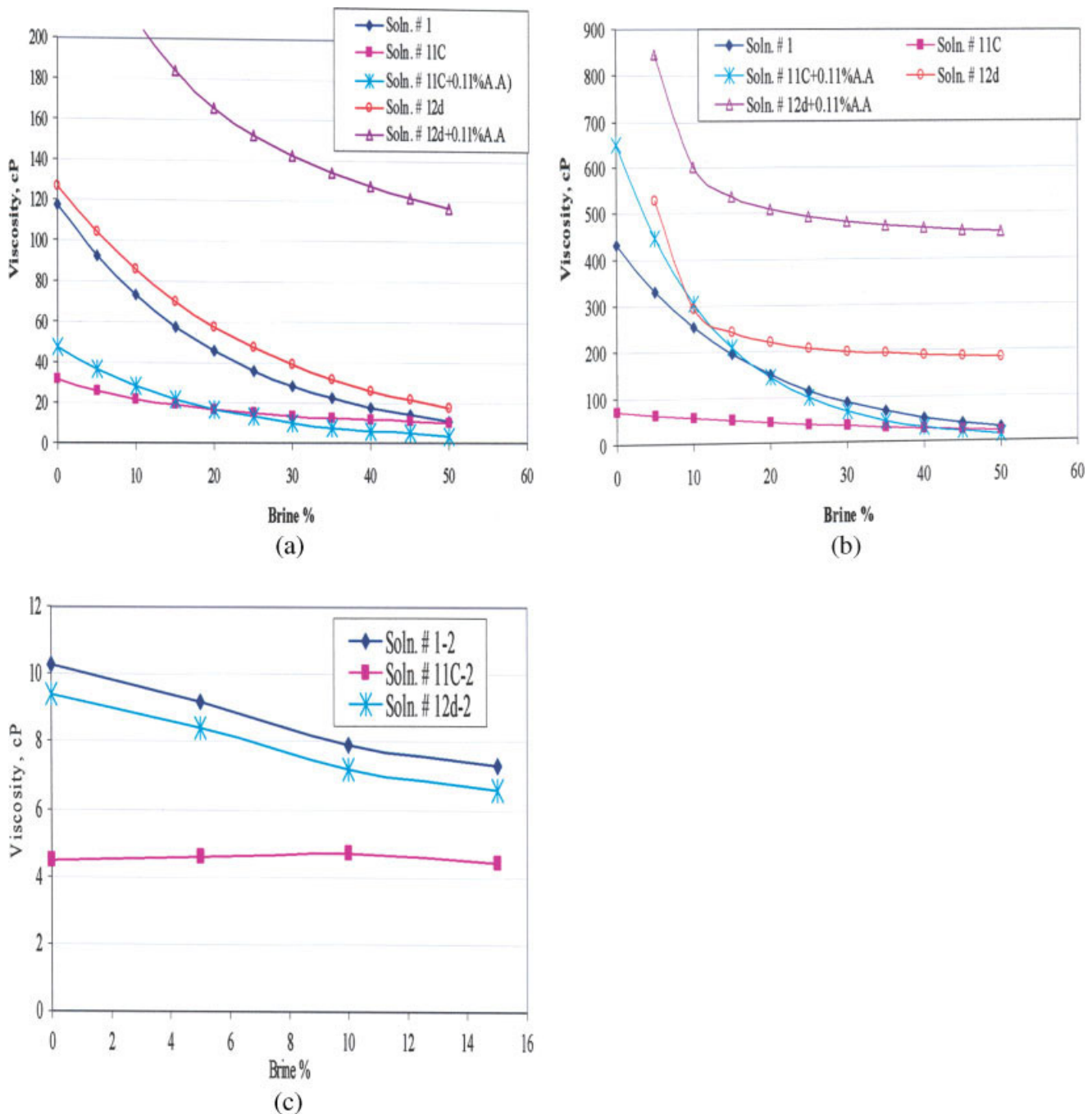
Figure 6 (a) Viscosity of different polymer compositions with different brine concentration after 0.5 h aging at 80°C and at 100 s^{-1}. (b) Viscosity of concentrated polymer compositions with different brine concentration after 4.0 h aging at 80°C and at 100 S^{-1} using Haake rotational viscometer. (c) Viscosity of dilute polymer compositions (10%) with different brine concentration at 80°C and at 100 s^{-1}. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

function of brine concentration at 80°C and at shear rate of 100 s^{-1}. Only a slight reduction in viscosity takes place, and the effect of brine is not as large as in the case of concentrated polymer compositions. Figure 7 shows the effect of brine concentration on the viscosity reduction of different polymer solutions, upon aging at 80°C. The data show that ∼ 50%

viscosity reduction could take place for brine concentration raging from 0.0% to 15% by weight of the polymer solution. Figure 7 also demonstrates that polymer solutions #1 and #11c, with and without crosslinkers, are more affected by brine than polymer solution #12d, indicating that dispersants could reduce this effect of viscosity reduction by brine.
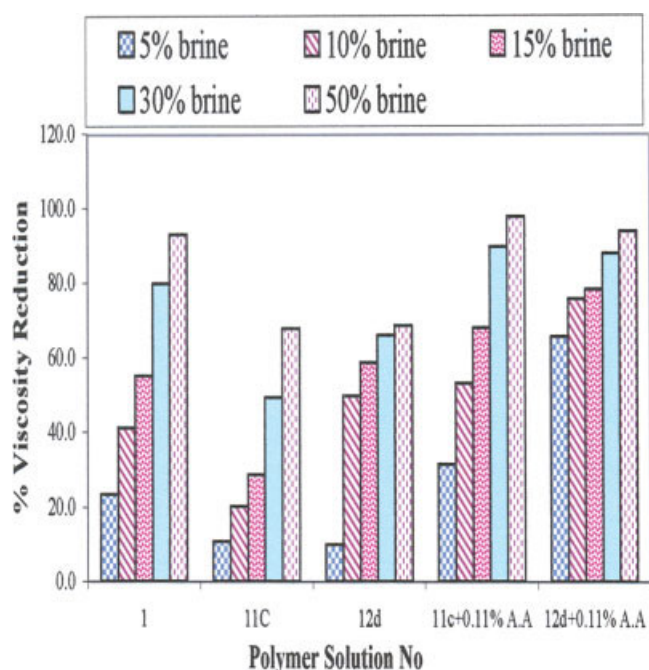
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Figure 7 Effect of brine concentration on the viscosity reduction of different polymer solutions upon aging at 80°C. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

CONCLUSIONS

The following conclusions can be drawn from this work:

1. For polymer compositions with concentrations ranging within 20–50%, the viscosity drops slightly as the shear rate increases initially within 0–10 s^{-1}, but decreases slowly as shear rates increase in the whole range of shear rates, up to 500 s^{-1}. This could imply yield behavior at low shear rates and indicates non-Newtonian behavior, which is more pronounced at lower temperature and at lower shear rate ($\leq 10s^{-1}$ shear rate and temperature ≤ 40°C).

2. For polymer compositions with concentrations ranging from 6.0–13%, the solutions exhibit shear thinning behavior, with the viscosities decreasing from 25 cP to ~ 3 cP, at 80°C, as the shear rate increases from 0 to 100 s^{-1}.

3. Viscosities of most polymer solutions increase with increasing concentration and with the addition of a crosslinker and decrease as temperature of the solution increases.

4. Brine 3% KCl has significant effect on viscosity for all the polymer compositions that were tested. As the concentration of brine increases from 0% to 15% in the polymer solutions, the viscosity of these solutions drops by almost a factor of 2 when tested at 80°C and 100 s^{-1} shear rate.

5. The effect of aging time, coupled with shear rates, on the viscosity depends on the initial concentration and viscosity of the polymer composition and on the concentration of the crosslinker. For initially high concentration and higher viscosity polymer solutions, the higher shear rate causes shear thinning, while for initially dilute polymer solutions, the higher shear rate causes shear thickening and, hence, accelerates crosslinking and gelation time. Possibly, at higher initial viscosity/concentration, shear does not add to the crosslinking efficiency of already closely packed polymer chains. In contrast, for dilute solutions, high shear rates enhance collisions among molecules and thus crosslinking efficiency.

6. Different polymer compositions have different gelation times that range from hours to days, depending on the final polymer composition and crosslinker concentrations and on other variables, such as degree of salinity and temperature. However, all the polymer compositions performed very well as effective water shutoff treatments without impairing the permeability to oil. Also most of these compositions induced significant compressive strength values to the treated unconsolidated sand samples, where the induced compressive strength was much more than 10 kg/cm^2. This is considered more than enough to sustain the shear stress bands that normally exist in the formation of oil producing wells according to Cobianco et al.[20]

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