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DEVELOPMENT OF CROSSLINKED, LOW-MOLECULAR-WEIGHT,  
FLEXIBLE POLYACRYLAMIDE GELS FOR MOBILITY CONTROL

Topical Report

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## TABLE OF CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	2
Acknowledgments.....	3
Experimental.....	3
Polymer.....	3
Crosslinking Agent.....	3
Sample Preparation.....	3
Results and Discussions.....	4
Crosslinking of HPAM1 with Chromium Chloride.....	4
Effect of Oxygen on Gelation.....	6
Crosslinking of HPAM1 with Cr(VI)/Thiourea.....	6
Crosslinking of HPAM2 with Chromium Chloride.....	7
Crosslinking of HPAM2 with Cr(VI)/Thiourea.....	7
Effect of High Shear on Gelation.....	9
Conclusions.....	9
References.....	10

## TABLES

1. Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8) at 22.5° C, 5.3 months.....	12
2. Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8) at 22.5° C under N <sub>2</sub> , 21 days (continuous agitation for 21 days).....	13
3. Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8) at 22.5° C under N <sub>2</sub> without agitation, 73 days.....	14
4. Gelation tests for HPAM1-Cr(VI)/thiourea in 53 meq/L NaCl (pH=6.8) at 22.5° C, 6 months.....	15
5. Gelation tests for HPAM2-Cr(VI)/thiourea in 53 meq/L NaCl (pH=6.8) at 22.5° C, 8.5 months.....	16
6. Gelation tests for HPAM2-Cr(VI)/thiourea in deionized water (pH=6.8) under N <sub>2</sub> at 22.5° C, 4 months.....	17



## ILLUSTRATIONS

	<u>Page</u>
1. Rheograms for the 13,000 ppm HPAM1/170 ppm Cr(III) gel system in 53 meq/L NaCl (pH=4.8) at 22.5° C. ....	18
2. Rheograms for the 12,000 ppm HPAM1/170 ppm Cr(III) gel system in 53 meq/L NaCl (pH=4.8) at 22.5° C. ....	19
3. Rheograms for the 17,000 ppm HPAM1/75 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH=4.8) at 22.5° C. ....	20
4. Rheograms for the 17,000 ppm HPAM1/100 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH=4.8) at 22.5° C. ....	21
5. Rheograms for the 15,000 ppm HPAM1/100 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH=4.8) at 22.5° C. ....	22
6. Rheograms for the 13,000 ppm HPAM1/175 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH=4.8) at 22.5° C. ....	23
7. Rheograms for the 13,000 ppm HPAM1/175 ppm Cr(VI) gel system in 53 meq/L NaCl (pH=4.8) at 22.5° C. ....	24
8. Effect of oxygen on the gelation time and gel strength of a 13,000 ppm HPAM1/Cr(III) system in 53 meq/L NaCl (pH=4.8). ....	25
9. Rheograms for the 13,000 ppm HPAM1/150 ppm Cr(VI) gel system in 53 meq/L NaCl (pH=6.8) at 22.5° C. ....	26
10. Rheograms for the 3,000 ppm HPAM2/2,400 ppm Cr(VI) gel system in 53 meq/L NaCl (pH=6.8) at 22.5° C. ....	27
11. Rheograms for the 6,000 ppm HPAM2/3,600 ppm Cr(VI) gel system in deionized water (pH=6.8) at 22.5° C. ....	28
12. Rheograms for the 15,000 ppm HPAM1/135 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH=4.8) at 22.5° C before and after injecting through a 48-ft long, 1/16 in. O.D. monel tubing at an apparent shear rate of 1,040 sec <sup>-1</sup> .....	29



# DEVELOPMENT OF CROSSLINKED, LOW-MOLECULAR-WEIGHT, FLEXIBLE POLYACRYLAMIDE GELS FOR MOBILITY CONTROL

By H. W. Gao and M. K. Tham

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## ABSTRACT

Shear degradation is a practical problem in field applications of conventional polyacrylamides as mobility control agents. This problem may be eliminated by using a novel system based on crosslinking a low-molecular-weight polyacrylamide. To develop shear-resistant flexible gels for mobility control, two partially hydrolyzed polyacrylamide polymers of molecular weights 400,000 (HPAM1) and 200,000 (HPAM2) were evaluated with chromium (pH=4.8) and chromium/thiourea (pH=6.8) crosslinking agents.

This report summarizes the screening tests which were conducted to determine the gel strength, type of crosslinking agent, the amount of crosslinking agent, and the conditions necessary for proper gel formation. Visual observations and viscosity measurements were used to identify potential gels for mobility control applications. Results of this study show that shear-resistant flexible gels can be formed from low-molecular-weight, partially hydrolyzed polyacrylamide polymers. It was found that the degree of hydrolysis of the polymer, polymer molecular weight, polymer concentration, type and concentration of crosslinking agent affect the strength and stability of the flexible gels.

The minimum polymer concentration for making HPAM1/Cr(III) gels (in 53 meq/L NaCl) for mobility control is about 13,000 ppm under a nitrogen atmosphere. Required crosslinker concentrations for crosslinking decrease with increases in polymer concentration. In our tests, the necessary concentrations of crosslinking agent were about 150 ppm for 13,000 ppm of HPAM1 and 25 ppm for 20,000 ppm of HPAM1. The upper limits of Cr(III) concentration for making gels for mobility control were about 200 ppm and 34 ppm for 13,000 ppm of HPAM1 and 20,000 ppm of HPAM1, respectively.

Using Cr(VI)/thiourea as the crosslinker, HPAM1/Cr(III) gels were formed at lower polymer concentrations (8,000 ppm to 10,000 ppm) than those using Cr(III) as the crosslinker. At polymer concentrations from 12,000 to 20,000 ppm, required chromium concentrations for making gels under aerobic conditions were about the same for both crosslinkers.

For HPAM2, gels were obtained only with sodium dichromate/thiourea (pH=6.8) in deionized water and in 53 meq/L NaCl. Using Cr(III) as the crosslinker, precipitation usually occurred before gels were formed. Unlike the HPAM1/Cr(VI) systems, the required minimum Cr(VI) concentrations for making HPAM2/Cr(VI) gels under nitrogen atmosphere increase with increase in polymer concentration.

## INTRODUCTION

Mechanical degradation<sup>1-11</sup> is a practical problem in field applications of high-molecular-weight ( $MW > 10^6$ ) polyacrylamides as mobility-control agents. Mechanical degradation usually results in substantial reduction in the high-molecular-weight polymer fraction, which is most effective in viscosifying the mobility-control slug, and reduces the slug's effectiveness. This problem may be eliminated by using a novel system based on crosslinking a low-molecular-weight polyacrylamide. Because of low molecular weight, the crosslinked gels should be less susceptible to mechanical degradation and can be used in lower permeability reservoirs than the conventional polyacrylamides. Under high shear conditions (near the wellbore), low crosslinking density of gelled polymer<sup>12</sup> should provide better injectivity than the conventional polyacrylamides. The ability of the crosslinked gels to reheel at low shear conditions<sup>12</sup> will permit the gel to develop the necessary viscosity to maintain a favorable mobility ratio in reservoir formations where the shear is low.

To investigate the feasibility of developing such an improved mobility-control method based on crosslinking a low-molecular-weight polymer, screening tests were conducted to determine the conditions for crosslinking two low-molecular-weight (designated as HPAM1 and HPAM2), partially hydrolyzed polyacrylamides with chromium chloride and sodium dichromate/thiourea crosslinkers. Visual observation and viscosity measurements were used to monitor the gelation process. Viscosity measurements on weak gels were made to identify potential gels (viscosity lies between 5 and 125 cP at a shear rate between 1 and 10  $\text{sec}^{-1}$ ) for mobility control. After promising gels are formulated, further tests on injectivity, mechanical degradation, and reheelability of gels in cores will be conducted. This report addresses the current status of screening tests.

## ACKNOWLEDGMENTS

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## EXPERIMENTAL

### Polymer

Two low-molecular-weight polymers (designated as HPAM1 and HPAM2) used in this work were partially hydrolyzed polyacrylamides. Both polymers were manufactured by American Cyanamid Company and supplied in powdered form. The weight average molecular weight of HPAM1 is 400,000 daltons and that of HPAM2, 200,000 daltons. The degrees of hydrolysis for these two samples, according to the manufacturer, are 10 and 70%, respectively.

### Crosslinking Agent

The crosslinking agents tested were Cr(III) and Cr(VI)/thiourea. Fisher certified grade chromic chloride,  $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$  (99.6% purity) and sodium dichromate,  $\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$  (99.3% purity) were used as the source of Cr(III) and Cr(VI), respectively. The reducing agent used was Fisher certified ACS grade thiourea ( $\text{NH}_2\text{CSNH}_2$ ) (99.2% purity). All chemicals were used as received. Hydrochloric acid and sodium hydroxide were used to adjust the pH.

### Sample Preparation

Samples were prepared by mixing required amounts of stock solutions of polymer, salt, and crosslinker and/or reducing agent. The stock solution of polymer was prepared by sprinkling the powdered polymer into the vortex of deionized water over a period of about 1 minute while stirring with a caged stirrer and mixed for 3 hours. The solution was allowed to stand overnight before diluting to 400,000 ppm. The stock solution was then transferred into a plastic bottle and stored in a refrigerator when it was not in use. Stock solutions of crosslinkers and reducing agent were freshly prepared in deionized water.

All samples were prepared and stored at 22.5° C. Before mixing, all stock solutions were adjusted to the desired pH with hydrochloric acid or sodium hydroxide. The pH used in all polymer/Cr(III) systems was 4.8. In all polymer/Cr(VI) systems, pH used was 6.8. The highest pH values that chromic

chloride and sodium dichromate can be dissolved in 53 meq/L NaCl without forming any precipitate are 4.8 and 6.8, respectively.

One salinity, 53 meq/L NaCl, was used for all samples of HPAM1/crosslinker and some samples of HPAM2/crosslinker. Deionized water was also used for samples of HPAM2/Cr(VI). The concentration of polymer tested ranged from 500 to 20,000 ppm for HPAM1 and from 100 to 30,000 ppm for HPAM2. Chromium concentrations, Cr(III) or Cr(VI), tested ranged from 5 to 2,400 ppm for HPAM1 and from 100 to 7,200 ppm for HPAM2. The concentration of reducing agent used was 4 moles of thiourea per mole of sodium dichromate, and 20 ml of each sample was prepared in 25-ml vials. A Contraves shear viscometer was used to measure the viscosities of the gels.

At the beginning of screening tests, there was no information on the range of polymer and chromium concentrations where gels would form. Therefore, a lot of samples were prepared to cover a wide range of polymer and chromium concentrations. To save time, these samples were not purged with nitrogen before sealing. After the approximate range of polymer and chromium concentrations for crosslinking was found, samples prepared were purged with nitrogen before sealing. In the following section, results are presented for samples prepared under aerobic conditions unless otherwise mentioned. Chromium concentrations in ppm refer to concentrations of Cr(III) or Cr(VI) in solutions.

## RESULTS AND DISCUSSIONS

### Crosslinking of HPAM1 With Chromium Chloride

All bottle tests with Cr(III) were conducted in 53 meq/L NaCl at pH=4.8. No visible gels were formed at polymer concentrations below 10,000 ppm and chromium concentrations below 6,780 ppm. At polymer concentrations from 2,400 to 20,000 ppm and chromium concentrations from 400 to 6,780 ppm, precipitates were formed.

Visible soft gels were formed at the compositions shown in table 1. The numbers in parentheses are the number of days elapsed before samples were rechecked. Visible gels were formed at polymer concentrations from 12,000 to 20,000 ppm and chromium concentrations above 34 ppm for the 20,000 ppm polymer or above 271 ppm for the 12,000 ppm polymer. Gelation time decreased with increasing polymer and crosslinker concentration. Viscosity measurements on

the visible gels showed that they were too viscous for mobility control applications. An example of the visible gel viscosity as a function of aging time is shown in figure 1 for the 13,000 HPAM1/170 ppm Cr(III) gel. In 56 days, the viscosity increased from 5.2 to 113 cP at a shear rate equal to  $0.95 \text{ sec}^{-1}$ . After 98 days of aging, the viscosity at  $0.081 \text{ sec}^{-1}$  was increased to 8,046 cP.

Viscosity measurements on four weak gels showed that they had potential for mobility control applications. Figure 2 shows an example of the viscosity of a weak gel (12,000 ppm HPAM1/170 ppm Cr(III)) as a function of aging time.

To formulate weak gels at polymer concentrations from 13,000 to 20,000 ppm, gelation tests were made with lower chromium concentrations than those listed in table 1. Under continuous stirring and a nitrogen atmosphere, six samples (table 2) formed weak gels (viscosity greater than 10 cP at  $0.95 \text{ sec}^{-1}$ ) and six samples formed very weak gels (viscosity less than 10 cP at  $0.95 \text{ sec}^{-1}$ ). The minimum Cr(III) concentration for crosslinking HPAM1 increased with decreasing polymer concentration. Below 25 ppm of Cr(III), no gel was formed at polymer concentrations below 19,000 ppm. At 20,000 ppm of HPAM1, no gel was formed at Cr(III) concentrations below 15 ppm. Gelation times (by viscosity measurements) for these samples are about 1 to 3 weeks. Figures 3 to 5 show the viscosity of three samples, 17,000 ppm HPAM1/75 ppm Cr(III), 17,000 ppm HPAM1/100 ppm Cr(III), and 15,000 ppm HPAM1/100 ppm Cr(III). These three figures show that gelation was almost completed in 4 weeks under continuous stirring. Gel viscosity increased with increasing chromium concentration (figures 3 and 4) and polymer concentration (figures 4 and 5).

At a polymer concentration of 13,000 ppm and Cr(III) concentrations from 125 to 200 ppm, only very weak gels (shown in table 2) were formed. Viscosity measurements on these four samples showed that viscosity continuously decreased as stirring continued (figure 6). Tests with two (Cr(III)=150 and 175 ppm) of the four compositions under the same nitrogen atmosphere but without stirring (table 3) showed that gels formed without stirring (figure 7) were stronger than gels formed under continuous stirring (figure 6). Tests with two other gel systems, 15,000 ppm HPAM1/100 ppm Cr(III) and 15,000 ppm HPAM1/125 ppm Cr(III), also showed the same effects of stir on the strength of gels.

From the above tests, the minimum chromium concentrations for making crosslinked flexible HPAM1/Cr(III) gels (in 53 meq/L NaCl under N<sub>2</sub>, pH=4.8) for mobility control were determined to be about 150, 100, 75, 50 and 20 ppm for polymer concentrations at 13,000, 15,000, 17,000, 19,000, and 20,000 ppm, respectively. The upper limits of Cr(III) concentrations were about 200, 170 and 34 ppm for 13,000, 15,000, and 20,000 ppm of HPAM1.

### Effect of Oxygen on Gelation

Figure 8 shows the effect of oxygen on the gelation time and gel strength of a 13,000 ppm/Cr(III) system in 53 meq/L NaCl (pH = 4.8). The concentrations of Cr(III) in the two samples shown in figure 8 are slightly different, being 175 ppm in the sample aged under a nitrogen atmosphere and 170 ppm in the sample aged under an aerobic condition. Though the sample that was aged under a nitrogen atmosphere had a higher Cr(III) concentration, it gave a lower viscosity than did the sample aged under an aerobic condition. This indicates that oxygen has a beneficial effect on the strength of the gel formed. As shown in figure 8, the completion of gelation was delayed by the presence of oxygen. Reasons for these need further investigation.

### Crosslinking of HPAM1 With Cr(VI)/Thiourea

Screening tests with Cr(VI)/thiourea (pH=6.8) for HPAM1 were conducted at polymer concentrations from 7,000 to 20,000 ppm and Cr(VI) concentrations from 50 to 2,400 ppm. Results are shown in table 4. Unlike the HPAM1/ Cr(III) systems, precipitate was not observed at Cr(VI) concentrations greater than 400 ppm. This was attributed to the slow release of the Cr(III) ion by a reducing agent (thiourea) in solutions.

After 6 to 7 months of aging, weak gels were formed at polymer concentrations from 8,000 to 14,000 ppm and Cr(VI) concentrations from 100 (14,000 ppm HPAM1) to 2,400 ppm (8,000 ppm HPAM1). Weak gels were formed at lower HPAM1 polymer concentrations with the Cr(VI)/thiourea crosslinker at pH=6.8 than with the Cr(III) crosslinker at pH=4.8. Figure 9 shows the viscosity of a 13,000 ppm HPAM1/150 ppm Cr(VI) gel system as a function of aging time. Gels made with 20,000 ppm of polymer and 50 to 400 ppm of Cr(VI) and with 15,000 ppm of polymer and 500 to 700 ppm of Cr(VI) eventually became nonpourable. At polymer concentrations between 12,000 and 20,000 ppm, both

Cr(III) and Cr(VI) crosslinker systems (tables 1 and 4) formed weak and visible gels with HPAM1 at about the same ranges of chromium concentrations.

#### Crosslinking of HPAM2 With Chromium Chloride

Bottle tests from HPAM2/CrCl<sub>3</sub> in 53 meq/L NaCl (pH=4.8) showed that no gels were formed at polymer concentrations below 30,000 ppm and Cr(III) concentrations below 135 ppm.

Precipitate was formed immediately after 100 ppm of chromium was added to 500 and 1,000 ppm of HPAM2 solutions. At a polymer concentration of 1,500 ppm, the solution became cloudy after 100 ppm chromium was added. The cloudiness decreased as the polymer concentration was further increased and then disappeared as the polymer concentration was increased to 6,000 ppm.

As the Cr(III) concentration was increased to greater than 135 ppm, precipitate was observed in solutions with HPAM2 concentrations from 10,000 to 30,000 ppm. Precipitate was also observed in samples with 20,000 and 30,000 ppm of HPAM2 at Cr(III) concentrations above 140 ppm in deionized water. Because of the precipitate, no further screening tests were conducted for the HPAM2/Cr(III) systems. Precipitation was believed due to the high degree of hydrolysis (70%) of the polymer. As a result of these tests, it is believed that for the HPAM2 polymer, gel could only be obtained by using a crosslinker system, such as the Cr(VI)/thiourea, which releases the Cr(III) slowly.

#### Crosslinking of HPAM2 With Cr(VI)/Thiourea

Screening tests with Cr(VI)/thiourea crosslinker for HPAM2 in 53 meq/L NaCl were conducted at polymer concentrations from 100 to 8,000 ppm and chromium concentrations from 100 to 4,800 ppm. These samples were not purged with nitrogen before sealing. Results of visual observations 8.5 months after the samples were made are shown in table 5.

At a polymer concentration of 500 ppm, precipitate was formed at chromium concentrations greater than 400 ppm. At 1,000 ppm of polymer, precipitate was not formed until the chromium concentration was increased to 1,000 ppm. As the polymer concentration was increased to 1,500 ppm, precipitate was not observed. Instead, an inhomogeneous gel was formed in the bottom layer at chromium concentrations greater than 1,200 ppm. The chromium concentration at

which the sample changed from a clear solution to a two-layer solution increased with polymer concentration. Viscosity measurements on some of the clear solutions showed no viscosity enhancement.

Of the 72 samples tested, only two samples, 3,000 ppm HPAM2/2,400 ppm Cr(VI) and 6,000 ppm HPAM2/4,800 ppm Cr(VI), formed gels. Viscosity measurements on these two samples showed that the 3,000 ppm HPAM2/2,400 ppm Cr(VI) sample had the potential for mobility control. Figure 10 shows the viscosity of this sample. The 6,000 ppm HPAM2/4,800 ppm Cr(VI) sample was too viscous to use as a mobility control agent.

Since the chromium concentration of the gel lies between that of the clear solution and that of the two-layer solution (see table 5), it can be deduced that gel can also be formed at chromium concentrations between 1,000 and 1,200 ppm, and between 2,400 and 4,800 ppm for the 1,500 ppm and 3,750 or 4,500 ppm HPAM2 solutions.

Screening tests with Cr(VI)/thiourea crosslinker were also conducted in deionized water at polymer concentrations from 3,000 to 10,000 ppm and Cr(VI) concentrations from 2,400 to 7,200 ppm at 22.5° C under a nitrogen atmosphere. Results are shown in table 6. Among the 25 samples tested, only one sample, 6,000 ppm HPAM2/ 3,600 ppm Cr(VI), formed a very clear gel. The gelation time for this sample (by visual observation) was longer than 2.5 months. Four other samples formed gels but also contained small amounts of suspensions. Gelation times (by visual observation) of these samples except the 4,000 ppm HPAM2/3,600 ppm Cr(VI) sample, were less than 2.5 months. Solid gels were formed at a Cr(VI) concentration of 7,200 ppm and polymer concentrations from 4,000 to 10,000 ppm. Solid gels were also formed at polymer concentrations from 4,000 to 8,000 ppm and a Cr(VI) concentration of 6,000 ppm.

Viscosity measurements on the 6,000 ppm HPAM2/3,600 ppm Cr(VI) gel indicate that this gel is very promising for mobility control. The viscosity (figure 11) increased from 7.6 cP at 128.5 sec<sup>-1</sup> to 52.54 cP at 0.512 sec<sup>-1</sup>. Before gelation, the viscosity of the gel system (figure 11) was lower than that of the plain polymer solution (12.53 cP at 0.95 sec<sup>-1</sup>) because of the increased concentration of metallic ions.

After increasing the Cr(VI) concentration from 3,600 to 4,800 ppm, the gel formed with the 6,000 ppm HPAM2 was much like a slurry. This indicates that the proper chromium concentration for forming a clear gel lies below that of an inhomogeneous gel. Hence, clear gels should be obtained at Cr(VI) concentrations between 2,400 and 3,600 ppm, 3,600 and 4,800 ppm, and 4,800 and 6,000 ppm for the 4,000, 8,000, and 10,000 ppm HPAM2 solutions, respectively.

Twenty-five samples at the same compositions as those listed in table 6 were also prepared and purged with nitrogen to investigate the effect of agitation on gelation. After 50 days of continuous stirring and aging for another 70 days, none of the samples formed clear, homogeneous gel. This indicates that continuous agitation will adversely affect the gelation.

### Effect of High Shear on Gelation

To test whether the gels will reheal after experiencing a high shear rate, a 15,000 ppm HPAM1/135 ppm Cr(III) gel (shown in figure 12) was injected through a 48-ft-long, 1/16-in.-O.D. monel tubing at an apparent shear rate of  $1,040 \text{ sec}^{-1}$ . Before injection, an identical polymer solution without a crosslinker was also injected through the same tubing at the same shear rate to ensure that no chemical reaction occurred between the polymer and tubing. It was found that the gel after injection through the tubing had a higher viscosity (as shown in figure 12) than the gel before injection. Since there was no chemical reaction between polymer and tubing, the increase in viscosity was due to a further reaction between the polymer and crosslinker, Cr(III). This indicates that gels can be used more effectively by injecting them through a high shear rate device before injecting them into reservoirs.

### CONCLUSIONS

1. Crosslinked, low-molecular-weight, polyacrylamide flexible gels for mobility control can be formulated with both Cr(III) (pH=4.8) and Cr(VI)/thiourea (pH=6.8) crosslinkers using HPAM1 polymer of MW=4000,000, which is 10% hydrolyzed.
2. HPAM1/Cr(VI) gels can be obtained at lower polymer concentrations than HPAM1/Cr(III) gels.

3. For the HPAM2 polymer, which is 70% hydrolyzed and has a molecular weight of 200,000, gels can only be obtained with a crosslinker, such as Cr(VI)/thiourea, that releases the crosslinking ion slowly.
4. The strengths of gels made from the same types of polymer and crosslinker increase with increase in polymer concentration and crosslinker concentration.
5. Oxygen can delay the completion of gelation but will increase the strengths of gels.
6. Continuous agitation can adversely affect the strength of gels.
7. Gels can be used more effectively by injecting them through a high shear device before injecting them into reservoirs.

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TABLE 1. - Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8) at 22.5° C, 5.3 months

Cr(III) conc., ppm	Polymer conc., ppm							
	7k	8k	10k	12k	13k	14k	15k	20k
0	<sup>1</sup> 2.81	3.09	3.70	4.45	4.8	5.15	5.49	7.83
34								VG(29)
68								VG(29)
102								VG(20)
136								
170	N <sup>2</sup>	N	VWG <sup>3</sup>	WG <sup>4</sup>	VG(98) <sup>5</sup>	VG(56)	VG(38)	
203				WG	VG(98)	VG(44)	VG(35)	
237						VG(44)	VG(19)	
271				VG(64)	VG(44)	VG(20)	VG(19)	
305								
339	N	N	VWG	VG(64)	VG(44)			
407			PPT+ WG PPT+VG(52)					
441								
475					PPT <sup>6</sup>			
509								
6,780								

<sup>1</sup>Viscosity of polymer solution in cP.

<sup>2</sup>N = No gel formed.

<sup>3</sup>VWG = Very weak gel (viscosity less than 10 cP at 0.95 sec<sup>-1</sup>).

<sup>4</sup>WG = Weak gel (viscosity greater than 10 cP at 0.95 sec<sup>-1</sup>).

<sup>5</sup>VG = Visible gel (too viscous for mobility control). The number in parentheses indicates the number of days elapsed before samples were rechecked.

<sup>6</sup>PPT = Precipitate formed in the sample.

TABLE 2. - Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8) at 22.5° C under N<sub>2</sub>, 72 days (continuous agitation for 72 days)

Cr(III) conc., ppm	Polymer conc., ppm						
	10,000	12,000	13,000	15,000	17,000	19,000	20,000
0	<sup>1</sup> 3.7	4.4	4.8	5.68	6.62	7.58	8.17
5							N
10						N	N
15						N	N
25					N	N	
50					WG	WG	
75				VWG	WG		
100				WG <sup>4</sup>	WG		
125			VWG <sup>3</sup>	WG			
150		N	VWG	WG			
175	N <sup>2</sup>	N	VWG				
200		N	VWG				
225	N	N					
250		N					
350	N						
400	N						

<sup>1</sup>Viscosity of polymer solution in cP.

<sup>2</sup>N = No gel formed.

<sup>3</sup>VWG = Very weak gel (viscosity less than 10 cP at 0.95 sec<sup>-1</sup>).

<sup>4</sup>WG = Weak gel (viscosity greater than 10 cP at 0.95 sec<sup>-1</sup>).

TABLE 3. - Gelation tests for HPAM1/Cr(III) in 53 meq/L NaCl (pH=4.8)  
at 22.5° C under N<sub>2</sub> without agitation, 73 days

Cr(III) conc., ppm	Polymer conc., ppm				
	10,000	12,000	13,000	15,000	20,000
5					N <sup>1</sup>
10					N
100				WG <sup>2</sup>	
125				WG	
150			WG		
175		N	WG		
200		N			
225	N				
350	N				

<sup>1</sup>No gel formed.

<sup>2</sup>Weak gel.

TABLE 4. - Gelation tests for HPAM1-Cr(VI)/thiourea in 53 meq/L NaCl (pH=6.8) at 22.5° C, 6 months

Cr(VI) conc., ppm	Polymer concentration, ppm							
	7,000	8,000	10,000	12,000	13,000	14,000	15,000	20,000
0	<sup>2</sup> 3.23	3.79	4.70	5.5	6.0	6.5	7.0	10.0
50								NPG <sup>3</sup>
100						WG	VG <sup>4</sup>	NPG
125								NPG
150				WG <sup>5</sup>	WG	WG	VG	NPG
170					VG	VG(38) <sup>6</sup>		
175				WG				NPG
200				WG	VG(42)	VG(38)	VG(31)	
225				VG	VG(42)	VG(31)	VG(31)	
250				VG	VG(38)	VG(31)	VG(31)	
275				VG	VG(30)	VG(31)		
300					VG(30)			
350					VG(30)			
400								NPG
500	N <sup>7</sup>	N					NPG	
600							NPG	
700			N				NPG	
1,000	N		WG					
1,500		N						
2,000	N	WG						
2,400	N	WG	VG					

<sup>1</sup>7 months for 7,000 ppm, 8,000 ppm and 10,000 ppm HPAM1 samples.

<sup>2</sup>Viscosity of polymer solution in cP.

<sup>3</sup>Nonpourable gel (too viscous for mobility control).

<sup>4</sup>Visible gel (too viscous for mobility control).

<sup>5</sup>Weak gel.

<sup>6</sup>The number in parentheses indicates the number of days elapsed before samples were rechecked.

<sup>7</sup>No gel formed.

TABLE 5. - Gelation tests for HPAM2-Cr(VI)/thiourea in 53 meq/L NaCl (pH=6.8) at 225° C, 8.5 months

Cr(VI) Conc., ppm	Polymer Concentration, ppm							
	500	1,000	1,500	3,000	3,750	4,500	6,000	8,000
0	<sup>1</sup> 1.26	1.59	1.91	2.98	3.60	4.12	5.46	7.27
100	N <sup>2</sup>	N	N	N	N	N	N	N
200	N	N	N	N	N	N	N	N
400	ppt <sup>3</sup>	N	N	N	N	N	N	N
600	ppt	N	N	N	N	N	N	N
800	ppt	N	N	N	N	N	N	N
1,000	ppt	ppt	N	N	N	N	N	N
1,200	ppt	ppt	2p <sup>4</sup>	N	N	N	N	N
2,400	ppt	ppt	2p	Gel	N	N	N	N
4,800	ppt	ppt	2p	2p	2p	2p	Gel	N

<sup>1</sup>Viscosity of polymer solution in cP.

<sup>2</sup>No gel formed.

<sup>3</sup>Precipitate formed in solution.

<sup>4</sup>Top layer was a clear solution, bottom layer was an inhomogeneous gel.

TABLE 6. - Gelation tests for HPAM2-Cr(VI)/thiourea in deionized water (pH=6.8) under N<sub>2</sub> at 22.5° C, 4 months

Cr(VI) Conc., ppm	Polymer Conc., ppm				
	3,000	4,000	6,000	8,000	10,000
0	<sup>1</sup> 7.73	10.24	12.53	15.05	18.08
2,400	Ge1 <sup>2</sup>	N <sup>3</sup>	N	N	N
3,600	IHG <sup>4</sup>	Ge1 <sup>2</sup>	Ge1 <sup>5</sup>	N	N
4,800	IHG	IHG	IHG	Ge1 <sup>2</sup>	N
6,000	IHG	SG <sup>6</sup>	SG	SG	Ge1 <sup>2</sup>
7,200	IHG	SG	SG	SG	SG

<sup>1</sup>Viscosity of polymer solution in cP at a shear rate of 0.95 sec<sup>-1</sup>.

<sup>2</sup>Gel contains small amount of suspension.

<sup>3</sup>No gel formed.

<sup>4</sup>Inhomogeneous gel.

<sup>5</sup>Very clear gel. Gelation time is longer than 2.5 months.

<sup>6</sup>Solid gel.

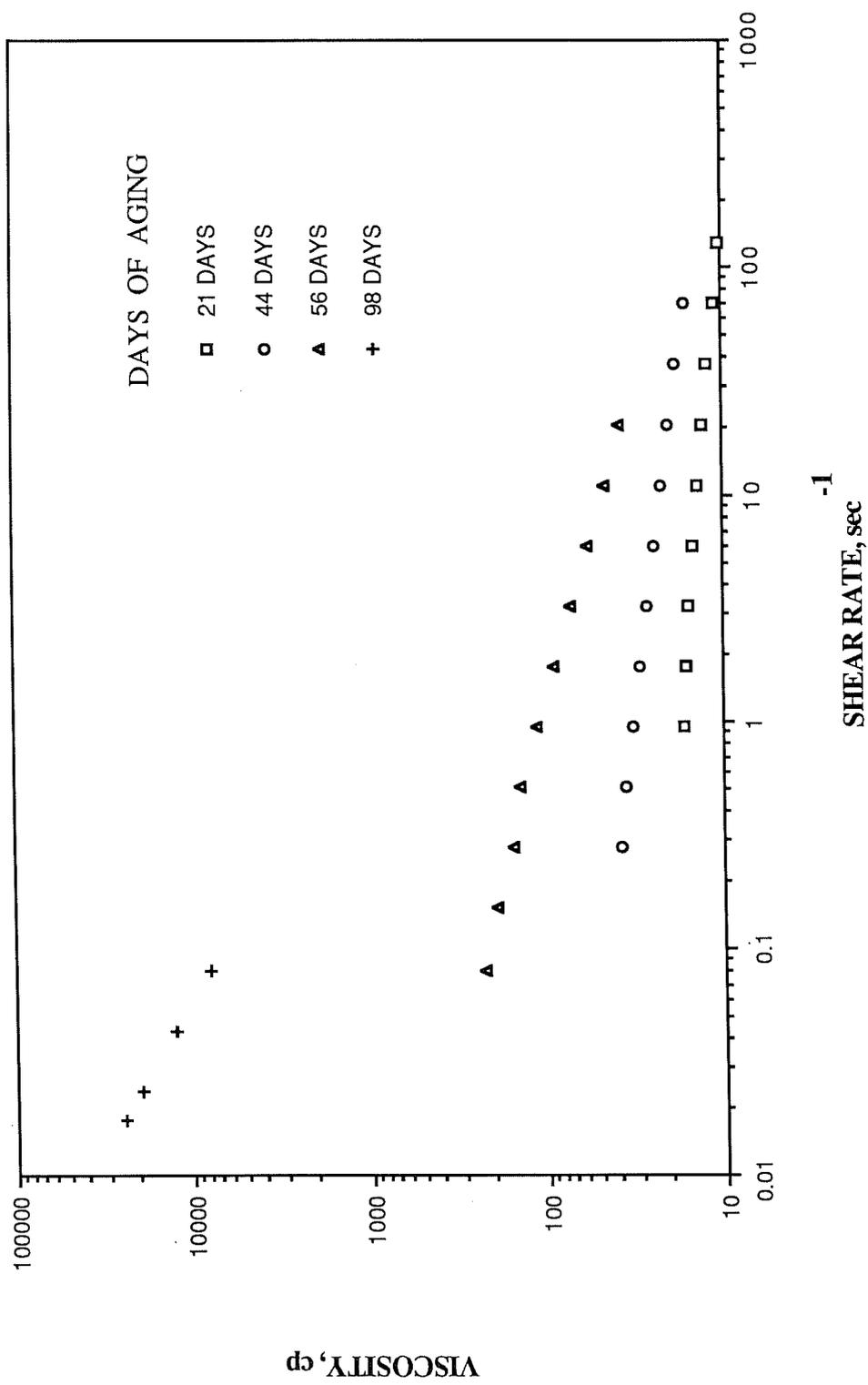


FIGURE 1. - Rheograms for the 13,000 ppm HPAM1/170 ppm Cr(III) gel system in 53 meq/L NaCl (pH = 4.8) at 22.5° C. The viscosity of the 13,000 ppm polymer solution at pH = 4.8 is 4.8 cP.

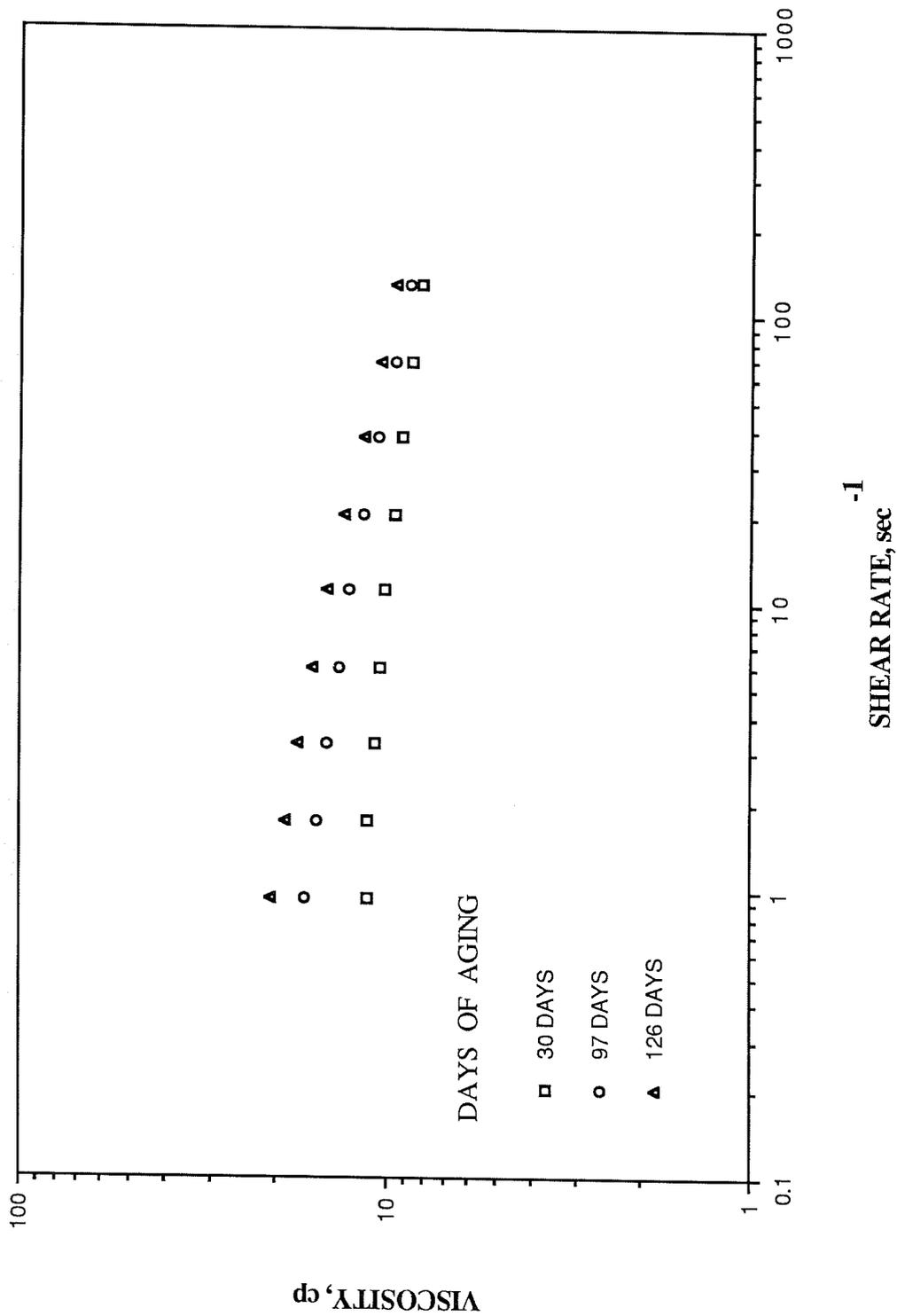


FIGURE 2. - Rheograms for the 12,000 ppm HPA. /170 ppm Cr(III) gel system in 53 meq/L NaCl (pH = 4.8) at 22.5° C. The viscosity of the 12,000 ppm polymer solution at pH = 4.8 is 4.45 cP.

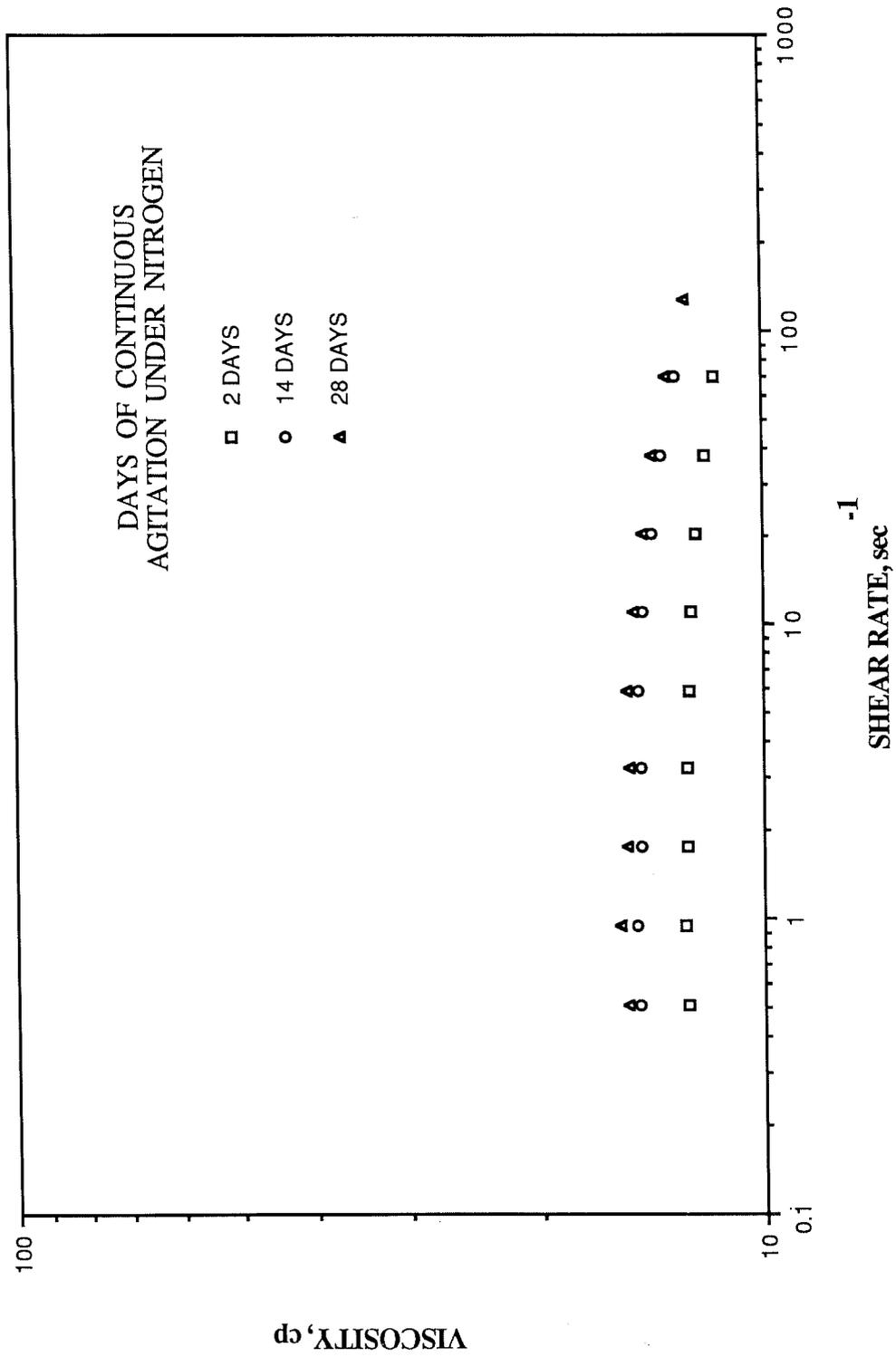


FIGURE 3. - Rheograms for the 17,000 ppm HPAM1/75 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH = 4.8) at 22.5° C. The viscosity of the 17,000 ppm polymer solution at pH = 4.8 is 6.62 cP.

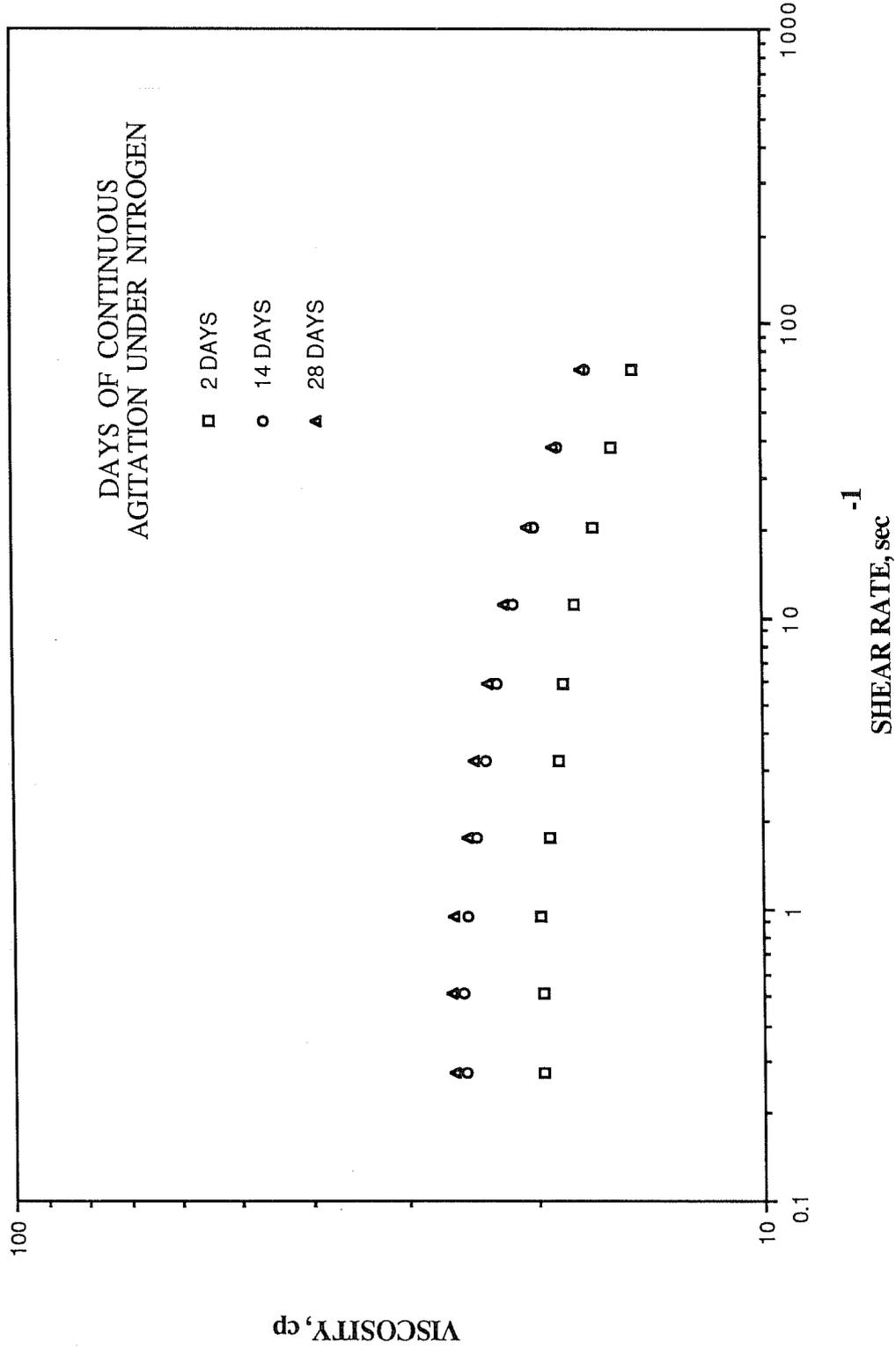


FIGURE 4. - Rheograms for the 17,000 ppm HPAM1/100 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH = 4.8) at 22.5 °C. The viscosity of the 17,000 ppm polymer solution at pH = 4.8 is 6.62 CP.

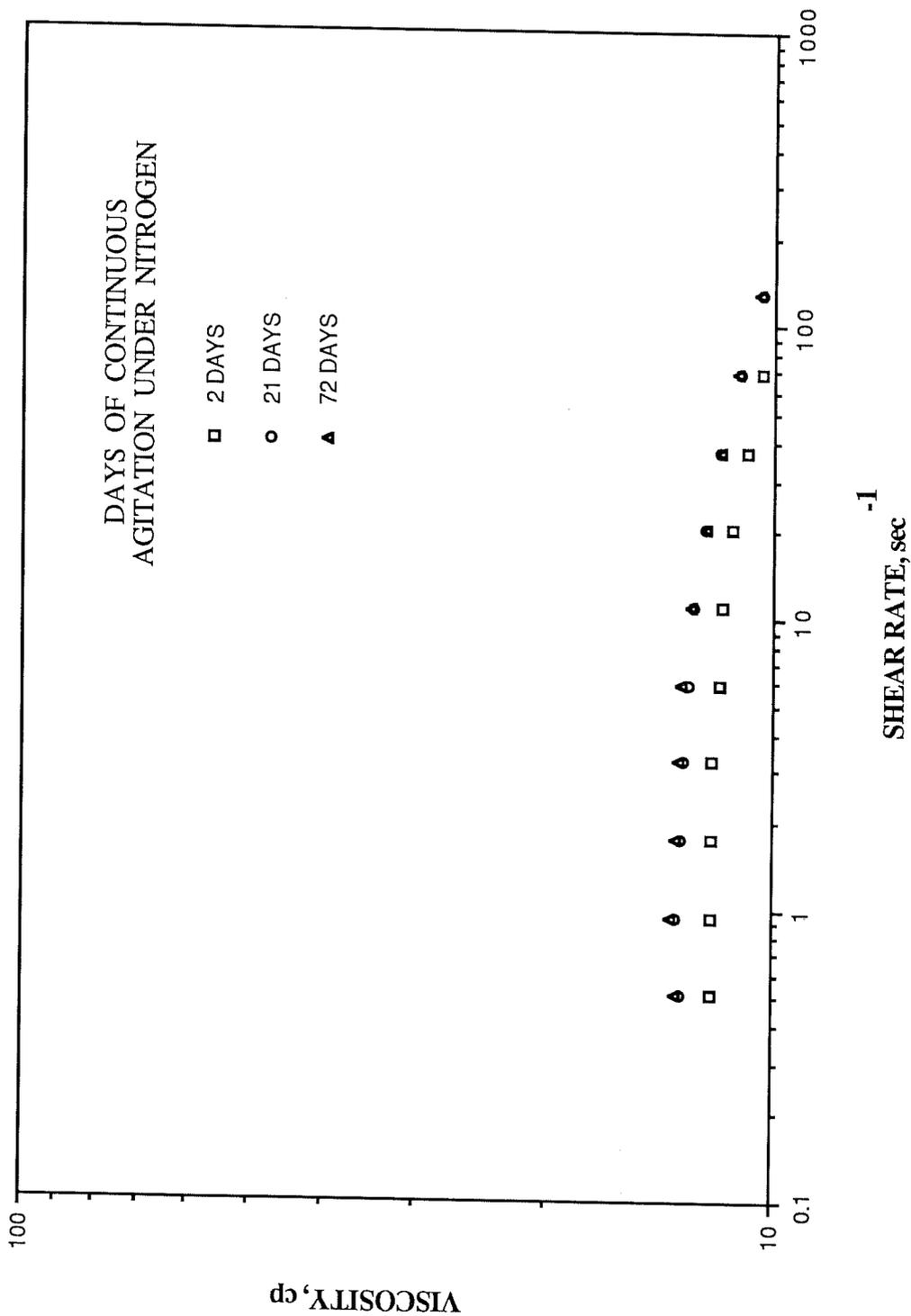


FIGURE 5. - Rheograms for the 15,000 ppm HPAM1/100 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH = 4.8) at 22.5 °C. The viscosity of the 15,000 ppm polymer solution at pH = 4.8 is 5.68 cP.

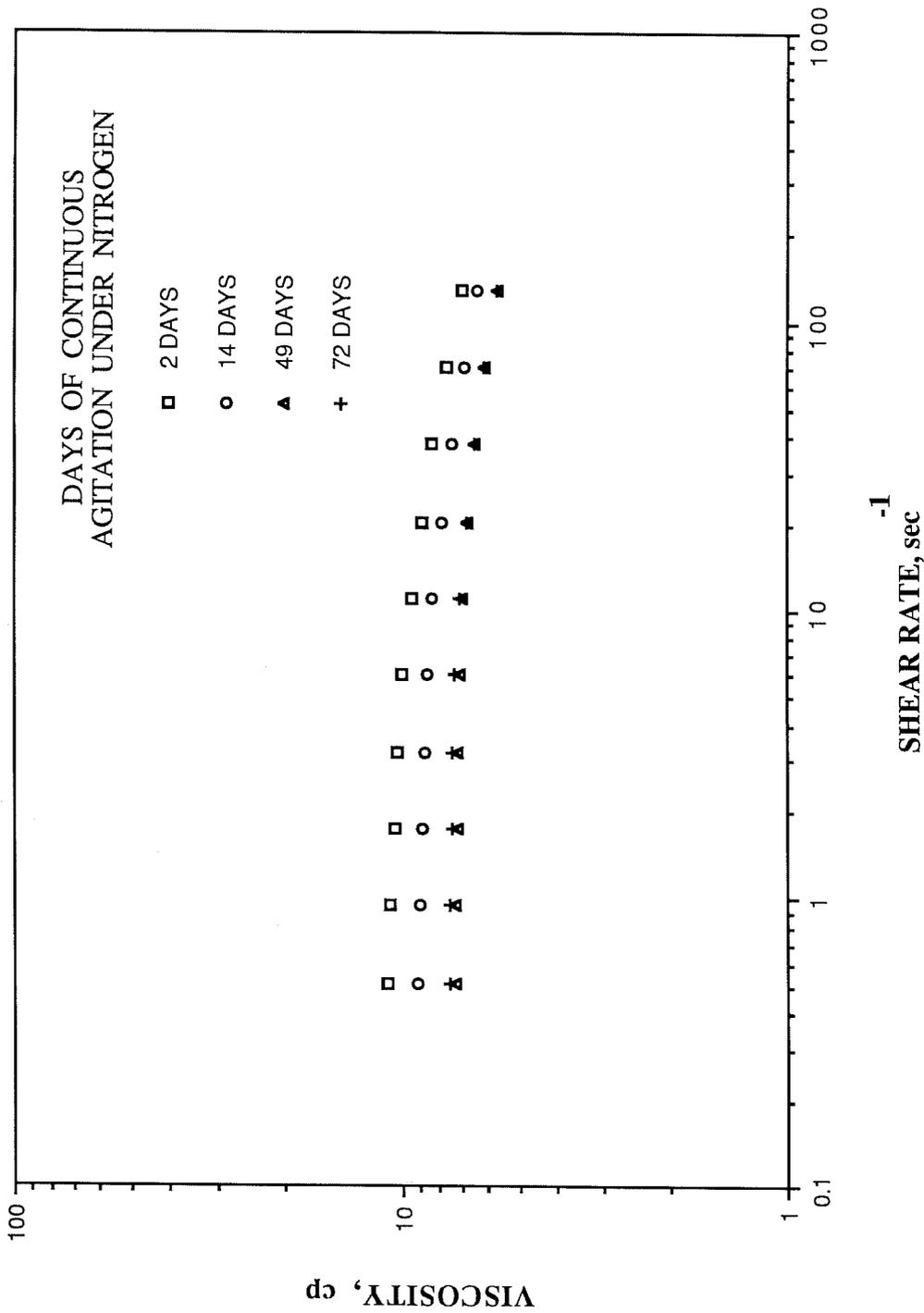


FIGURE 6. - Rheograms for the 13,000 ppm HPAM1/175 ppm Cr(III) gel system (under continuous agitation in 53 meq/L NaCl, pH = 4.8) at 22.5 °C. The viscosity of the 13,000 ppm polymer solution at pH = 4.8 is 4.8 cP.

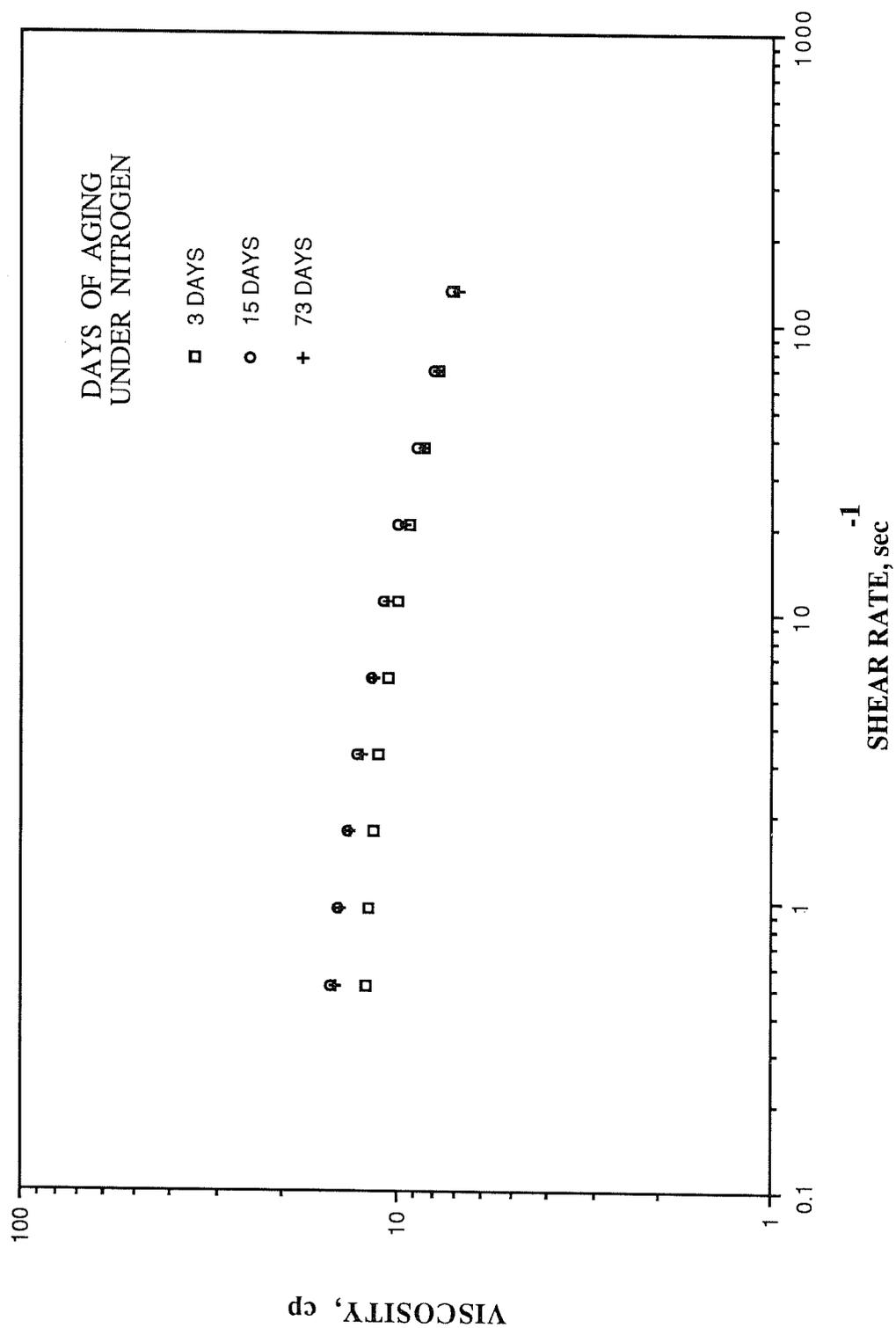


FIGURE 7. - Rheograms for the 13,000 ppm HPAM1/175 ppm Cr(III) gel system in 53 meq/L NaCl (pH = 4.8) at 22.5° C. The viscosity of the 13,000 ppm polymer solution at pH = 4.8 is 4.8 cp.

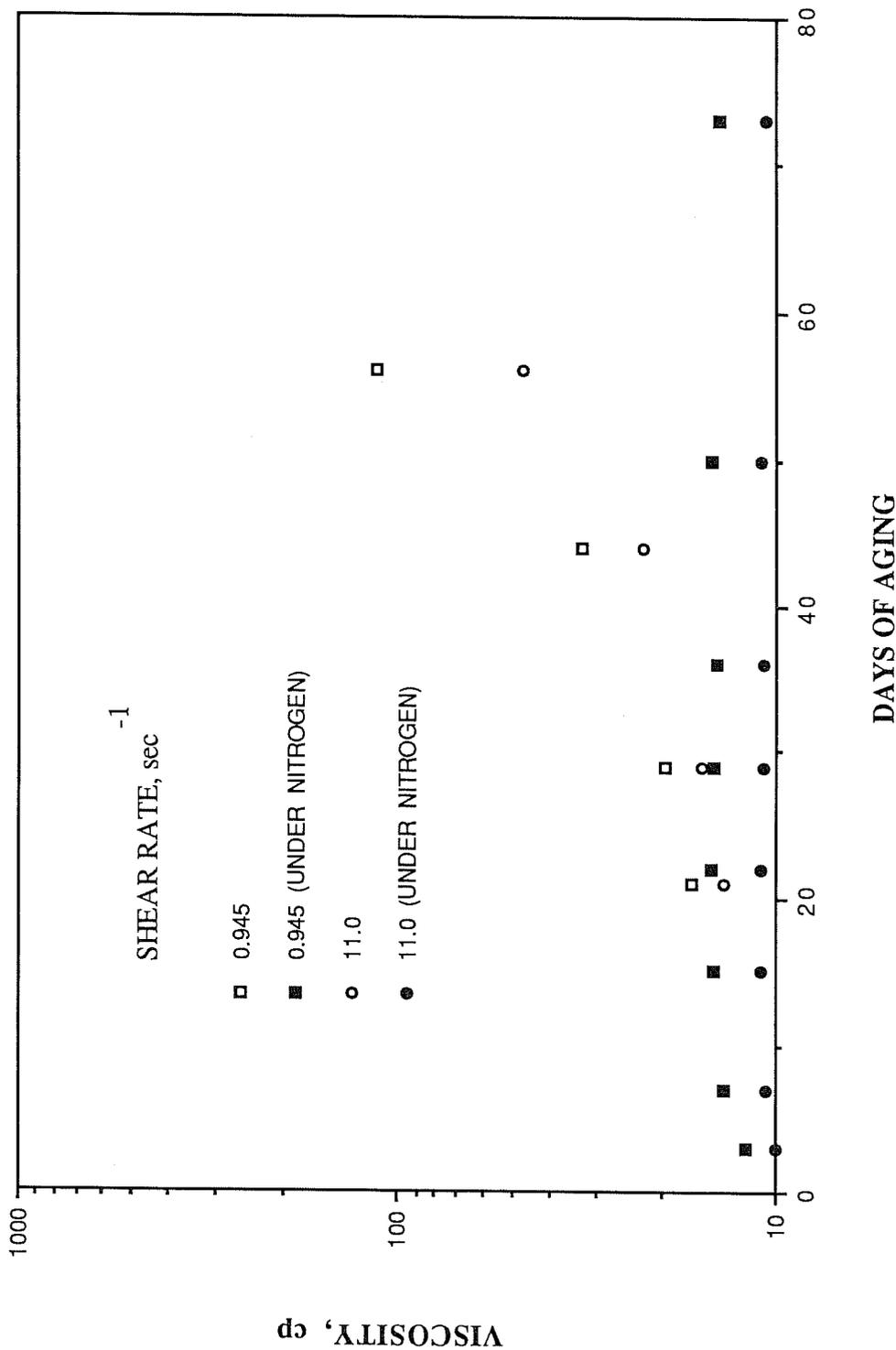


FIGURE 8. - Effect of oxygen on the gelation time and gel strength of a 13,000 ppm Cr(III) system in 53 meq/L NaCl (pH = 4.8). The Cr(III) concentrations are 175 ppm in the sample aged under a nitrogen atmosphere and 170 ppm in the sample aged under an aerobic condition.

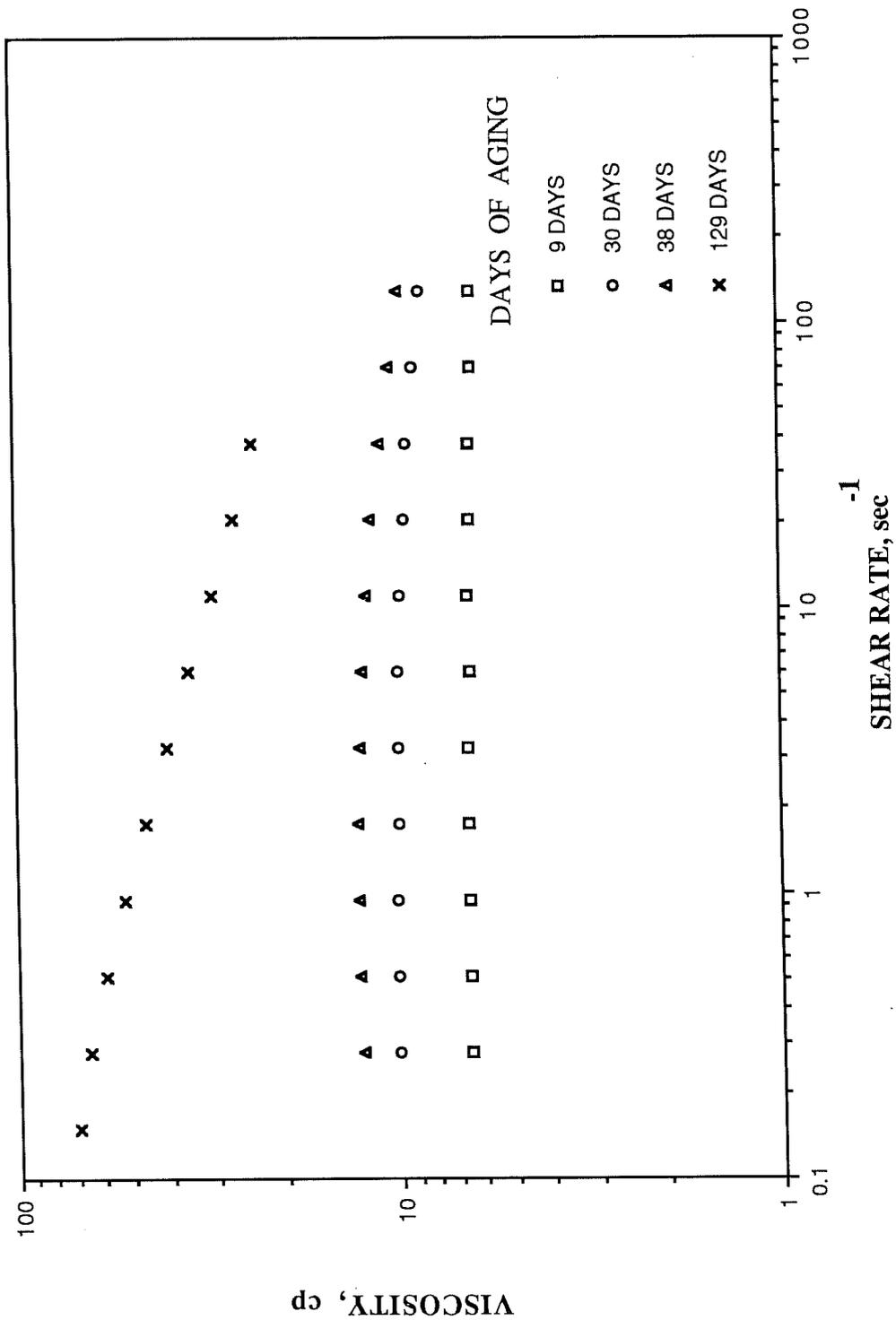


FIGURE 9. - Rheograms for the 13,000 ppm HPAM1/150 ppm Cr(VI) gel system in 53 meq/L NaCl (pH = 6.8) at 22.5° C. The viscosity of the 13,000 ppm polymer at pH = 6.8 is 6.0 cP.

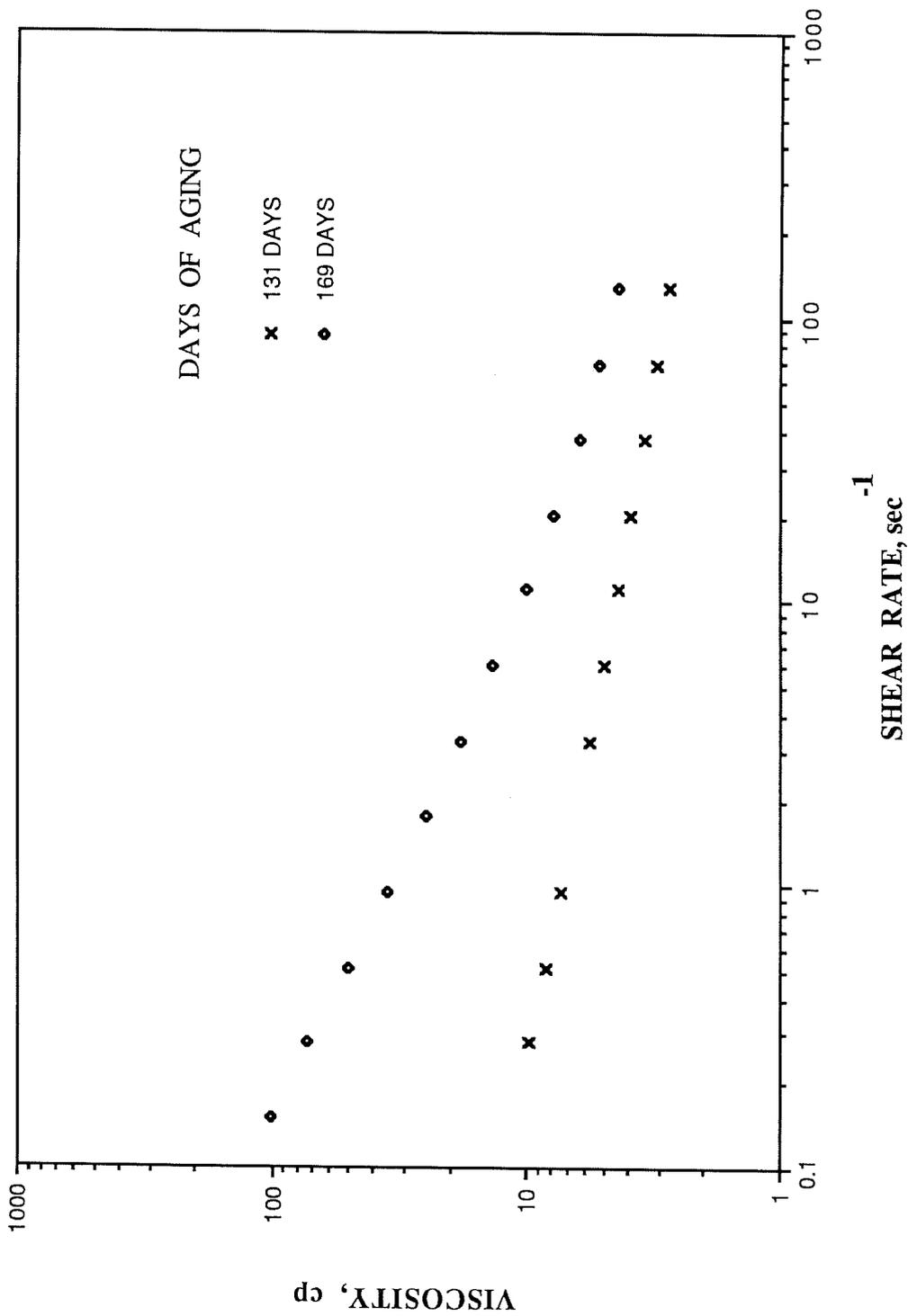


FIGURE 10. - Rheograms for the 3,000 ppm HPAM2/2,400 ppm Cr(VI) gel system in 53 meq/L NaCl (pH = 6.8) at 22.5° C. The viscosity of the 3,000 ppm HPAM2 solution at pH = 6.8 is 2.98 cP.

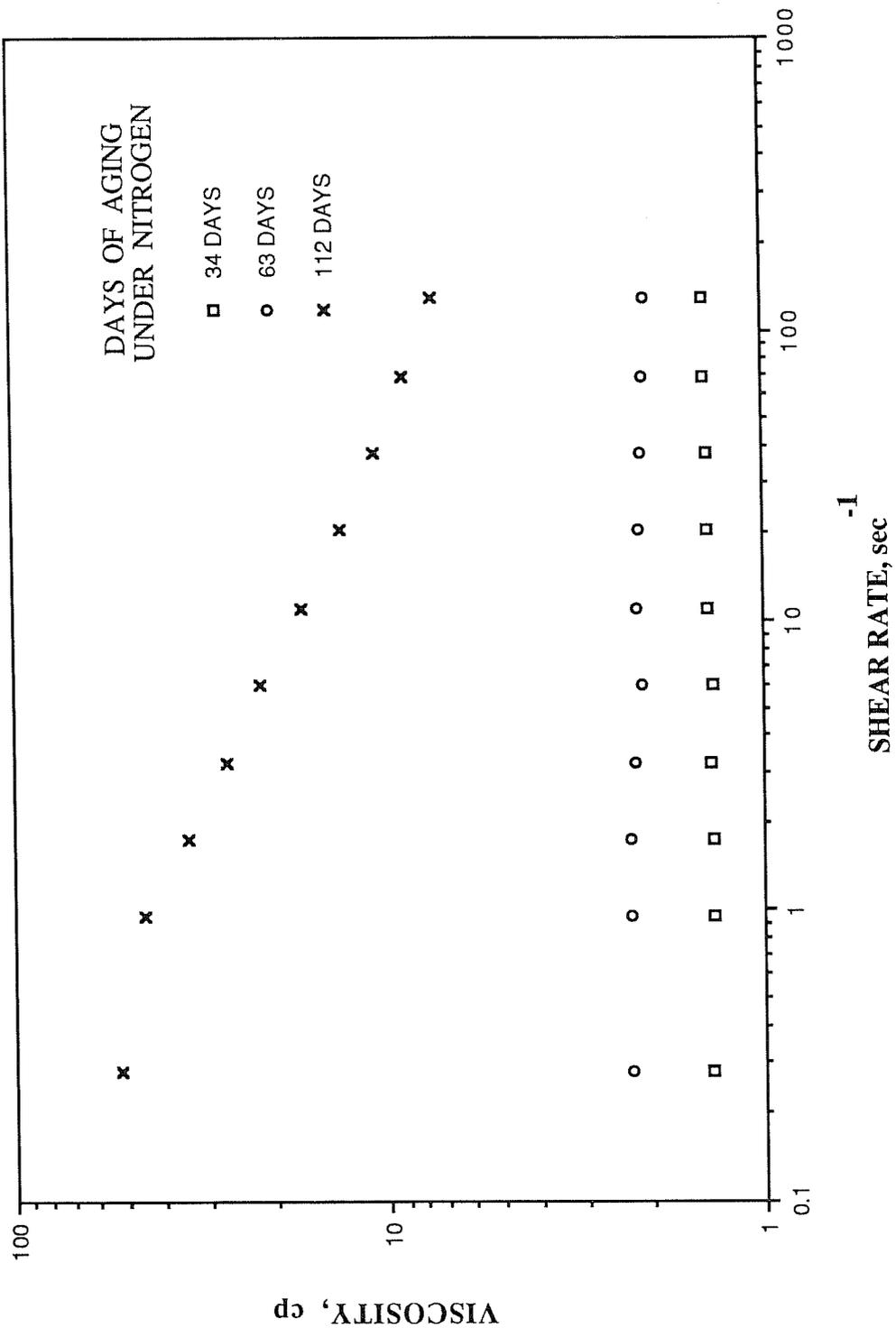


FIGURE 11. - Rheograms for the 6,000 ppm HPAM<sub>2</sub>/3,600 ppm Cr(VI) gel system in deionized water (pH = 6.8) at 22.5° C. The viscosity of the 6,000 ppm polymer at pH = 6.8 is about 12.5 cp.

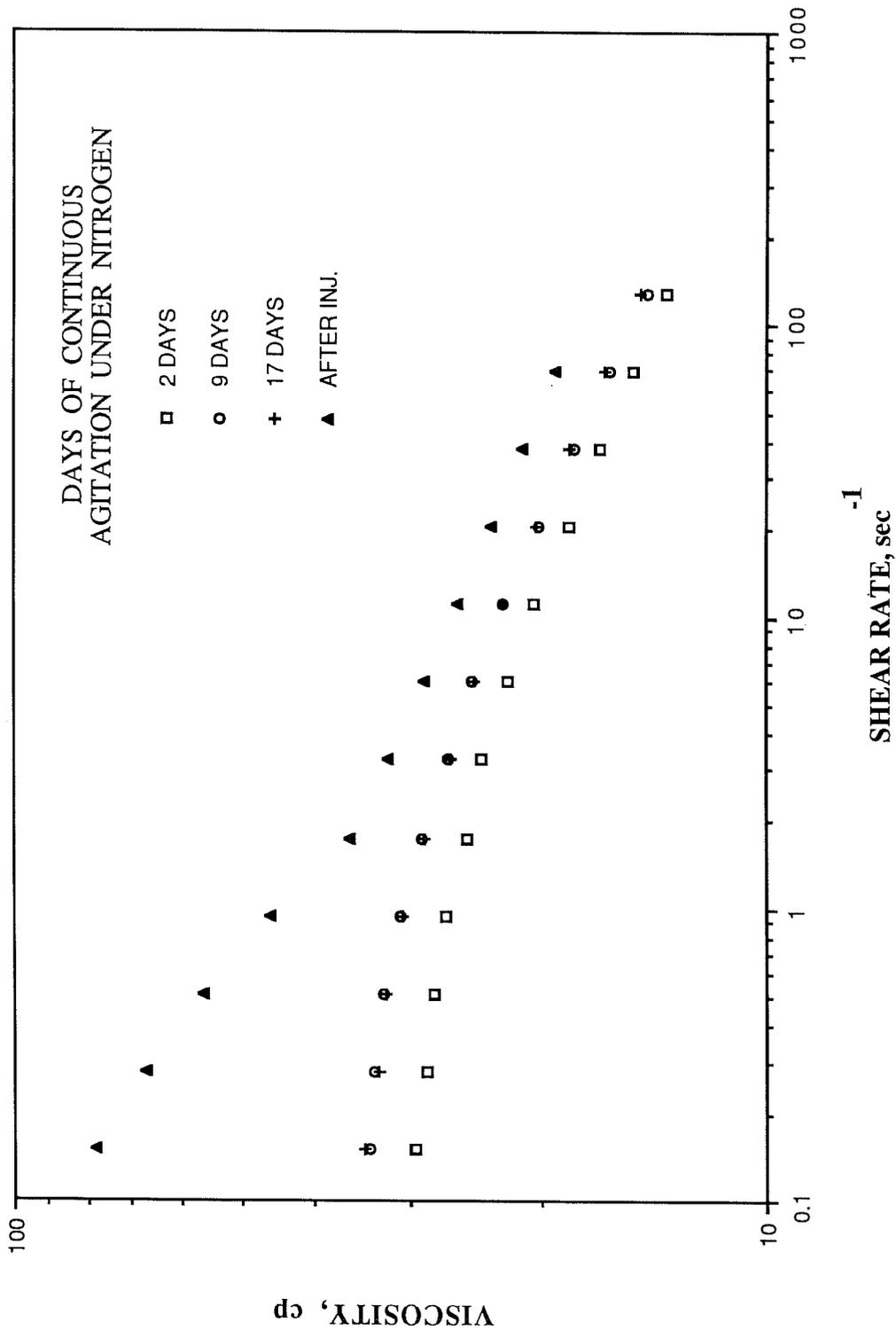


FIGURE 12. - Rheograms for the 15,000 ppm HPAM1/135 ppm Cr(III) gel system (under continuous stir in 53 meq/L NaCl, pH = 4.8) at 22.5 °C before and after injecting through a 48-ft-long, 1/16-in. O.D. monel tubing at an apparent shear rate of 1,040 sec<sup>-1</sup>.

