Bulk and rheological properties of polyacrylamide hydrogels for water shutoff treatment

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Abstract−Presenting an optimal hydrogel for water shutoff, based on the bulk and rheological properties, was the main purpose of this research. To determine gelation time, a bottle test was conducted using central composite design method with two factors, AN125VLM and Cr(OAc)$_3$, as copolymer and crosslinker, respectively. To select hydrogel with high strength network, crosslinking density and consistency modulus were also measured. Hence, a hydrogel with 26,340 ppm concentration of copolymer, 0.12 ratio of crosslinker/copolymer, maximum value of crosslinking density (1,950) and consistency modulus (31,900 Pa) was selected as the optimal one. To study the gelation time among different factors in porous media, rheological experiments were carried out by Plackett-Burman design to screen the eight factors (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay). Accordingly, temperature was the most effective factor controlling the gelation time, while pH and other factors had negligible effect on the gelation time of the optimal hydrogel.

Keywords: Hydrogel, Bottle Test, Rheological Tests, Crosslinking Density, Consistency Modulus, Central Composite Design, Plackett-Burman Design

INTRODUCTION

Accompanying high water production in oil producing wells, conformance challenges have always been an issue for petroleum engineers. For several decades, engineers have applied various improved methods to overcome high water production problems to increase oil recovery [1]. Water shutoff methods can be classified in two different types: mechanical and chemical. Mechanical methods are limited to the application of specific completion tools as dual systems to avoid water conning or the use of hydro-cyclones to separate water while it is being produced [2]. On the other hand, chemical methods, extensively used in the last decade [3,4], consist mainly of chemical products that are pumped into producer or injector wells. A more recent development is the use of an internally crosslinked polymer that expands to form a blocking phase far from the injection well. These gels, which are the basis of the most water shutoff treatments, can partially or completely block the channels through which water is being produced. Several authors have reported the characteristics of gel polymers (hydrogels) utilized for other purposes in detail [5-7]. Selection of a polymer gel system for a given well treatment strongly depends on reservoir conditions such as temperature, hardness and the pH of the water used for preparation of the gelant. Salinity of the formation water, permeability of the target zone, and the lithology of the formation are the other parameters that could be considered for the proper selection of a given polymer gel system [8-11]. Gelation time and gel strength are the main factors to select the suitable gel system. Among the

different techniques that measure the consistency of gelling systems (such as bottle test and rheological tests), rheology is considered as the most complete technique of characterization the polymer systems [14]. The rheological research shows that Cr(III)-acetate-HPAM gels are viscoelastic, meaning that their properties are intermediate between those of elastic solids and viscous liquids. The gelation of HPAM by Cr(III) using rheological and spectroscopic methods was studied by Allain and Salome [15]. They related measurements of viscosity and elastic modulus to the number of crosslinks formed during gelation. Broseta et al. [16] used rheological measurements to study polyacrylamide/chromium (III) gelation as a function of temperature, crosslinker concentration, polymer concentration and polymer molecular weight. They showed that the gelation time was a weak function of crosslinker concentration for acrylate/chromium (III) (molar ratio between 1.5 and 10) and a much stronger function of polymer concentration. Because of disproportionate permeability reduction (DPR) property of polymer gels in water shutoff operations in petroleum field, the yield stress as a rheological property of the gel systems must be investigated to assure gel placement into the fractures of the reservoirs [17-19]. Nanocomposite type of hydrogels (NC gels) was also used by Zolfaghari et al. [20] by crosslinking the polyacrylamide/montmorillonite (Na-MMT) clay aqueous solutions with chromium (III). They showed that the rate of gelation was retarded especially for the gelant solution composed of 2% (v/v) sodium lactate as retarder. They observed that gel syneresis decreased by increasing retarder content.

It is desirable to approach an optimal hydrogel with eligible performance of water shutoff operation in terms of bulk and rheological properties. Considering this purpose, the statistical design of the experiments by response surface methodology (RSM) [21] using central composite design (CCD) was applied for bottle test indicat-

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ing the gelation time, gel strength and thermal stability, visually. Hydrogels were prepared by using a low MW copolymer of sulfonated polyacrylamide and chromium triacetate as a crosslinker. As the bottle test method would not be a suitable way to select a hydrogel with high strength network lonely, the rheological tests were carried out by the dynamic rheometer on the candidate hydrogels through the results of a bottle test. Among them, the hydrogel with maximum value of crosslinking density and consistency modulus was selected as an optimum one. Moreover, study of the effective factors of porous media such as temperature, pH, salinity of the formation water and operating factors (before the field operation) is necessary while they have significant effect on the gelation time of the hydrogels along with the components value. Therefore, the important role of an appropriate composition of the hydrogel (providing a hydrogel with minimum impact on the operating factors) in the success of the field operation is expected. To conduct the fewest experiments, Plackett-Burman design [22] was used to screen eight factors (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay). Rheological tests were carried out for viscosity measurements on the optimal hydrogel to present the most effective factor. Therefore, the optimal hydrogel would contain both bulk and rheological properties such as the suitable gelation time, gel strength, thermal stability and low sensitivity to the factors of porous media.

EXPERIMENTAL

The experimental procedures of this work were represented in a schematic diagram (Fig. 1) to determine the optimum hydrogel with desirable properties for water shutoff.

1. Materials

The hydrogels were prepared by a copolymer of 2-acrylamido-2-methyl-propanesulfonic-acid sodium salt (AMPS) and acrylamide (AcA) (Fig. 2), with a low molecular weight of 2 million Dalton and sulfonation degree of 25%, provided by SNF Co. (France). It is also called sulfonated polyacrylamide (PAMPS), under the trade name of AN125VLM, in powder form. Furthermore, chromium triacetate, as an ionic crosslinker, purchased from Carlo Erba Co. (Italy), was used in powder form. NaCl, CaCl$_2$, MgCl$_2$ and KCl of
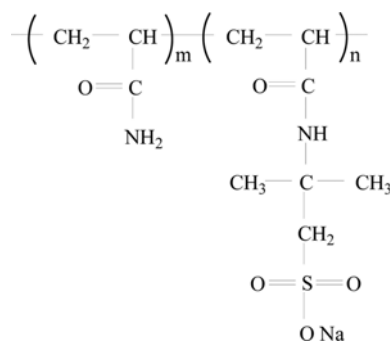

Fig. 2. Sulfonated polyacrylamide structure.

analytical grade, HCl and NaOH solutions were purchased from Merck Co. (Germany). Nanoclay used in this study was Na-montmorillonite with d_{001} interplanar spacing of 12, supplied from Advanced Technology (China). Sodium lactate was also used as retarder, and was provided by Merck Co. (Germany) in the form of a colorless liquid.

2. Samples Preparation

First, to prepare the PAMPS solution at a concentration of 3%, the co-polymer powder and distilled water were mixed for 24 hours. The mixture was then held, without stirring, for two days to obtain a solution. Shortly before the experiment, the PAMPS solutions were diluted to the required concentrations and the mixtures were stirred for 5 min. Then the second solution (contain crosslinker and other possible additives according to the experimental design composition of each part) was also mixed with distilled water at room temperature, using a magnetic stirrer (Stuart CB162, UK) for 5 min. Finally, the PAMPS and second solutions were mixed for 10 min to obtain a homogeneous gelant solution.

3. Bottle Test

The bottle test method, as an experimental technique, provides a semi quantitative measurement of gelation time and gel strength. As a simple and basic method to study the gel performance, bottle test results can be used to determine the gelation time, stiffness and final gel consistency of the gel by visual examination. In this method, which was defined by Sydansk [10], gel strength during develop-
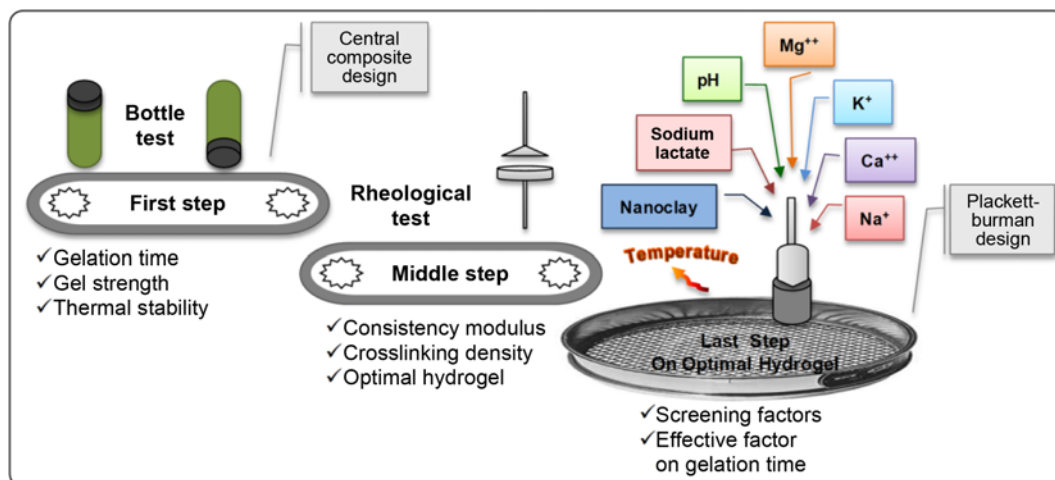

Fig. 1. A schematic diagram of experimental procedure in three steps (bottle test, rheological tests, screening the effective factors).

Table 1. Gel strength of Sydansk code [10]

Gel strength code	Gel description
A	No detectable gel formed
B	Highly flowing gel
C	Flowing gel
D	Moderately flowing gel
E	Barely flowing gel
F	Highly deformable non flowing gel
G	Moderately deformable non flowing gel
H	Slightly deformable non flowing gel
I	Rigid gel

ment of gelation kinetic is expressed as an alphabetic code of A through I shown in Table 1. According to this method, the gel strength codes range from high flowing gels with barely any gel structure visibly detectable to rigid rubbery gels. To select the optimal component of the hydrogel, the CCD method, the most popular method of RSM was used for experiments [21,22]. For this purpose, gelant solution was prepared according to the CCD plan at 90 °C and then transferred into high thermal resistance glass tubes (Screwthread GL32). The glass tubes were inverted at various time intervals and the corresponding gel property was recorded under the influence of gravity. The samples were kept for eight weeks in an oven (90°C) to study the thermal stability of the gels.

4. Rheological Test

To investigate the crosslinking density and consistency modulus of the hydrogels and select of optimal hydrogel, dynamic rheological measurements of the gel samples were performed. For this purpose, a Paar-Physica universal spectrometer, model MCR501 (Austria), with thermal controller and with smooth plate-plate surfaces of 50 mm diameter and 3 mm gap was used under 90 °C. Each sample was measured with rheometer for 60 minutes under constant strain of 1% and a frequency of 1 Hz (fitted with the desired linear viscoelastic range of gel). Consistency modulus, G^*, which quantifies the total consistency of the system, represents the fluid resistance to external perturbation:

$$|G^*| = |G^2 + G^2|^{0.5} \tag{1}$$

where G^{ϵ} and $G^{=}$ represent the elastic and viscous response, respectively. The increase of elastic modulus of the gelant with time shows the reaction forming between polymer chains and crosslinker. So in order to measure the crosslinking density versus time of the gel network, the following equation is used [23]:

$$G - G_o = qukT \tag{2}$$

where G_o^{ϵ} is the storage modulus at a given time, G^{ϵ}, is the storage modulus of the gelant, υ, is the density of created bonds, k, the Boltzmann factor, T, temperature, and q represents the distance between two entanglements in polymeric bonds. Studies [23] show that the value of crosslinking density indicates the progress of the reaction. The highest value of crosslinking density besides the maximum value of the compound consistency modulus would be the best compound for the gel preparation used in water shutoff operation.

During the hydrogel operation, the gelation time is more important than the other operating factors. Therefore, the sensitivity of

the gelation time to the effect of operating factors must be investigated. For this purpose, to conduct the fewest experiments, a 12-run Plackett-Burman design [22] was used to screen eight factors on the gelation time. To screen these factors on the gelation time, rheological tests were carried out with a Rheolab QC (US200, Anton Paar, Austria) for viscosity measurements.

EXPERIMENTAL DESIGN METHOD

1. Central Composite Design

The bottle test was carried out using the central composite design as a response surface method [22] with two factors in five levels and the gelation time as response. According to the central composite design, the total number of experimental combinations is $2^k + 2k + n_0$, where k is the number of independent variables and n_0 is the number of repetitions of the experiments at the centre point. For statistical calculation, the experimental variables X_i have been coded as x_i according to the following transformation equation:

$$x_i = \frac{X_i - X_0}{\delta X} \tag{3}$$

where x_i is the dimensionless coded value of the variable X_i, X_0 is the value of X_i at the center point, and δX is the step change. This design consists of the following parts: (1) a full factorial or fractional factorial design, (2) a central point, and (3) an additional design, often a star design in which experimental points are at the distance from their center ($\pm\alpha$). The value of star points can be obtained as well: $\alpha = 2^{k/4}$. Since two factors were used in this study, the value of α was 1.41. This design consisted of twelve experimental runs. Enough information could be generated to fit a second-order polynomial called "quadratic", using these many levels. Standard statistical software can compute the actual fitting of the model. Coded factors can be presented in five levels ($-\alpha, -1, 0, +1, +\alpha$). The optimum gelation time condition having satisfactory performance can be achieved with minimum number of experiments without any need of studying all possible combinations experimentally [16,21]. To evaluate the random error, three central points were designed in the table to evaluate each factor in average value of its minimum and maximum. So the random error and the amount of model significance would be determined by using the analysis of variance (ANOVA).

2. Plackett-Burman Design

Plackett and Burman have developed a saturated fractional factorial design that allows the researcher to investigate accurately many factors simultaneously without having to investigate all the possible combinations of the factors. This design allows determination of the effect of variables with a minimum number of experiments. The disadvantage is that it does not yield estimates of the extent or type of interaction between variables. However, within the bounds of these limitations, the use of this screening procedure invariably results in a well designed, efficient experiment, the outcome of which can be supported with statistical significance [22]. During the injection operation of polymer gel, gelation time is more important than the other operating factors. Therefore, the effect of process variables during gel formation must be investigated to have a suitable gelation time. To conduct the fewest experiments, a 12-run Plackett-Burman design was used to screen all factors influencing the gelation time.

Table 2. Experimental plan for bottle tests with CCD method

Sample No.	A		B	
	Coded	Actual (ppm)	Coded	Actual
1	−1	8,660	−1	0.12
2	+1	26,340	−1	0.12
3	−1	8,660	+1	0.43
4	+1	26,340	+1	0.43
5	−1.41	5,000	0	0.28
6	+1.41	30,000	0	0.28
7	0	17,500	−1.41	0.05
8	0	17,500	+1.41	0.50
9	0	17,500	0	0.28
10	0	17,500	0	0.28
11	0	17,500	0	0.28
12	0	17,500	0	0.28

Fig. 3. Predicted values vs. actual values of the gelation time (y_i: the experimental data, $\hat{y}$: the values predicted by the model, label 2 : the number of replications of one point).

RESULTS AND DISCUSSION

The bottle tests were performed using the CCD method with two factors in five levels and the gelation time as response. A wide range of copolymer concentration (5,000-30,000 ppm) and crosslinker/co-polymer ratio (0.05-0.5) were selected to determine their effect on the gelation time. The experimental plan for hydrogel preparation is presented in Table 2. The coded value of each factor was used because of the final equation for the response prediction in terms of dimensionless coded values. Four center points (samples 9 to 12) were also designed and assumed to measure the probable random errors during the experiments. The final results can be observed in Table 3. As can be observed, some samples had repulsion of water out of the gel structure due to the shrinkage in the hydrogel volume (syneresis). To determine the effect of copolymer concentration and crosslinker/copolymer ratio on the gelation time, the samples with an alphabetic code of G were considered and corresponding in terms of day. The results were inserted in Design Expert (DX) software (State-Ease, version 7.1.3, USA). Among several possible models, the following quadratic polynomial was found as the best correlation to fit the experimental data:

Gelation Time (days)=3.7−11.02A+1.56B−0.8AB   (4)

In this quadratic polynomial all variables are indicated through the coded values, where A is copolymer concentration, B is crosslinker/
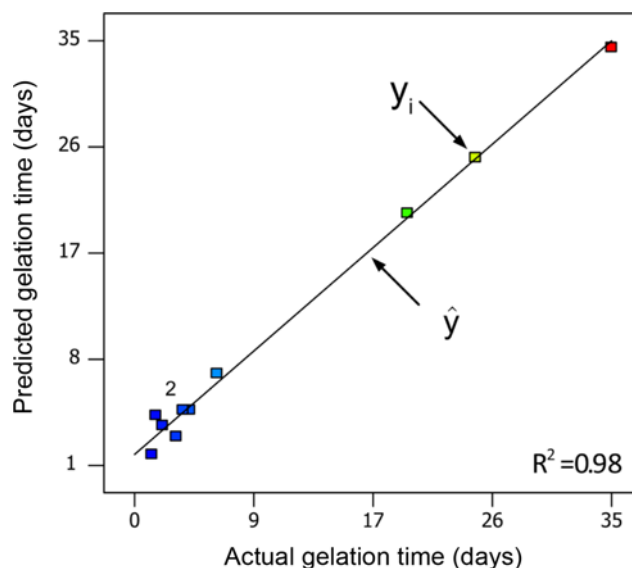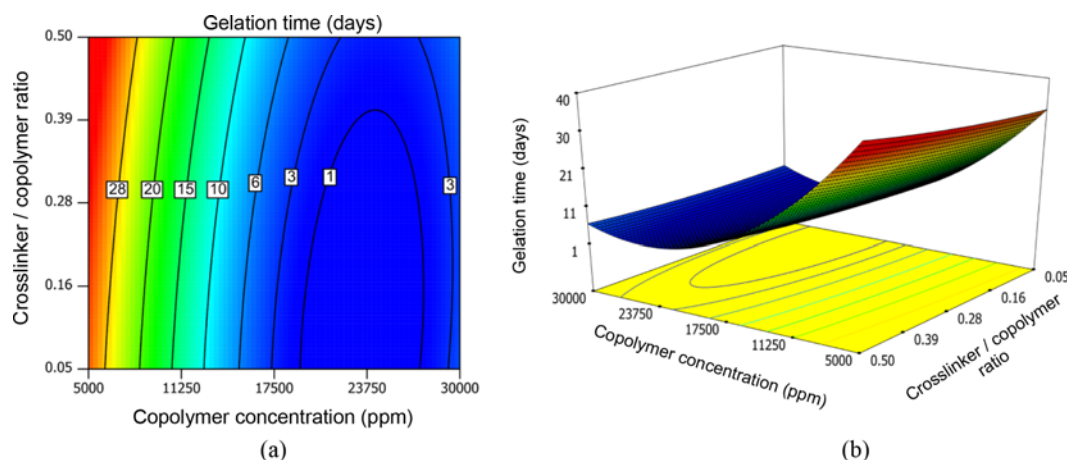
copolymer ratio and AB is the interaction of the two factors on the gelation time as a response. The coefficient of each factor and its sign indicate the importance and type of the effect of factors on the response. As can be seen, the copolymer concentration, with the greatest coefficient, was identified as the main effect on the gela-tion time. Fig. 3 shows the experimental data versus the predicted response values. It is worth to mention that y_i, $\bar{y}$ and $\hat{y}$ show the experimental data, the average of the experimental data and the values predicted by the model, respectively. The overlap of actual data and the predicted response is due to two reasons: the R-square value is 0.98, and the F-value of this curve compared with other curves (linear, third order and more) is larger. The results of the analysis of variance for fitted quadratic curve (Table 4) show the high accuracy of the presented model (P<0.0001). The interaction effect of two factors on gelation time can be observed in Fig. 4(a). As shown, at constant values of crosslinker/copolymer ratio the gelation time decreased by increase of copolymer concentration. It is also indicated that in constant concentration of copolymer, the variation of crosslinker/copolymer ratio had negligible effect on the gelation time. As illus-trated in Fig. 4(a), the gelation time occurred in less than a day for

Table 3. The results of bottle test for hydrogels designed with CCD

Sample No.	1 Day	2 Days	3 Days	7 Days	14 Days	21 Days	56 Days
1	A	D	E	F	F	G	Syneresis
2	G	H	H	I	I	I	I
3	A	A	A	F	F	G	Syneresis
4	F	F	G	H	H	H	H
5	A	A	A	A	C	F	F
6	G	H	I	H	I	I	I
7	G	G	G	H	H	H	Syneresis
8	B	D	E	G	H	H	H
9 (Center point)	D	E	G	G	H	Syneresis	Syneresis

Table 4. ANOVA results of the developed model for the gelation time

		Sum of square	DOF	Mean square	F-value	P-value
Gelation time (days)	Model	1368.1	5	273.62	192.91	<0.0001
	Residual	8.51	6	1.42	-	-

Fig. 4. Effect of copolymer concentration and crosslinker/copolymer ratio on the gelation time ((a) Contour, (b) response surface plot).

crosslinker/copolymer ratios lower than 0.38 and concentrations of 20,000 to 26,000 ppm of copolymer. Since gelant penetration depth in porous media is dependent on the gelation time, hydrogels with the above compositions and short gelation time cannot be recommended in the field operation [24]. Fig. 4(b) shows the response surface plot. The variety difference of the surface slope because of the changes of factor A and B can be observed, while it is greater with the copolymer changes. In addition, the maximum value of the response was in the minimum value of copolymer concentration, while it was not sensitive to crosslinker/copolymer ratio. Therefore, the concentration of copolymer was the controlling factor of the gelation time.

As the results indicated, samples 3 and 9 for the syneresis, sample 5 for the weak strength of the gel network, sample 7 for short lifetime and syneresis, and sample 1 for the long time of the gelation and the lack of economic value [24] were not appropriate in field operations. According to the gel structure, there is two-phase heterogeneity in its structure which is due to the network processing [25,26]. It is possible that by increasing the copolymer concentration at constant ratio of crosslinker/copolymer, the gel network structure in the bottle was created due to the physical entanglements of polymer chains. So the gel network would not have appropriate strength via strain and shear of the injection and gel placement in the porous media. Thus rheological experiments would be necessary to determine the suitable components of the hydrogel for strengthening of the gel network. Samples 2, 4, 6 and 8 were the candidates in the next step to be studied rheologically for selecting the optimal gel. Figs. 5 and 6 show the results of crosslinking density and consistency modulus of the four candidate samples, respectively. According to the results of experimental design, the highest strength would be found in high concentration of copolymer and low ratio of crosslinker/copolymer. Therefore, sample 4 compared with sample 2 (with the same concentration of copolymer) had lower strength due to the higher ratio of crosslinker/copolymer. Accordingly, regarding the

Fig. 5. Comparison of the crosslinking density between the gelant samples 2, 4, 6 and 8.

Fig. 6. Comparison of the consistency modulus between the gelant samples 2, 4, 6 and 8.

relation of gel strength with consistency modulus and crosslinking density of the gels and also based on the results of bottle and rheological tests, at last the gel sample 2, with the copolymer concentration of 26,340 ppm, the crosslinker/copolymer ratio of 0.12, maximum

Table 5. Level of variables in PB design with eight factors (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay)

Variable	(+1)	(−1)
A: NaCl concentration (ppm)	15000	0
B: CaCl$_2$ concentration (ppm)	15000	0
C: KCl concentration (ppm)	15000	0
D: MgCl$_2$ concentration (ppm)	15000	0
E: Temperature (°C)	90	60
F: pH	11	3
G: Sodium lactate (%w/w)	1	0
H: Nanoclay (%w/w)	1	0

Table 6. Experimental plan of the 12-run PB design with eight factors (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay) and their responses (gelation time)
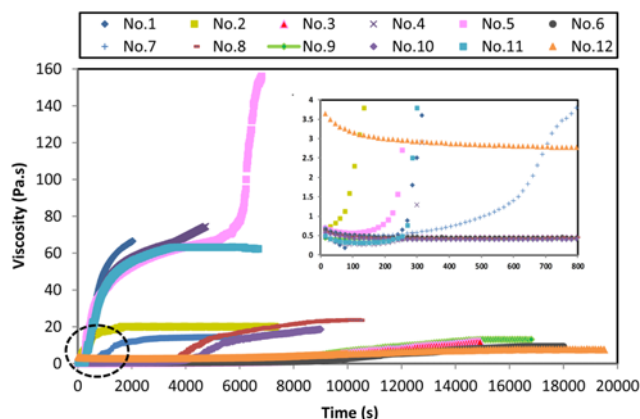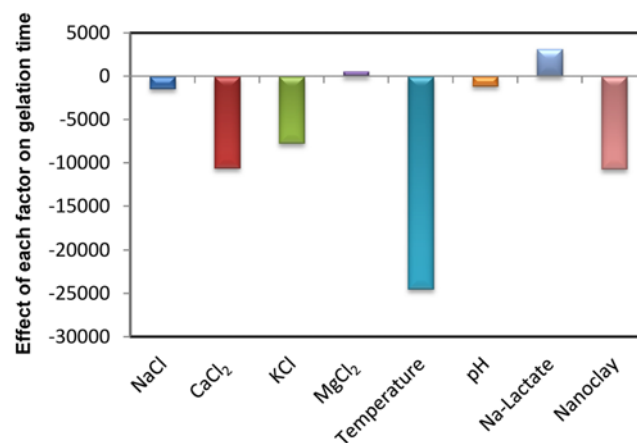
Sample No.	A	B	C	D	E	F	G	H	Gelation time (sec)
1	+1	+1	−1	+1	+1	+1	−1	−1	250
2	−1	+1	+1	−1	+1	+1	+1	−1	15
3	+1	−1	+1	+1	−1	+1	+1	+1	3300
4	−1	+1	−1	+1	+1	−1	+1	+1	420
5	−1	−1	+1	−1	+1	+1	−1	+1	15
6	−1	−1	−1	+1	−1	+1	+1	−1	2000
7	+1	−1	−1	−1	+1	−1	+1	+1	275
8	+1	+1	−1	−1	−1	+1	−1	+1	2300
9	+1	+1	+1	−1	−1	−1	+1	−1	3670
10	−1	+1	+1	+1	−1	−1	−1	+1	4020
11	+1	−1	+1	+1	+1	−1	−1	−1	15
12	−1	−1	−1	−1	−1	−1	−1	−1	1520

Fig. 7. Viscosity vs. time for 12 runs of screening using PB design with eight factors (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay).

Fig. 8. Effect of each factor (NaCl, CaCl$_2$, KCl and MgCl$_2$ concentrations, temperature, pH, sodium lactate and nanoclay) on the gelation time with column chart.

value of crosslinking density (about 1,950), and maximum value of consistency modulus (about 31,900 Pa), was selected as an optimum composition. In fact, by increasing of the Cr(OAc)$_3$/copolymer ratio, crosslinking density increased dramatically so the space between polymer network connection was reduced.

The eight factors (NaCl, CaCl$_2$, MgCl$_2$ and KCl concentrations, temperature, pH, sodium lactate and nanoclay) with the selected range are presented in Table 5.

Table 6 shows the experimental plan of PB design and corresponding responses from which the main effect(s) of variables were evaluated, using DX7 software. The hydrogels were prepared with constant component of copolymer concentration and crosslinker/copolymer ratio of sample 2 and the designed additives according to the plan. Then viscosity versus time was measured for each sample, keeping constant shear rate of 5 1/s and using Rheolab QC (US200, Anton Paar, Austria), a coaxial viscometer with the spindle of CC27. As can be seen, the viscosity had increasing jump by the time of the gelation (Fig. 7). The time at which the gelant changes to the gel is called the gelation time [12].

According to the PB results and Eq. (4) (shown for instance for the factor A where R is the response), the effect of each factor was measured on the gelation time of the hydrogel and illustrated among other factors in Fig. 8.

$$mA = -R_1 - R_2 - R_3 - R_4 + R_5 + R_6 + R_7 + R_8 - R_9 + R_{10} - R_{11} + R_{12} \quad (5)$$

As can be seen, the gelation time decreased by increase of temperature and pH, while increased by increase of the other factors. The temperature had the most effect on gelation time in comparison with other factors, mentioned as the main effect on gelation time. As Fig. 8 illustrates, monovalent and divalent ions (Na$^+$, Ca^{2+}, K$^+$ and Mg^{2+}) had increasing effect on the gelation time, while the effect of calcium ion was more than the other ions. It can be described as the penetration of electrolyte solution counterions into the hydrogel network makes their screening effect more evident on the anionic groups (SO^{-3} and COO$^-$) of the polymer chains, leading to an electrostatic repulsion and consequently to decrease of the gelation time [13,27]. The effect of temperature on the gelation time is also shown in Fig. 8. As the gelatin reaction is an endothermic one [28], so an increase in temperature increased the reaction rate and decreased the gelation time. Also, at high pH, because of oxygen deprotonation, amide groups acted like ligands and could be bonded with chromium, so that the gelation time decreased. The pH had negligible effect on the gelation time of this hydrogel, which is the preference for it.
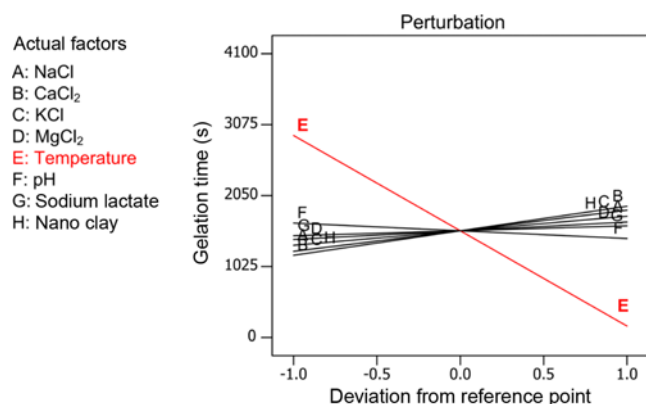
Fig. 9. The deviation of each factor (NaCl, CaCl₂, KCl and MgCl₂ concentrations, temperature, pH, sodium lactate and nanoclay) of PB design versus the gelation time (perturbation plot).

Fig. 8 shows the increasing effect of sodium lactate on the gelation time. When sodium lactate is mixed with $Cr(OAc)_3$, the acetate ligand is exchanged with lactate, which is a weaker ligand [28]. Consequently, it takes longer time for chromium to separate from its ligand (lactate) and react with the polymeric chains. Hence, the gelation time increases in the presence of sodium lactate. In addition, it is evident that by increasing of the nanoparticles (clay), the gelation time increased. In the absence of Na-montmorillonite in the polymer solutions, the polymer chains crosslinked randomly to the crosslinker while in the presence of Na-montmorillonite; they were trapped in the clay layers of hydrogel network, leading to the high strength of the gel network [13].

Fig. 9 shows a perturbation plot showing the deviation of eight factors versus gelation time to compare the effect of all factors at a particular point. As illustrated, the gelation time was plotted by changing only one factor over its range while holding the other factors constant. A steep slope in factor E (temperature) showed that the gelation time was sensitive to it among the other factors.

According to the results of screening tests and the negligible effect of effective factors of the porous media on the gelation time, such as mono-and divalent ions, pH etc., temperature had the most effect on the gelation time, and it is the main effect during gel injection into the well. Also, this result confirmed the goodness point of the presented hydrogel of negligible effect of its gelation time on the factors in porous media.

CONCLUSIONS

An optimal hydrogel has been presented through the experimental series of bulk and rheology. The bottle test was conducted to select the optimum composition of the hydrogel using the CCD method with two factors of copolymer concentration and crosslinker/copolymer ratio. The candidate hydrogels were studied rheologically to select a hydrogel with high strength network via their crosslinking density and consistency modulus value. To screen the eight effective factors (NaCl, CaCl₂, KCl and MgCl₂ concentrations, temperature, pH, sodium lactate and nanoclay) on the desirable hydrogel, rheological tests were conducted for viscosity measurements using Plackett-Burman design. The main findings of this experimental

study can be summarized as the following:

The bottle test:
• The copolymer concentration was the main factor on the gelation time.
• Four hydrogels (samples 2, 4, 6 and 8) were selected as candidates among all designed hydrogels, while the others were not appropriate for field operating because of repulsion of water out of the hydrogel structure due to shrinkage in gel volume (syneresis), the weak strength of the hydrogel network, the longtime of gelation and the lack of economic value.

The dynamic rheological test with MCR501:
• According to the main purpose of this research to present the optimal hydrogel with the appropriate gelation time, thermal stability and gel strength the hydrogel with the copolymer concentration of 26,340 ppm and the crosslinker/copolymer ratio of 0.12 were selected with the maximum value of crosslinking density (about 1,950) and consistency modulus (about 31,900 Pa).

The screening of porous media factors:
• The gelation time decreased by increase of pH and temperature but increased by increase of the other factors.
• The temperature was the most effective factor on the optimal hydrogel controlling the gelation time, while pH and other factors had negligible effect.

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