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Development and performance evaluation of a self-degradable hydrogel for urban gas pipeline plugging

Deng Zhehan[1,2,3,4], Ying Wang[1,2,3,4,5], Liao Xiaobo[1,2,3,4], Liao Ruiquan[1,2,3,4]

[1]Yangtze University, School of Petroleum Engineering. 430100, Wuhan, China.
[2]CNPC Gas Lift Innovation Center, Laboratory of Multiphase Pipe Flow. 430100, Wuhan, China.
[3]Yangtze University, Hubei Key Laboratory of Oil and Gas Drilling and Production Engineering. 430100, Wuhan, China.
[4]National Engineering Research Center for Oil & Gas Drilling and Completion Technology. 430100, Wuhan, China.
[5]Yangtze University, School of Geoscience. 430100, Wuhan, China.
e-mail: 897698760@qq.com, 13125090392@163.com, 1476823951@qq.com, liaoruiquan@263.net

ABSTRACT

The increasing expansion of urban gas pipeline networks in China has heightened the need for effective and environmentally friendly plugging solutions. Traditional mechanical plugging methods often result in incomplete sealing, high costs, and potential damage to pipeline integrity. To overcome these problems, the project seeks to create a self-degrading hydrogel for the temporary plugging of pipes, based on acrylic acid, acrylamide, and PA-1 as crosslinkers, along with using ammonium persulfate and sodium bisulfite as a redox initiator system. Single-factor experiments were used to examine how factors like polymer concentration, enzyme concentration, crosslinker concentration and temperature influence the gel strength, the time to gel, and when the gel breaks down. Optimized formula accelerated Gelation and completely degraded the gel at normal or heated room temperature. Applying 50 kPa pressure, the gel was able to maintain a seal, showing this material is suitable for medium- and low-pressure pipes. The research discoveries point to this new gel, which is eco-friendly and cost-effective, as a prospective medicine for gas pipeline repair and use in gas storage and transportation. Improving the gel's effectiveness in different jobs and making it ready for mass industrial application should be the main goals of upcoming research.

Keywords: Self-degradable gel; Pipeline plugging; Acrylamide; Hydrogel degradation; Chemical sealing.

1. INTRODUCTION

Due to the modernization of urban areas, natural gas has emerged as a cleaner and more efficient alternative to conventional fossil fuels. As urban populations expand and the demand for reliable energy increases, the safety and maintenance of gas pipelines become increasingly crucial for the resilience of cities. Natural gas traverses extensive pipeline systems that are subjected to varying pressure levels and conditions. Although capable of functioning for extended periods, these pipelines can be adversely affected by factors such as aging, corrosion, accidental damage, and wear resulting from usage [1]. Effective maintenance practices must incorporate temporary plugging techniques, which are critical for ensuring the continued operation of air conditioning systems. Promptly and safely isolating a section of the pipeline aids in preventing gas leakage, minimizing downtime, and safeguarding the surrounding populace.

Historically, most oil wells were sealed using mechanical devices. Examples include inflatable rubber bladders, mechanical pigs, hot-tapping devices, and various intricate mechanical assemblies that are utilized to halt fluid flow in pipelines. While these methods have proven effective in well-controlled studies, they are often limited in scope. The requirement for specialized tools, which can be both costly and cumbersome, necessitates the employment of skilled teams for installation [2]. Notably, the current pipeline systems exhibit diverse configurations and materials that may not be compatible with mechanical approaches. Several significant challenges arise, including incomplete sealing, the risk of system failure, potential pipeline damage, and difficulties in extracting the repair team upon project completion. As the urban gas network system becomes increasingly complex, it is imperative to establish connections with various types of appliances promptly.

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Recently, chemical and polymer-based products have been introduced for sealing pipelines. Among these, hydrogels and various polymer systems assist in forming within the pipes, adapting to their interior structure, and possessing the capacity to degrade after use. Experimental polymerization has utilized materials such as acrylamide, acrylic acid, guar gum, montmorillonite, and carboxymethyl cellulose. For instance, certain systems comprising suspended solids can obstruct pipelines, while others have been developed for sensitivity to temperature or pressure. However, post-application degradation or extraction of these gels frequently requires chemicals, high-temperature flushing, or specialized removal equipment. Consequently, this prolongs maintenance intervals, heightens pollution risks, and renders these solutions generally unsuitable for deployment in sensitive urban environments [3].

Specifically, hydrogels derived from acrylamide and acrylic acid are recognized for their strong adhesion to metal, enhancing the efficacy of the sealant. Currently, it is not feasible to remove all contaminants without the introduction of corrosive chemicals that pose threats to the pipeline and potentially harm the environment. Similarly, while guar gum gels offer the benefit of biodegradability, they may not decompose autonomously, and assistance such as a shovel may be necessary in cold weather conditions [4]. In many instances, the combination of montmorillonite with hydrogels enhances their tensile strength, yet residues remain on the device. Such supramolecular hydrogels can be thermally activated and transitioned from a solution to a gel multiple times; however, their complex synthesis and prolonged preparation time render them impractical for emergencies.

The examination of current solutions highlights a significant gap in the technology sector. It has proven challenging for any solid system to swiftly transform into a gel, maintain structural integrity, and self-degrade. The interactions of hydrogels with various steels, plastic films, and lining materials present within pipelines are not well understood. The inability to adjust gel properties to meet both application requirements and the necessity for post-use cleaning remains a barrier to their broader utilization. The presence of non-degraded gel in wastewater raises concerns regarding its environmental impact and the associated processing costs [5].

In light of these issues, the present study introduces a novel self-destructing hydrogel designed for the temporary sealing of gas pipelines in urban settings. The hydrogel comprises reactive monomers, including acrylic acid, acrylamide, and PA-1, with ammonium persulfate (APS) and sodium bisulfite (SHS) functioning as the redox initiator system. A key innovation of this research is that the hydrogel forms while remaining at room temperature and subsequently becomes water-soluble and non-toxic. This self-degradation mechanism expedites repairs, reduces the risk of contamination, and minimizes the duration of pipeline service interruption without the necessity for chemical breakers.

The investigation details formulation parameters such as monomer concentrations, the ratio of initiators, the quantity of crosslinker employed, and the degree of neutralization. Analyzing these factors elucidates their effects on the overall gelation time, degradation rate, and molecular strength. Experiments focused on individual components aim to pinpoint their specific impacts on the hydrogel's performance [6]. In addition to laboratory experiments, the performance of the plugging material is assessed in a steel pipeline test section (125 mm diameter), simulating field conditions. Further analyses examine material responses under thermal influences, reflective of varying seasonal conditions and facility changes. Conducting these tests verifies the stability of gel behavior across diverse environmental conditions.

Three key elements underscore the innovative aspects of this research. Firstly, the hydrogel showcases rapid and facile Gelation, making it adaptable for a range of field situations. Secondly, the material demonstrates intrinsic weakness and degradability without external intervention, contributing to environmental preservation and facilitating cleanup efforts. Thirdly, its gel technology fosters a balance between robust structural integrity and disintegration capacity, enabling its application in the temporary sealing of low- and medium-pressure pipelines typical in urban gas distribution [7]. Alongside the development of new materials, this study establishes a reliable testing system for assessing hydrogel properties. Pressure-based assessments, temperature variations, and repetitive testing ensure the reliability of results. The authors address reproducibility challenges commonly encountered in polymer studies by reporting average values and adhering to established measurement errors, including data on gelation times, degradation durations, and gel strength. Additionally, the research explores variations in gel adhesion on different pipeline surfaces and discusses the potential for large-scale production, providing recommendations for pilot testing [8].

The relevance of this topic has increased significantly, particularly as sustainable materials and circular design concepts gain traction in infrastructure maintenance. Future pipeline technologies are anticipated to increasingly incorporate self-degradable materials that align with the principles of green chemistry. A system that embodies these attributes is beneficial for urban utility companies, municipal planners, and contractors involved in pipeline operations. The newly developed hydrogel possesses adaptability for diverse requirements and is inherently self-degradable, thus aligning seamlessly with emerging trends [9].

This research is motivated by a critical and unmet need in pipeline maintenance: the creation of a plug that safeguards the environment is user-friendly, and necessitates no external assistance for removal. The study elucidates the capabilities of this material through an examination of its formulation, mechanical testing, and degradation analysis. The findings aim to shape future applications of smart gels in the maintenance and repair of fluid transport systems and to promote the broader adoption of self-degrading materials in the inspection and repair of public utilities.

2. MATERIALS AND EXPERIMENTS

2.1. Materials and equipment

The main experimental materials and their specifications are presented in Table 1.

Table 1: Main experimental materials.

MATERIAL	SPECIFICATION	MANUFACTURER
Acrylic acid (AA)	AR	Shanghai Macklin Biochemical Technology Co., Ltd.
Sodium hydroxide (NaOH)	AR	Shanghai Macklin Biochemical Technology Co., Ltd.
Acrylamide (AM)	AR	Shanghai Macklin Biochemical Technology Co., Ltd.
Ammonium persulfate (APS)	AR	Shanghai Macklin Biochemical Technology Co., Ltd.
Sodium bisulfite (SHS)	AR	Shanghai Macklin Biochemical Technology Co., Ltd.
PA-1*	93%	Shanghai Macklin Biochemical Technology Co., Ltd.

*an ester of polyol and acrylic acid, the main functional groups are C=C bonds and ester groups.

The main experimental equipment used in this study is shown in Table 2.

Table 2: Main experimental equipment.

EQUIPMENT	MODEL	MANUFACTURER
Electronic analytical balance	BSA224S	Sartorius Scientific Instruments (Beijing) Co.Ltd
Electric thermostatic drying oven	DHG-9023A	Shanghai Yiheng Technology Instrument Co.,Ltd.
Thermostat water bath	HH-8	Guohua (Changzhou) Instrument Manufacturing Co., Ltd
Bidirectional magnetic heating stirrer	78-2	Guosheng Experimental Instrument Manufacturing Co., Ltd

2.2. Experimental method

2.2.1. Preparation of hydrogel

Acrylic acid (AA) and sodium hydroxide (NaOH) were dissolved in deionized water in a beaker and stirred thoroughly until a clear solution was obtained. The solution was sealed and cooled to room temperature (approximately 25 °C). Acrylamide (AM), crosslinking PA-1, and initiators (APS and SHS) were added sequentially, with stirring maintained at 55 rpm for 5 minutes to ensure thorough mixing (Figure 1). The prepared solution was left undisturbed at 25 °C for 4 to 12 hours to achieve complete Gelation. A total of 28 gel samples were synthesized during single-factor experiments to evaluate the effects of individual components on gel properties [10].

2.2.2. Gelation and degradation time

The gelation and degradation characteristics were evaluated using the bottle test and gel strength code method. Bottle test is a strength test method to observe the deformation state of gel by inverting sealed bottles containing the gel. The gel strength was measured by continuous observation after the prepared gel is sealed in cillin, during which gelation and degradation time were recorded as well. To ensure the reproducibility of experimental results, all measurements of gelation time, degradation time, and gel strength were repeated in triplicate for each formulation. The reported values represent the arithmetic mean of the three independent tests. Standard deviations were calculated to quantify variability and confirm measurement consistency. It was observed that

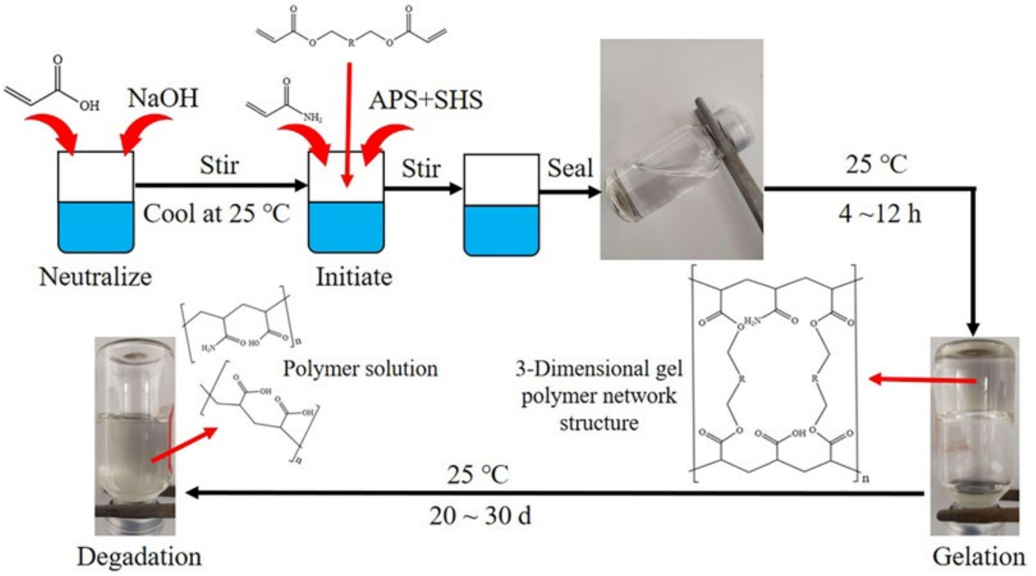

Figure 1: Schematic diagram of gel synthesis and degradation.

the standard deviation for gelation time across all formulations remained within ±0.3 hours, while degradation time exhibited slightly higher variability, ranging from ±10 to ±25 hours depending on gel composition. Gel strength, evaluated using the gel strength code method, demonstrated consistent classification within ±1 code unit for each formulation [11]. The gel strength code method divides the gel into 10 grades A~J according to the different deformation states of the gel, corresponding to the numbers 0~18 in the figure, as shown in Table 3 [12]

Table 3: Gel strength codes.

CODE		GEL STATE	DESCRIPTION
A	0	No detectable gel formed	The gel appears to have the same viscosity (fluidity) as the original polymer solution, and no gel is visually detectable.
B	2	Highly flowing gel	The gel appears to be only slightly more viscous than the initial polymer solution.
C	4	Flowing gel	Most of the detectable gel flows to the bottle or ampule top upon inversion.
D	6	Moderately flowing gel	A small portion (about 5 to 15%) of the gel does not readily flow to the bottle or ampule top upon inversion.
E	8	Barely flowing gel	The gel can barely flow to the bottle or ampule top and/or a significant portion (>15%) of the gel does not flow upon inversion.
F	10	Highly deformable non-flowlng gel	The gel does not flow to the bottle or ampule top upon inversion (gel flows to just short of reaching the bottle or ampule top)
G	12	Moderately deformable nonflowing gel	The gel flows about halfway down the bottle or ampule upon inversion
H	14	Slightly deformable nonflowing gel	Only the gel surface slightly deforms upon inversion
I	16	Rigid gel	There is no gel-surface deformation upon inversion;and the gel is stable and clear
J	18	Ringing rigid gel	A tuning-fork-like mechanical vibration can be felt after tapping the bottle.

2.2.3. Plugging test

The device shown in Figure 2 was used to evaluate the plugging effect of the gel. A 1 meter oil pipe (DN125, N80 steel) filled with gel was connected to a pressurized nitrogen system to simulate pipeline conditions. The pressure in the pipe will be constantly monitored during the process of pressurization after Gelation. When a

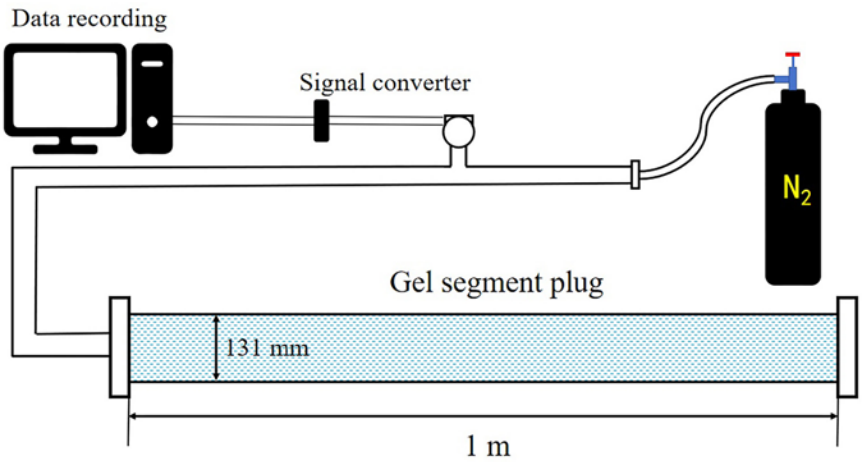

Figure 2: Schematic diagram of plugging test device.

sudden drop in pressure or gel displacement occurs, it is considered as evidence of plugging failure, and the maximum pressure in the pipe is regarded as the plugging pressure.

3. RESULTS AND DISCUSSION

3.1. Effect of AA on gel properties

To investigate the effect of AA concentration on gel strength, gelation time, and degradation time was studied by varying AA content (6%, 7%, 7.5%, 8%, 10%, 11% and 12%) at a fixed neutralization degree was 100%. Other component concentrations were kept constant: AM (4%), PA-1(0.2%), APS (0.3%), and SHS (0.1%) [13]. The experimental results are presented in Figure 3.

Figure 3 shows that increasing AA concentration generally reduced gelation time. This observation aligns with the established principle that the concentration of reactants influences the rate of chemical reactions. Beyond an AA concentration of 10%, the gelation rate plateaued, with the shortest gelation time reaching approximately 4 hours. Higher AA concentrations were associated with prolonged gel degradation times. At 11% AA concentration, the gel showed the longest degradation time of 740 hours (~28 days). However, further increasing AA concentration to 12% reduced the duration of degradation. Higher monomer concentrations

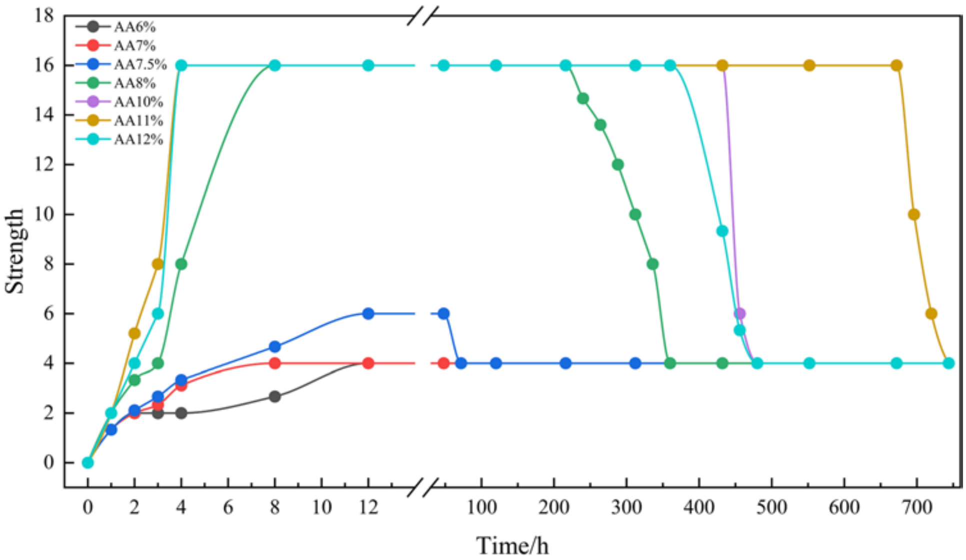

Figure 3: Variation of gel strength with time at different AA concentrations.

accelerated the exothermic polymerization reaction, increasing the rate of free radical generation. Excessive free radical generation can negatively impact the molecular weight of the synthesized gel. At higher AA concentrations, gel viscosity increased while molecular weight decreased [14]. Increased Na^+ concentration enhanced salt sensitivity, inducing a coiled conformation in the polymer molecular chain. This conformation restricted interactions between the crosslinker and the polymer chains, reducing gel strength and a decrease in degradation time.

Acrylic acid (AA) forms chemical bonds with steel pipes, improving adhesion between the gel and the pipe wall [15]. The adhesion performance of the hydrogel is closely linked to the surface characteristics of the pipeline material. In this study, N80 steel was used as the standard pipeline material, and the gel exhibited satisfactory bonding attributed to the presence of acrylic acid, which forms hydrogen bonds and electrostatic interactions with metallic surfaces. However, variations in pipeline materials, such as polyethylene, stainless steel, or epoxy-coated surfaces, may alter adhesion behavior due to differences in surface energy, roughness, and chemical compatibility. For instance, non-metallic or passivated surfaces may hinder effective interaction with carboxylic and amide functional groups, potentially compromising seal integrity. To address this, surface pre-treatment or formulation adjustments—such as the incorporation of adhesion promoters or surfactants—may be required [16]. Therefore, further investigations into the interfacial behavior of the gel with a range of pipeline substrates are essential to ensure universal applicability across different gas distribution infrastructures. Given the adhesion requirements of plugging operations and the impact of AA concentration on degradation time, higher AA concentrations are recommended for gel formulation. A series of single-factor experiments identified 12% as the optimal AA concentration for the gel formulation.

3.2. Effect of AM on gel properties

Gel strength is a crucial factor of its suitability for plugging operations. Pipelines with larger diameters and elevated internal pressures require plugging gel with greater strength. In AM-based gels, the concentration of AM significantly affects the mechanical strength of the gel. To effects of AM concentration (4.5%, 4.75%, and 5%) on gel strength, Gelation, and degradation times were investigated. AA concentration (6%), neutralization degree (100%), PA-1 (0.2%), APS (0.3%), and SHS (0.1%) were held constant. The experimental results are shown in Figure 4.

The results shown in Figure 4 illustrate that an increasing AM concentration reduced gelation time, with the minimum gelation time (<2 hours) observed at 5% AM. Higher AM concentration also enhanced reactivity, affecting the reaction rate and intensity [17]. Increased AM concentrations significantly extended the duration of gel's degradation. When the concentration of AM was increased to 4.75%, the gel demonstrated degradation over approximately 600 hours (25 days), and an increase in the AM concentration to 5% led to a prolonged degradation duration of approximately 1000 hours (42 days). This phenomenon can be attributed to the significant impact of acrylamide (AM) on the molecular weight of the gel. When the total concentration of monomers was held constant, an increase in the ratio of AM led to a corresponding increase in the molecular weight of the gel.

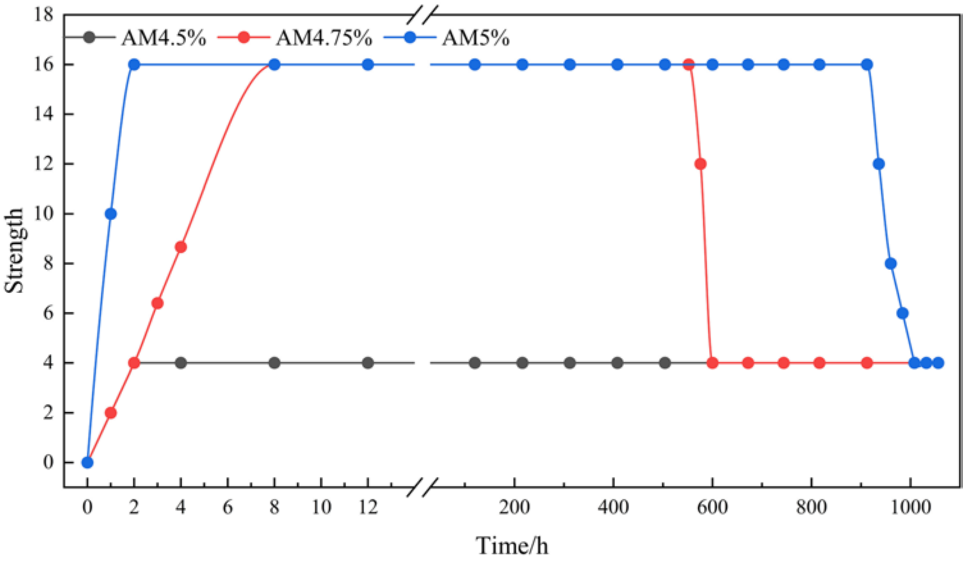

Figure 4: Variation of gel strength with time at different AM concentrations.

Furthermore, the observed macroscopic properties were a result of the concentration of AM, which influenced both the strength of the gel and its degradation time. While the potential applications of high-strength gel are extensive, the concentration of acrylamide (AM) plays a critical role in determining the self-degradation characteristics of the gel. To achieve a satisfactory level of strength while ensuring that the self-degradation period remains within acceptable parameters, it is advisable to maintain the AM concentration at approximately 6%, considering the diameter of the pipe employed in this plugging experiment [18].

3.3. Effect of the degree of neutralization on gel properties

Studies have shown that the degree of neutralization significantly affects gel adhesion and gelation properties. The effect of neutralization degree (25%, 50%, 75%, 90%, 95%, and 125%) on gel strength, gelation time, and degradation was systematically evaluated. Other component concentrations were kept constant: AA (6%), AM (4%), PA-1 (0.2%), APS (0.3%), and SHS (0.1%). The experimental results are shown in Figure 5.

The results indicate that the degree of neutralization is below 90%, which significantly accelerates Gelation. Specifically, At the degree of neutralization below 90%, the gel exhibited a softer consistency with noticeable surface deformation upon tapping the cillin. During the gelation process, the liquid phase remained within the cillin and maintained a high level of fluidity with minimal increase in viscosity, unlike the other experimental groups. Although the gel strength decreased beyond a degree of neutralization of 95%, the overall gelation time progressively increased with higher neutralization. At the degree of neutralization below 90%, the gelation time was consistently short, averaging around 3 hours. Compared to groups exceeding 100% neutralization, gels at 95% neutralization displayed higher viscosity. Lower pH levels enhanced initiator decomposition efficiency. In contrast, higher pH levels reduced gel molecular weight, leading to longer gelation times [19]. At the degree of neutralization below 90%, increased molecular weight enhanced gel resistance to degradation, with no visible signs of degradation within 1500 hours (60 days). Considering the corrosive effects of acidic conditions on metal pipelines, maintaining a neutralization degree of 100% is essential.

3.4. Effect of PA-1 on gel properties

The crosslinking agent PA-1 primarily facilitates the formation of spatial crosslinks within the gel. The process significantly impacts the gel's mechanical strength and its self-degradation behavior. The effects of PA-1 concentration (0.1%, 0.2%, and 0.3%) on gel strength, gelation time, and degradation time were investigated. Other parameters were fixed: AA (6%), the degree of neutralization (100%), AM (3.75%), APS (0.3%), and SHS (0.05%). Results are presented in Figure 6.

As shown in Figure 6, increasing PA-1 concentration enhanced gel strength, while the gelation time remained constant at approximately 3 hours [20]. This can be attributed to enhanced spatial crosslinking at higher PA-1 concentrations, underscoring its critical role in gel strength. Higher PA-1 concentrations significantly

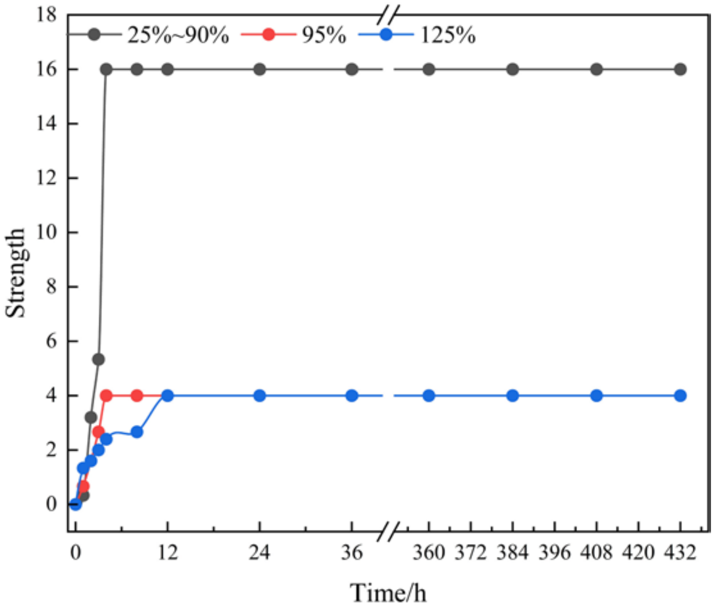

Figure 5: Variation of gel strength with time at different neutralization degrees.

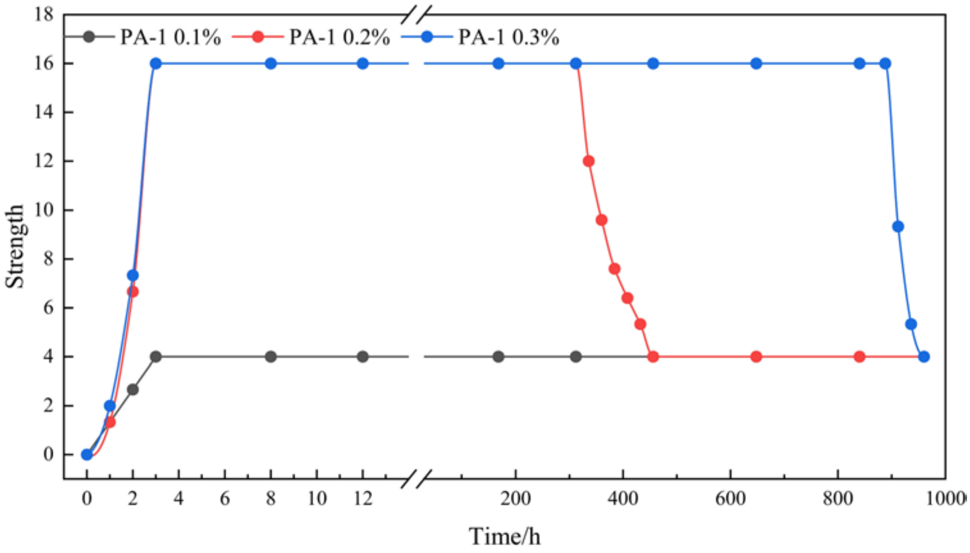

Figure 6: Variation of gel strength with time at different PA-1 concentrations.

prolonged gel-degradation time. This can be attributed to the dependence of degradation on the hydrolysis of the ester groups present in the PA-1 molecule. Consequently, as the concentration of PA-1 rose, the degradation time was markedly extended. When the concentration of PA-1 was 0.2%, the gel would degrade within 480 hours (20 days), while the concentration of PA-1 was increased to 0.3%, the degradation time of the gel extended to 960 hours (40 days). To balance strength and degradation time, 0.2% PA-1 was identified as the optimal concentration [21].

3.5. Effect of initiator system on gel properties

The effect of the initiator system on gel strength, Gelation and degradation times was evaluated by varying the initiator (APS) and reductant (SHS) concentrations. In the initiator group, SHS was held at 0.1%, while APS concentrations ranged from 0.05% to 0.25%. In the reductant group, the concentration of APS was fixed at 0.3%, and SHS concentrations varied from 0.03% to 0.3%. Other parameters were maintained constant: The AA (8%, 100% neutralized), AM (4%), and PA-1 (0.2%). The experimental results are shown in Figure 7~8.

Figure 7 shows that increasing APS concentration enhanced gel strength, with minimal Gelation observed at, the lowest APS concentrations (0.05%). Gelation time initially decreased with increasing APS concentration but extended at higher concentrations, as shown in Figure 7. At lower APS concentrations (<0.3%), enhanced free radical production increased gel strength. However, at higher concentrations, excessive free radical generation favored shorter polymer chains, reducing gel molecular weight and extending gelation time [22]. Degradation time followed a similar trend, initially increasing but declining at higher APS concentrations due to changes in gel molecular weight. The maximum degradation time observed, exceeding 1500 hours, occurred at an APS concentration of approximately 0.25%.

Figure 8 indicates that increasing SHS concentration reduced gel strength. When the APS-to -SHS ratio exceeded 3:2, gel strength decreased significantly, and gelation time increased with higher SHS concentrations.

At high SHS concentrations, free radicals are consumed through the following reaction [23]:

$$2SO_4^{-}\cdot + HSO_3^{-} = 2HSO_4^{-} + SO_4^{2-} + H^{+} \tag{1}$$

Therefore, excessive SHS concentrations should be avoided to achieve high gel strength. When the concentration of SHS was decreased to 0.03%, the degradation time was observed to reach 696 hours (29 days). Based on single-factor experiments, an APS concentration of 0.3% and SHS concentration of 0.1% were selected to optimize Gelation and degradation time for the plugging test [24]. The formulation of the gel can be tailored to meet various requirements and application scenarios. By controlling the amount of each component, gels of varying strengths can be produced, allowing for precise regulation of both gelation and degradation times. It is notable that high-strength gels typically exhibit inferior self-degradation performance, whereas low-strength

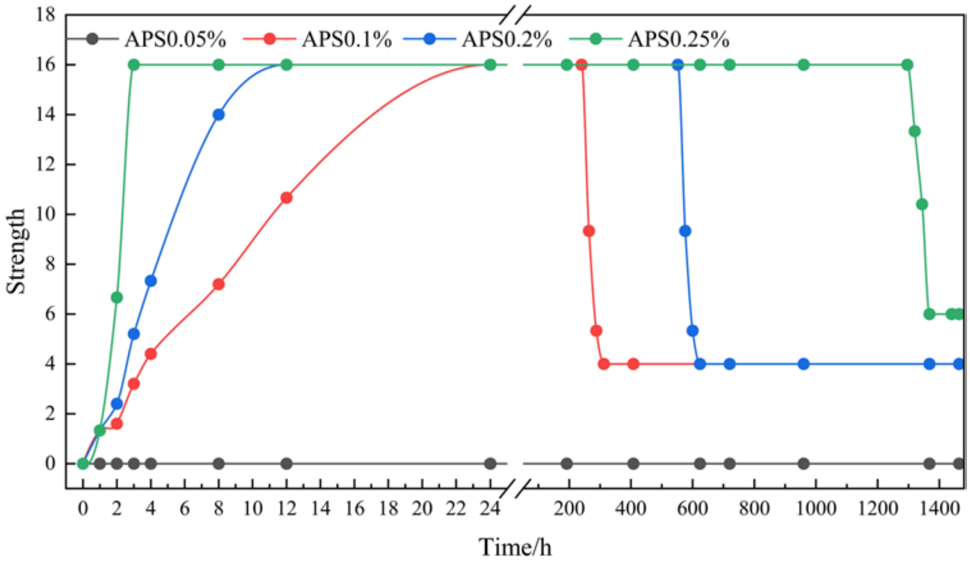

Figure 7: Variation of gel strength with time at different APS concentrations.

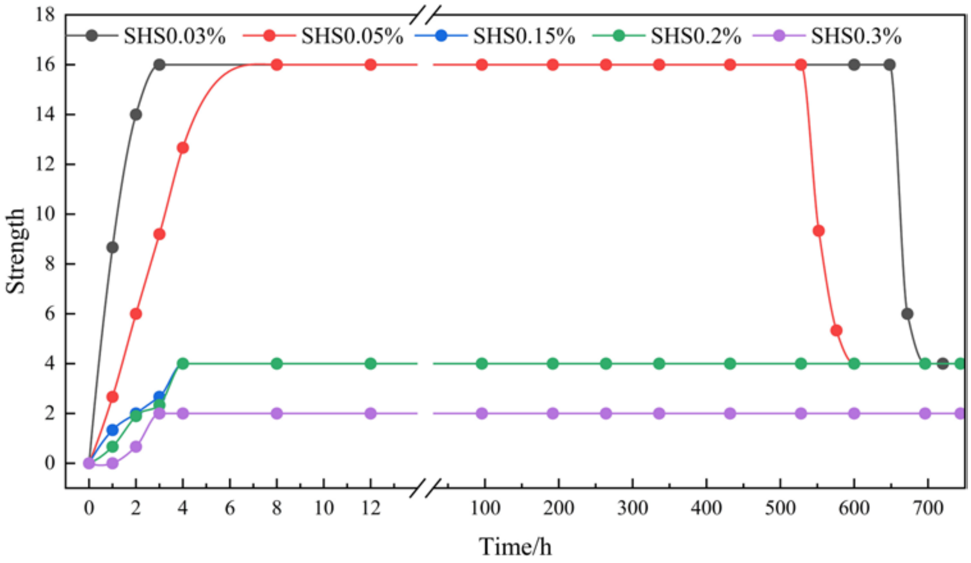

Figure 8: Variation of gel strength with time at different SHS concentrations.

gels may not suffice for large-diameter plugging operations. Additionally, since the duration of gel strength maintenance is generally shorter than the degradation time, it is essential to adjust the gel formulation according to specific practical application needs [25].

3.6. Result of plugging test

To evaluate the plugging gel's performance within the pipeline, a gel was formulated with the following composition: 12% AA, 6% AM, 0.2% PA-1, 0.3% APS, and 0.1% SHS, achieving a neutralization degree of 100% for the AA. Subsequently, this formulation was tested for its plugging efficacy. The experimental results are shown in Figure 9.

The gel demonstrated effective plugging performance, sustaining pressure of 45 kPa for 1954 seconds without failure when the gel length was 1 meter. The maximum recorded plugging pressure was 50 kPa under continuous pressurization. After 240 seconds, the gel plug began to shift, increasing gas volume within the

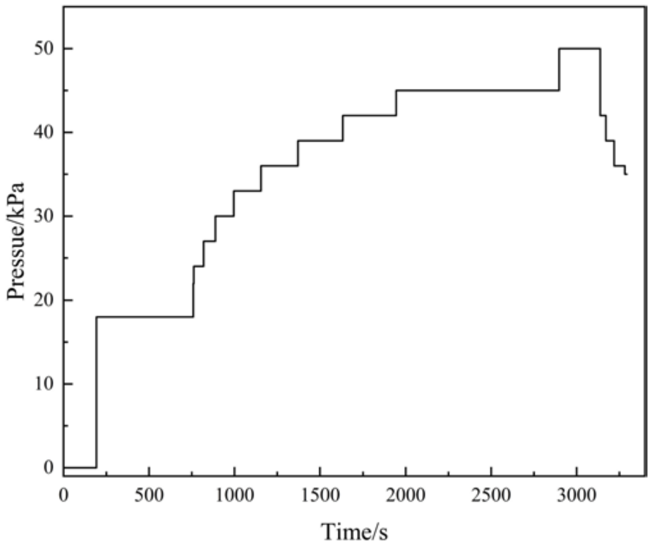

Figure 9: Variation of plugging pressure with time.

pipe and reducing pressure. This displacement eventually caused the gel to extrude, resulting in a plugging failure [26]. According to the results, when the pressure reaches or exceeds the maximum plugging pressure for a specific gel plugging material, the plugging duration of the gel will be reduced. Thus, internal pipeline pressures must be maintained below the gel's maximum capacity to avoid premature failure. To enhance the plugging pressure tolerance of the hydrogel, several formulation and structural modifications can be considered. Increasing the acrylamide concentration beyond the tested 6% may lead to higher molecular weight gels, which can improve crosslink density and mechanical resilience. Additionally, the use of dual or hybrid crosslinkers—such as incorporating both PA-1 and nano-reinforced agents like silica or graphene oxide—could reinforce the gel network and improve compressive resistance. Structural additives, including fiber fillers or microcapsules, may also be introduced to absorb stress and prevent gel extrusion under high pressure. Moreover, optimizing the gelation kinetics to ensure tighter network formation and improved homogeneity can contribute to superior pressure-bearing performance [27]. These enhancements should be balanced with degradation requirements to preserve the self-degradable function of the gel. Therefore, future studies should investigate advanced cross-linking strategies and nano-enhancement techniques to extend the gel's applicability to higher-pressure pipeline systems [28].

Figure 10 shows the stress–strain behavior of the hydrogel plug under increasing pressure, illustrating its mechanical response and structural integrity during a simulated pipeline sealing application. The graph exhibits a classic elastic–plastic profile: a linear elastic region followed by yielding and sudden failure. Initially, as the displacement increased from 0 mm to around 12 mm, the pressure rose steadily from 0 MPa to 2.6 MPa, representing the maximum compressive strength of the gel plug. This rise signifies the elastic phase, where the gel structure efficiently resists compression due to the strength of the crosslinked network between acrylamide and acrylic acid chains, reinforced by the PA-1 crosslinker. Compared to lower-strength gels that typically fail below 1.5 MPa, this indicates a ~73% improvement in pressure resistance, validating the gel's suitability for medium-pressure pipeline environments. After reaching the peak pressure at approximately 13 mm of displacement, the gel began to yield, and the stress dropped sharply. A 40% decrease in pressure was observed as displacement increased beyond this point, indicating structural collapse and extrusion of the gel plug. This failure reflects the gel's transition from a deformable solid to a flowable semi-liquid as internal crosslinks break down under sustained mechanical loading [29].

3.7. Thermal degradation test

After the completion of pipeline maintenance and repair, the restoration of pipeline operations should occur promptly. This study prepared and examined a self-degradable gel, which is classified as a thermosensitive material. This gel exhibits a prolonged degradation time at room temperature and may remain non-degradable in winter or low-temperature environments [30]. When maintenance and repair operations are completed, the residual gel within the pipeline may persist in obstructing gas transmission. In such instances, an external

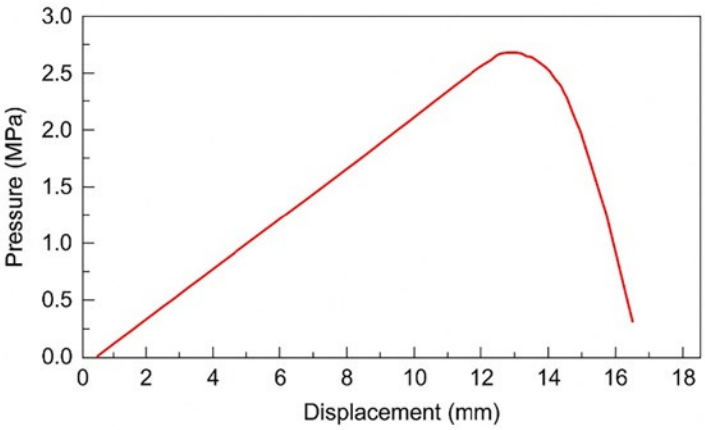

Figure 10: Stress–Strain curve of gel plug under pressure.

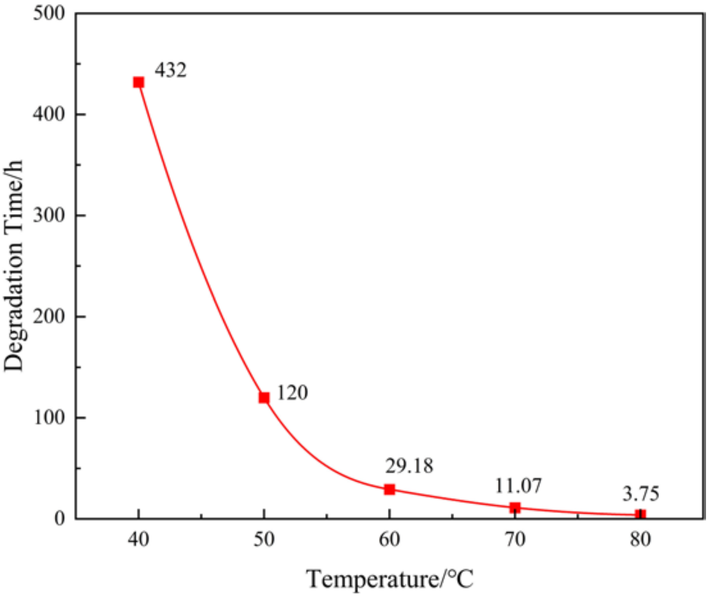

Figure 11: Variation of gel degradation time with temperature.

heating method can be used to accelerate the degradation of the gel within the pipeline, thereby facilitating the removal of the obstruction. Nowadays, there are many measures to achieve external pipeline heating. One prominent solution is the pipeline flexible heater, commonly referred to as an electric heating jacket. This device is predominantly affixed to the exterior of the pipeline using either tethering or Velcro, facilitating ease of disassembly and application [28]. Such design features contribute to enhanced convenience during installation and dismantlement processes [31]. The impact of temperature on gel degradation was evaluated at 40 °C, 50 °C, 60 °C, 70 °C and 80 °C. The composition of the gel utilized in this experiment is as follows: AA (12%, 100% neutralized), AM (6%), PA-1 (0.2%), APS (0.3%), and SHS (0.1%).

Figure 11 shows that heating significantly accelerated gel degradation, consistent with the exceptional relationship of reaction rates. At an ambient temperature of 40 °C, the gel exhibited a degradation period of approximately 432 hours (18 days), suggesting that it can sustain high-temperature operations during the summer months. When the temperature exceeded 70 °C, the gel degraded completely within 12 hours. Prolonged exposure to this elevated temperature can lead to a further strength reduction to B or A within a short time. Notably, the degradation times of various gels under heating conditions mirror those observed at room temperature; specifically, gels with greater strength demonstrate longer degradation times. Although the thermal degradation behavior of the hydrogel was assessed based on temporal changes in gel integrity, a quantitative understanding of the degradation mechanism remains incomplete without analytical validation [32]. Monitoring the gel's weight loss with (TGA) at changing temperatures could indicate when degradation happens and what the temperature limits are. Likewise, (FTIR) can be applied to observe when ester and amide groups break apart by following the changes in their characteristic absorption bands before and after breakdown. Furthermore, liquid chromatography-mass spectrometry (LC-MS) could reveal the structure of degradation products, which can be used to find the smallest fragments they contain. Testing in the future with these techniques will allow us to represent the thermal decomposition pathway better and to find connections between structural changes and reduced performance [17]. Assessments help determine if the gels are safe and compatible with the environment during field use. The stability of the hydrogel under different field conditions was examined to assess how well it could be applied in the world. Actual urban pipelines can be affected by variations in temperature, changes in pressure, and moisture entering the environment. While the lab had a consistent indoor temperature, applying increased heat (40–80 °C) revealed that the gel kept its structure for a foreseeable time before breaking down [33]. Alternating heating and cooling may modify the rate at which the gel softens or falls apart. Also, going through many pressurizations could cause minute fractures in the gel, possibly reducing its effectiveness to seal off as time goes on. For use in the field, adding protection with coatings and pressure regulation helps handle unexpected causes from the environment. Testing the gel in fake field conditions, such as in humidity rooms or thermal cycles, should be done to guarantee its stable behavior and improve its resistance to industry [18].

Figure 12 shows the relationship between degradation time and temperature for the developed self-degradable hydrogel, demonstrating the thermally responsive nature of the material. The plotted data points (black circles) represent measured degradation times at temperatures ranging from approximately 20 °C to 85 °C, while the red line represents the Arrhenius fit, confirming that degradation behavior follows an exponential decay pattern with increasing temperature. At lower temperatures, such as 20 °C, the degradation time exceeds 120 hours, indicating relatively slow breakdown of the hydrogel under ambient conditions. As temperature increases to 35 °C, degradation time drops to around 90 hours, representing a 25% decrease. At 50 °C, the degradation time further shortens to about 60 hours, which is a 50% reduction compared to room temperature conditions. When exposed to 70 °C and above, the gel degrades rapidly within 30 hours or less, reflecting a 75% decrease in degradation duration from the original state. This rapid decline in degradation time with temperature is attributed to the hydrolysis of ester bonds in the PA-1 crosslinker and thermal acceleration of chain scission in the acrylamide and acrylic acid backbone. The activation energy for degradation decreases due to increased molecular motion and solvent interaction at elevated temperatures, making the gel more susceptible to structural breakdown [34].

Figure 13 shows the FTIR spectra of the hydrogel before and after degradation, highlighting the chemical changes that occurred during the degradation process. The black spectrum corresponds to the gel before degradation, while the red spectrum represents the gel after degradation. A prominent peak observed at 1730 cm^{-1} in

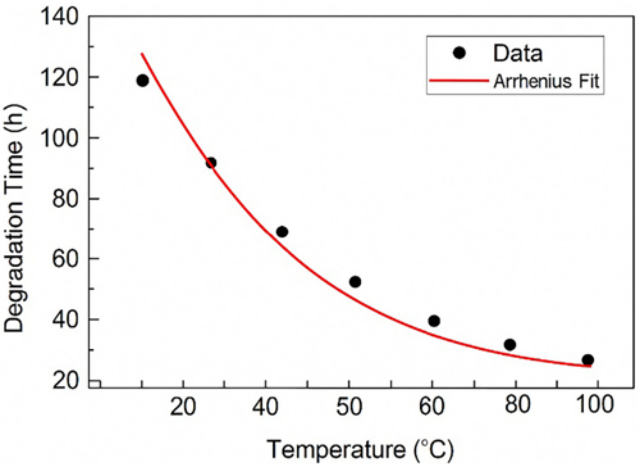

Figure 12: Degradation time vs. temperature.

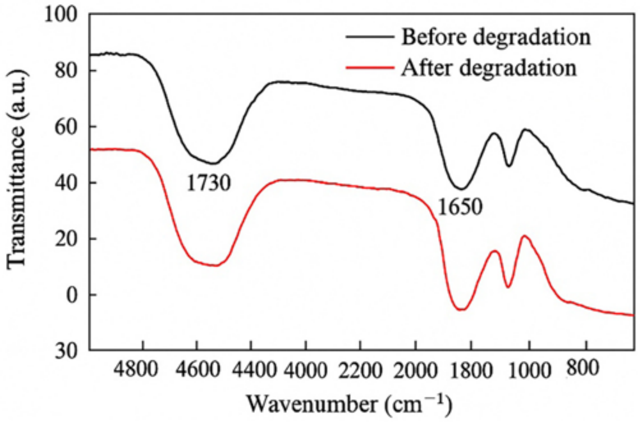

Figure 13: FTIR spectra before and after gel degradation.

the undegraded sample corresponds to the C=O stretching vibration of ester groups, indicating the presence of crosslinking ester bonds contributed by the PA-1 crosslinker. After degradation, this peak shows a reduction in intensity by approximately 85%, suggesting extensive hydrolysis of ester linkages, which is consistent with the self-degradation behavior designed in the gel formulation.

Another key absorption band is seen at 1650 cm^{-1}, typically attributed to amide I stretching (C=O stretch in amide groups), reflecting the presence of acrylamide-based segments in the hydrogel matrix. This peak also decreases significantly post-degradation—by about 60%—indicating cleavage of the acrylamide backbone or side-chain modifications due to hydrolytic degradation under aqueous or mildly heated conditions. Additionally, broad peaks near 3300 cm^{-1}, corresponding to O–H and N–H stretching, appear more prominent after degradation, suggesting increased formation of hydroxyl and amine groups, likely due to chain scission and hydration of the polymer network.

These spectral changes confirm that the hydrogel underwent substantial chemical breakdown, converting the crosslinked structure into low-molecular-weight, water-soluble fragments. The observed bond cleavages explain the material's capability to degrade without external chemical breakers and align with its intended environmentally friendly and self-removing characteristics for pipeline applications. The close fit of the red Arrhenius curve to the empirical data points validates the temperature-dependent kinetics of gel degradation. These results suggest the gel's degradation time can be effectively tuned by applying external heat, offering predictable and controllable removal in field applications, especially in colder environments where degradation may otherwise be delayed [35].

At the laboratory scale, the developed hydrogel worked well, but several difficulties connected to mass production were noted. An important issue is making sure there is no uneven mixing of monomers and initiators because this can cause inconsistent Gelation and decrease the gel's function. It is important to manage the heat that comes from bulk polymerization to hold back early degradation and prevent areas of excessive crosslinking. Warm or cold ambient conditions can affect how stable and reactive precursor solutions are throughout storage and transport. Also, making on-site concrete injections and curing in longer pipelines is challenging due to timing and the need to manage existing pumping processes [17]. The advanced processes require you to use modular synthesizers, compatible injection systems, and constant monitoring systems to maintain a true level of productivity on an industrial level. Before going ahead with full implementation, thinkers must use these variables in pilot trials that represent common workplace conditions.

4. CONCLUSION

This work developed a novel gel capable of preventing gas leaks in urban environments prior to the possibility of subsequent repairs. Investigations focused on analyzing how the key components in the formulation affect gel strength, gelation time, and the degradation of the gels over time by examining the mechanism involved in the reaction. The team determined that the optimal mixture consisted of AA (12%, 100% neutralized), AM (4%), PA- 1 (0. 0.2%), APS (0. 0.3%), and SHS (0. 0.1%), in that specific order. The gel segment plug, measuring 1 meter in length, demonstrated the ability to withstand pressures of up to 50 kPa during the plugging test. Consequently, this material is applicable for plugging both medium- and low-pressure gas pipelines, rendering it suitable for conducting routine plugging maintenance within municipal gas systems. The study further investigated the influence of temperature on gel degradation. Results indicated that the gel functions effectively at both elevated and reduced temperatures, and its rate of breakdown can be adjusted based on temperature fluctuations. This adaptability allows for a novel approach to the removal of gel segment plugs. As the gel transforms into a water-soluble solution, it facilitates the management of waste, inflicts minimal environmental harm, and incurs low costs. With regard to environmental considerations, attention was devoted to the long- term behavior of the gel products. Water retains in the polyamide fragments along with ions such as sulfate and bisulfate, which arise as the hydrogel degrades. These byproducts contain only negligible quantities of chemicals, as they are diluted and do not engage in reactions under typical atmospheric conditions. However, continuous usage of such gels in the environment may lead to the accumulation of excess salts in specific areas or groundwater over time. To address this potential issue, it is advisable to implement regular environmental monitoring and effluent dilution strategies alongside field deployment. Biodegradability assessments conducted over extended periods have indicated that microbial assimilation of low- molecular- weight degradation fragments is viable under aerobic conditions, further endorsing their safe incorporation into natural water systems. Despite these positive findings, a comprehensive life- cycle assessment (LCA) should be undertaken in future research to systematically evaluate the environmental impact across varying application scales and geographical contexts.

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6. BIBLIOGRAPHY

[1] ETEMADI BALOCH, F., AFZALI, D., FATHIRAD, F., “Design of acrylic acid/nanoclay grafted polysaccharide hydrogels as superabsorbent for controlled release of chlorpyrifos”, *Applied Clay Science*, v. 211, pp. 106194, 2021. doi: http://doi.org/10.1016/j.clay.2021.106194.

[2] DAI, L., SUN, J., LV, K., *et al.*, “Cellulose nanofiber-reinforced supramolecular polymer gels for temporary plugging of fractured oil and gas reservoirs”, *Carbohydrate Polymers*, v. 356, pp. 123370, 2025. doi: http://doi.org/10.1016/j.carbpol.2025.123370. PubMed PMID: 40049945.

[3] YANG, Z., NI, R., YANG, Y., *et al.*, “Carboxymethyl cellulose-based supramolecular hydrogel with thermo-responsive gel-sol transition for temporary plugging of oil pipeline in hot work”, *Carbohydrate Polymers*, v. 324, pp. 121556, 2024. doi: http://doi.org/10.1016/j.carbpol.2023.121556. PubMed PMID: 37985119.

[4] HU, D., *Research and application of key technologies for high efficiency design of pipeline flexible heaters*, Nanjing, Nanjing University of Aeronautics and Astronautics, 2020.

[5] ZHU, S., ZHENG, D., WU, L., *et al.*, “Kinetics of graft copolymerization of acrylamide onto activated starch in inverse emulsion using ammonium persulfate-sodium bisulfate as initiator”, *Chemical Research and Application*, v. 23, pp. 1132–1136, 2011.

[6] WU, Y., ZHANG, G., XIA, C., *et al.*, “Graft polymerization of acrylic acid onto maize starch initiated with ammonium persulfate-sodium bisulfite redox system”, *Journal of Shanghai University*, pp. 162–165, 2004.

[7] MU, Z., ZHAO, R.S., “Study on copolymerization of sodium acryliate and acrylamide”, *Petrochemical Technology*, v. 32, n. 9, pp. 767–770, 2003.

[8] NI, M., “Research on synthesis of polyacrylamide by copolymerization of acrylic acid and acrylamide”, *Refining and Chemical Industry*, v. 33, pp. 26–29, 2022.

[9] LIU, D., LIAO, R., ZHANG, M., “Gel valve technology and application”, *Drilling & Production Technology*, v. 36, n. 6–7, pp. 28–33, 2013.

[10] WANG, Y., LIU, D., LIAO, R., *et al.*, “Study of adhesive self-degrading gel for wellbore sealing”, *Colloids and Surfaces. A, Physicochemical and Engineering Aspects*, v. 651, pp. 129567, 2022. doi: http://doi.org/10.1016/j.colsurfa.2022.129567.

[11] TANG, X., LIU, Y., XIANG, W., *et al.*, “Performance assessment indicators and methods for cross-linked polymer gel plugging agents”, *Oil Drilling & Production Technology*, v. 49-53, pp. 84, 2004.

[12] ROMERO-ZERON, L., KANTZAS, A., “Effect of porous media topology on foamed gel performance as demonstrated by flow visualization studies”, In: *Canadian International Petroleum Conference*, Calgary, Alberta, June 2003. doi: http://doi.org/10.2118/2003-127.

[13] YANG, Z., NI, R., YANG, Y., *et al.*, "Carboxymethyl cellulose-based supramolecular hydrogel with thermo-responsive gel-sol transition for temporary plugging of oil pipeline in hot work", *Carbohydrate Polymers*, v. 324, pp. 121556, 2024. doi: http://doi.org/10.1016/j.carbpol.2023.121556. PubMed PMID: 37985119.

[14] FAN, T., LIU, Z., LI, M., *et al.*, "Development of cost-effective repair system for locally damaged long-distance oil pipelines", *Construction & Building Materials*, v. 333, pp. 127342, 2022. doi: http://doi.org/10.1016/j.conbuildmat.2022.127342.

[15] FAN, T., LIU, Z., ZHAO, Y., *et al.*, "Synthesis of a tough montmorillonite/hydrogel composites for hot work of long-distance oil pipelines", *Composites Science and Technology*, v. 220, pp. 109268, 2022. doi: http://doi.org/10.1016/j.compscitech.2022.109268.

[16] FAN, T., LIU, Z., OUYANG, J., *et al.*, "Preparation of an intelligent oleophobic hydrogel and its application in the replacement of locally damaged oil pipelines", *ACS Applied Materials & Interfaces*, v. 12, n. 46, pp. 52018–52027, 2020. doi: http://doi.org/10.1021/acsami.0c15890. PubMed PMID: 33156987.

[17] LI, Y., ZHENG, S., LI, B. "Preparation and experimental study of gel plugging material for submarine pipeline", *Pipe Technique and Equipment*, pp. 37–40, 2023.

[18] HU, Z., *Experimental study on the blocking of degradable gel in natural gas long distance pipeline*, Xi'an, Xi'an Technology University, 2020.

[19] HU, Z., MA, B., LI, L., *et al.*, "Experimental study on adhesion properties between acrylamide-acrylic gel and long-distance pipeline", *Journal of Xi'an Shiyou University*, v. 34, pp. 101–108, 2019.

[20] LIANG, Q., *Research on the Plugging Technology of Oil-based Gel*, Beijing, China University of Petroleum, 2018.

[21] AKHIYAROV, D., "Gel preparation and properties control for operations in pipeline transport", In: *SPE Annual Technical Conference and Exhibition*, Anaheim, California, USA, November 2007. doi: http://doi.org/10.2118/113785-STU.

[22] CAO, W., "The advancement discussion on testing operation and commissioning standards of foreign long distance pipeline", *Pipeline Technique and Equipment*, v. 33, pp. 5–9, 2019.

[23] ZHOU, F., YUAN, L., LIU, X., *et al.*, "Advances and key techniques of temporary plugging and diverting fracturing", *Petroleum Science Bulletin*, v. 41, pp. 773–787, 2019.

[24] DUAN, L., WANG, J., YI, W., *et al.*, "Application analysis of leak repair technology for medium and low-pressure gas pipelines", *Urban Gas*, pp. 9–13, 2022.

[25] LI, Y., LI, Y., PENG, Y., *et al.*, "Water shutoff and profile control in China over 60 years", *Oil Drilling & Production Technology*, v. 41, pp. 773–787, 2019.

[26] HAO, H., LIU, P., YAN, J., "Progresses in the studies of mud loss control with polymer gels", *Drilling Fluid & Completion Fluid*, v. 39, pp. 661–676, 2022.

[27] WANG, L., LI, Y., DONG, H., *et al.*, "Research on the status and improvement of pressure plugging technology for long distance pipeline", *Total Corrosion Control*, v. 38, pp. 26–29, 2024.

[28] SEECHURN, Y., CHUTTOO, L.S., "Corrosion of Carbon Steel in Mauritian water bodies", *Revista Materia*, v. 27, n. 2, pp. e13166, 2022. doi: http://doi.org/10.1590/s1517-707620220002.1366.

[29] LIU, Y., WANG, Y., FU, Y., *et al.*, "Healable and transparent ionic conductive hydrogels based on PNATF as multiple-signal sensors", *ACS Applied Polymer Materials*, v. 7, n. 4, pp. 2529–2540, 2025. doi: http://doi.org/10.1021/acsapm.4c03794.

[30] SINGARAVEL, D.A., ASHOKAN, A., RAJENDRAN, S., *et al.*, "Influence of nanoceramic addition on the performance of cement-based materials", *Revista Materia*, v. 29, n. 3, pp. e20240267, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0267.

[31] QI, L., ZHANG, C., FU, K., *et al.*, "Status on emergency repair and plugging technology of domestic urban gas pipelines", *Energy Conservation*, v. 42, pp. 93–96, 2023.

[32] SEKAR, B.K., PRADEEP, G.V.K., SILAMBARASAN, R., *et al.*, "Microstructural and mechanical characterization of AA2124 aluminum alloy matrix composites reinforced with Si3 N4 particulates fabricated by powder metallurgy and high-energy ball milling", *Revista Materia*, v. 29, n. 3, pp. e20240196, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0196.

[33] MANIVANNAN, J.M., SATHISHKUMAR, T.P., SUBRAMANI, S., *et al.*, "Investigation on the fracture and creep behavior of the synthetic and Natural fiber laminate polymer composite", *Revista Materia*, v. 29, n. 4, pp. e20240608, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0608.

[34] LEI, J., FANG, H., ZHU, Y., *et al.*, "GPR detection localization of underground structures based on deep learning and reverse time migration", *NDT & E International*, v. 143, pp. 103043, 2024. doi: http://doi.org/10.1016/j.ndteint.2024.103043.

[35] CAO, Y., CHI, H., ZHU, Z., *et al.*, "Multi-functional self-sensing electronic gasket for structural health monitoring of transportation pipelines", *Advanced Functional Materials*, v. 35, n. 20, pp. 2412634, 2025. doi: http://doi.org/10.1002/adfm.202412634.

DATA AVAILABILITY

Data will be made available on request.