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Modeling and Simulation for Utilisation of Chitosan-Polybenzoxazine Crosslinked Polymers for Pipeline Transportation of Crude Oil

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Abstract

In this work, in the first time, the use of dynamic model for prediction of stress-strain properties of chitosan/polybenzoxazine (CTS-PBZ) pipelines under high internal pressures was reported. Simulations of the stress-strain properties-based on ANSYS software for various CTS-PBZ pipelines with different ratios were investigated. Resistance of CTS-PBZ pipelines were studied for a wide range of internal pressures. The pipelines with different ratios of CTS-PBZ were compared with data in literature for pipelines that were made from polypropylene, polyethylene, styrene, and polycarbonate. The results suggested that the pipeline with 20/80 wt% of CTS-PBZ provides excellent mechanical properties than the other studied polymers. The results also showed that the prediction of stress of CTS-PBZ crosslinked polymer is significantly dependent on the composition of blend polymers. As internal pressure increases, the stress strength increased from 41.9 to 83.6 MPa with an increase in PBZ content from 40 wt% to 80 wt%. The relationship between stress strength and pressure is mostly linear. Before explosion the pipeline, a maximum stress strength of 83.6 MPa where achieved at applied internal pressure of 11.5 bar.

Keywords: Natural gas and crude oil; pipeline transportation; polymeric pipelines; modeling and simulation; mechanical properties.

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1. Introduction

Beyond exploration of oil and gas, the product is to be transported to the processing facilities and plants. Even though various methods have been used to transport oil and gas from resources to processing facilities, transportation through pipelines is the preferred method [1]. Pipe-material is of great importance for fluid transportation, especially when meet a high internal pressure [2]. Among of the available materials, carbon-steel has been widely used as a pipe-material for fluid transportation in various industries such as oil, water and gas due to their high strength [3]. However, there are some disadvantages associated with using steel including high cost, tendency to corrode, and mechanical damage [4, 5]. In addition, during natural gas (NG) transportation, metallic pipelines are sensitive to internally expose to organic acid agents (CO_2 and H_2S) [6, 7]. To overcome these problems, polymeric pipelines have been proposed to replace the metallic pipelines [8]. High-strength polymeric pipes are being developed in order to reduce replacing cost, easy processing, and increase pipeline-life [8-11].

In recent years, a rapid growth in polymer applications for transportation pipelines has been observed. Due to this significant growth, polymers with outstanding mechanical parameters have been developed [9]. For fluid transportation via pipelines, resistance to internal pressure for thermoplastic polymers has been investigated [8, 11]. Among of these polymers, polypropylene, polyethylene, polycarbonate, poly urethane, and polystyrene have been tested

to transport crude oils. Polybenzoxazine (PBZ) belongs to be one of the most versatile classes of polymers with a simple preparation method. PBZs can be prepared for both rigid and flexible thermosetting depending upon the choice of the initial reactants [12]. The interesting of the benzoxazine (BZ) processing, BZ monomers can soften and become viscous liquids when heated for processing and then become solid when cooled. PBZ resins allow for faster molding with chemical reactions during the curing process, while this process is irreversible. The interesting of PBZ-based products is that the products possess unique mechanical integrity due to crosslinking density [12-14].
For research, analytical methods are more attractive than experimental measurements because experiments are expensive, time consuming, safety issues, and difficulty to create the exact conditions in the laboratory. Modelling and simulations are becoming important tools for predicting mechanical properties of pipelines under high pressures. In the present study, analysis of possibility for replacing chitosan-polybenzoxazine (CTS-PBZ) cross-linked polymers of metallic pipelines has been investigated. Simulations of effect of internal pressure on mechanical properties for various polymeric pipelines were modelled using ANSYS software. In addition, the relation of internal pressure and wall-thickness on mechanical properties of (CTS-PBZ) was demonstrated.

2. Modeling of Mechanical Properties

Mechanical properties were calculated using the full trajectory from the simulator run of the established modules using ANSYS software. Based on this concept, ANSYS Models were created for pressurized pipelines to investigate the effect of internal pressure on the mechanical properties of polymeric pipelines. Table 2.1illustrates the polymers parameters associated with the different features of the material behavior. The specimens were designed as pipelines with an outside diameter (OD), wall thickness (WT), and length (L). After the run of the model, the internal pressure was applied onto the inner side of the pipeline as seen in Figure 2.1. The applied pressure for all models started from P about 0 bar and gradually ramped until to achieve explosion of the pipe. The stress values were obtained as function on the actual load of pressure.

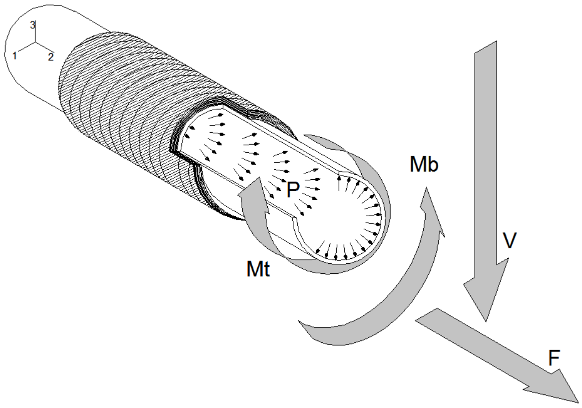

Figure 2.1: Actions working inside a pipe section [Adapted from Ref. 5].

Among the available models in literature, van Mises model [5] was used to investigate the effect of internal pressure on stress of pipelines in the study. As seen in Figure 2.1, the load was applied to the internal surface of the pipe. The possible different load-actions including tension/compression force (F), bending moment (M_b), shear force (V), and torsional moment (M_t) during fluid transportation. The relationships between these actions produce different types of stresses, including normal stress on both axis (σ_1 and σ_2) and the shear plane (σ_{12}) as illustrates in Table 2.2 [5]. Equivalent tensile stress (σ_v) as a result of loading internal pressure on a pipeline was obtained using Equation 2.1.

$$\sigma_v = \sqrt{(\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 + 3\sigma_{12}^2)} \qquad (2.1)$$

where σ_1 and σ_2 are the normal stress on both axis as shown in Figure 2.1 and σ_{12} is the shear plane.

3. Results and Discussion

3.1. Effect of polymer type

Polymer type is one of the important factors that affecting on performance of pipelines for transportation of fluids. Therefore, in this study, the mechanical properties of various polymeric pipelines have been evaluated. The effect of internal pressure on the stress properties has been studied in details for polymeric pipes that were made from polycarbonate, polyethylene, polypropylene, epoxy, and polybenzoxazine. The typical tensile properties of the tested materials are shown in Figure 3.1a and the maximum values for tensile strength and elongation

Table 2.1: Data of polymers that were needed for simulations using ANSYS models.

Polymer full name	Sample code	Stress (MPa)	E (GPa)	Elongation (%)	Poisson's ratio (–)
Chitosan/polybenzoxazine-80%	CTS-PBZ-80%	82	4.1	2	0.35
Polycarbonate	PC	70	3	2.333	0.38
Chitosan/polybenzoxazine-60%	CTS-PBZ-60%	60.52	3.56	1.7	0.35
Polypropylene	PP	35	1.2	2.9	0.46
Chitosan/polybenzoxazine-40%	CTS-PBZ-40%	42	3	1.4	0.35
Polyethylene	PE	40	0.14	28.5	0.46

Table 2.2: The relationships between load-actions working inside a pipe section and stresses.

Stress	Internal pressure (P)*	Axial load (F)	Bending (M_b)	Torsion (M_t)	Shear (V)
Axial* (σ_2)	$\frac{PD_p}{4t_p}$	$\frac{F}{\pi D_p t_p}$	$\frac{4M_b}{\pi D_p^2 t_p}$	0	0
Hoop (σ_1)	$\frac{PD_p}{2t_p}$	0	0	0	0
Shear (σ_{12})	0	0	0	$\frac{2M_b}{\pi D_p^2 t_p}$	$\frac{V}{\pi D_p t_p}$

as function in internal pressure are tabulated in Table 3.1. As seen in Figure 3.1a, both tensile modulus and tensile strength increase whereas elongation decreases. The results indicated that the sample of CTS-PBZ-80% crosslinked polymer showed the highest strength than the other samples. This high value of the strength is attributed to the fact that benzoxazine monomer leads to higher crosslinking density than the thermoset plastic [12, 13]. The stress-strain curves of the CTS-PBZ samples that obtained from ANSYS in this study were compared with previously reported experimental results [14] and a good agreement was achieved. Thus, the accuracy of the developed computational simulations was validated.

In order to investigate the influence of internal pressure on resistance of pipelines, internally pressurized each pipe-model was performed using ANSYS software. The model was set up and internal pressure loads were gradually applied into the pipe. Figure 3.1b represents the stress-internal pressure curves of the studied pipelines. The results for all polymers indicated that the stress has a linear relationship with internal pressure whereas samples of CTS-PBZ 80% and polycarbonate showed the highest internal pressurized values than the other polymer samples. Table 3.1 illustrates the maximum internal pressure and ultimate stress of all studied polymers.

Table 3.1: Summary of mechanical properties of various polymers.

Sample code	Maximum internal pressure (bar)	Strain (%)	Stress strength (MPa)
CTS-PBZ-80%	8.30	2.25	83.60
PC	8.00	4.26	69.80
CTS-PBZ-60%	6.00	1.85	61.20
PP	3.70	5.40	34.90
CTS-PBZ-40%	4.40	2.52	41.88
PE	4.10	32.4	39.87

3.2. Effect of PBZ-crosslinking

The effect of BZ content as a crosslinking agent on the mechanical properties of CTS-PBZ pipelines has also been studied. The strengths of pipes for both stress and internal pressure increase with an increase in the PBZ concentration in the pipe as seen in Figure 3.1. The variation could come from the nature of the PBZ due to the high crosslinking density (see Figure 3.2). The more is the applied pressure, the more will be the high resistance of the pipe and the high would be the amount of PBZ. For

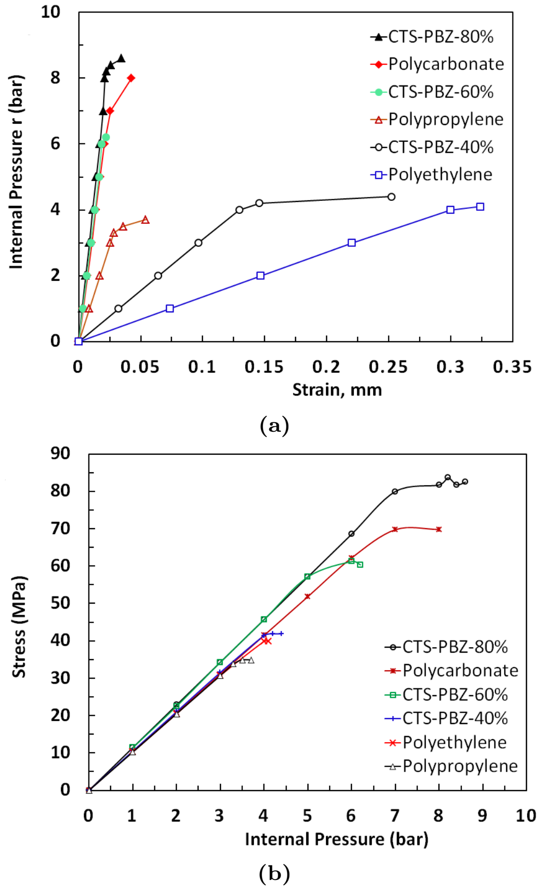

Figure 3.1: Mechanical properties of studied polymers: (a) Effect of internal pressure on strain properties and (b) Effect of internal pressure on stress properties.

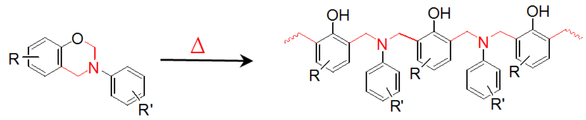

Figure 3.2: Polymerization of benzoxazine monomers [12].

example, the stress strengths values are 80, 60, and 40 MPa whereas the applied internal pressure are 8, 5, and 4 bar for samples CTS-PBZ-80%, CTS-PBZ-60%, and CTS-PBZ-40%, respectively. A number of experimental studies were conducted to investigate the relationship between mechanical properties and crosslinking density of polybenzoxazines. The high mechanical integrity is due to the increase in the crosslinking density with PBZ content [12-14].

3.3. Effect of diameter and thickness

Thickness (t_c) of the pipe is another parameter involved in the design of pipelines for fluid transportation. Therefore, the maximum allowable internal pressure for the pipe was calculated as a function of the wall thickness of the pipe. In this study, the pipe thickness was considered as a function on the diameter.

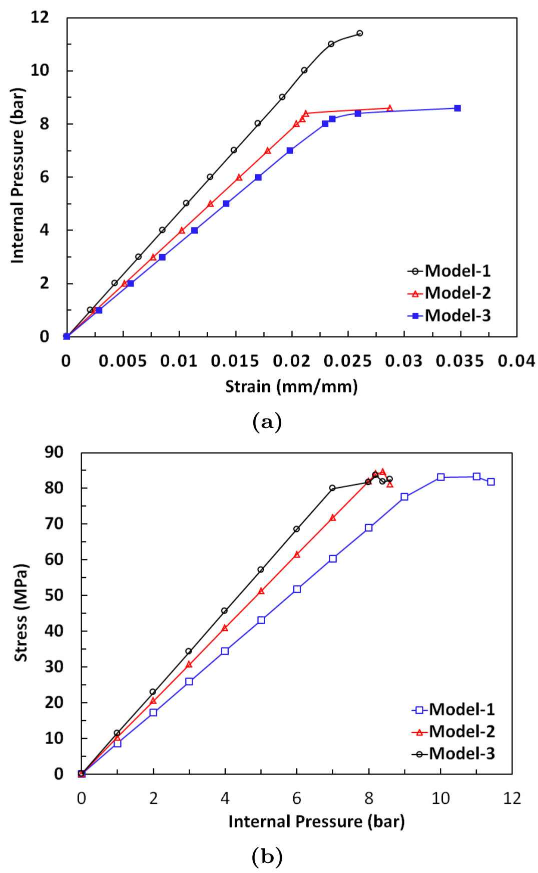

Figure 3.3: Mechanical integrity of CTS-PBZ-80% with different internal diameters: Model-1 is 160 mm, Model-2 is 195 mm, and Model-3 is 270 mm.

Yagubov E. S [15] reported various minimum thicknesses of composite material to assure the safety of applied pressure into inside pipelines under operating conditions. Table 3.2 illustrates the different design thicknesses were considered in this study. The maximum allowable internal pressure for the each model was calculated based on ANSYS simulator considering the effect of internal diameter of the

Table 3.2: Maximum mechanical parameters for CTS-PBZ-80% at various diameters.

Model	Internal diameter (mm)	Thickness (mm)	Length (mm)	Maximum internal pressure (bar)	Strain (%)	Stress (MPa)
Model-1	160	11	1000	11.50	2.25	83.60
Model-2	190	11	1000	8.30	2.87	81.22
Model-3	270	13	1000	8.00	2.60	81.76

pipe. Figure 3.3 demonstrates the effects of internal pressure on stress and strain of CTS-PBZ-80% pipelines and the summary of results are listed in Table 3.2. The results indicated that the internal pressure is a function on the pipe-diameter. The maximum internal pressure values are 11.50, 8.30, and 8.00 bar whereas the ultimate strain values are 2.25%, 2.87%, and 2.60% for pipelines of model-1, model-2, and model-3, respectively. However, the results in Figure 3.3b indicated that no effect of pipe-diameter on the pipe strength. In fluid transportation, the preferred model is one that provides the minimum strain value. In summary, the simulations showed that the diameter of model-1 is the best model for design of pipeline for transportation of fluids with a maximum internal pressure of 11.50 bar. These investigations are in agreement with literature [16].

3.4. Simulation of the effect of pipeline-joints

In this study, two models of different pipe with and without joints were simulated to investigate effect of internal pressure on pipeline-joints. Loading, including the internal pressure and axial load induced by the internal pressure, were gradually applied to the model. The pressure was then gradually increased to the point that the analysis could not proceed and was terminated due to the high level of deformation. Figures 3.4 and 3.5 demonstrate results of ANSYS simulations for effect pipe-joints on mechanical properties of CTZ-PBZ-80% pipelines. At the maximum applied pressure, the strain values in the designed pipes are 5.2% to 2.5% for pipes with and without joints, respectively. However, there is no significant change in the stress of the designed pipes (*i.e.* stress values are 80.79 and 80.55 MPa for pipes with and without joints, respectively). The simulated images indicated that the areas at the ends of pipe have lower strain whereas the maximum values were obtained at the near area to the ends. However, pipes with joints, the area of joints at the middle of pipe shows similar strain behavior of pipe-ends. Besides, the joint plays as a throat to the pipe in the middle. These investigations indicated that pipelines with-joints are more applicable for fluid transportation than that without joints.

4. Conclusion

A series of polymeric pipelines were modeled and their mechanical properties were simulated using ANSYS software. The simulation provides a prediction of the maximum strength and ultimate strain values as a function of applied internal pressure. The obtained data predicted that CTS-PBZ cross-linked polymer is the best polymer than polycarbonate, polyethylene and polypropylene for fabrication of polymeric pipelines for fluid transportation. For design of pipelines, model-1 with internal diameter of 160 mm shows the highest internal pressure compared with other studied models. Also, the simulations indicated that pipe-joints enhance the mechanical properties of pipelines of fluid transportation. This study has shown that ANSYS simulator provides an excellent prediction of mechanical integrity of CTS-PBZ derived pipeline as well as demonstrates the optimum parameters insight into the design of fluid transportation pipelines.

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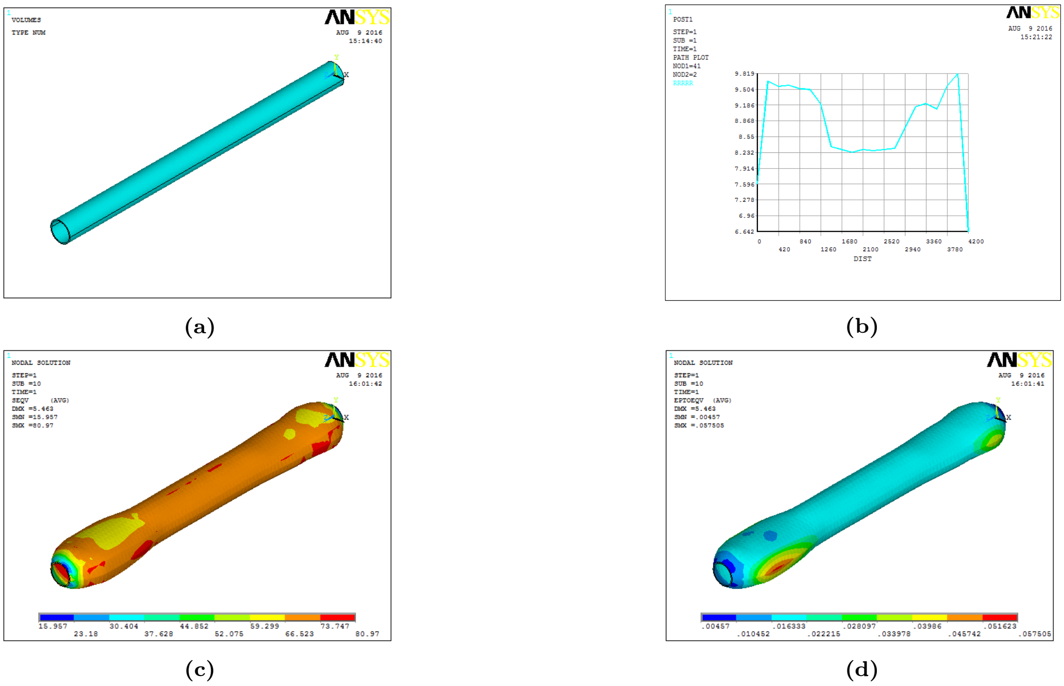
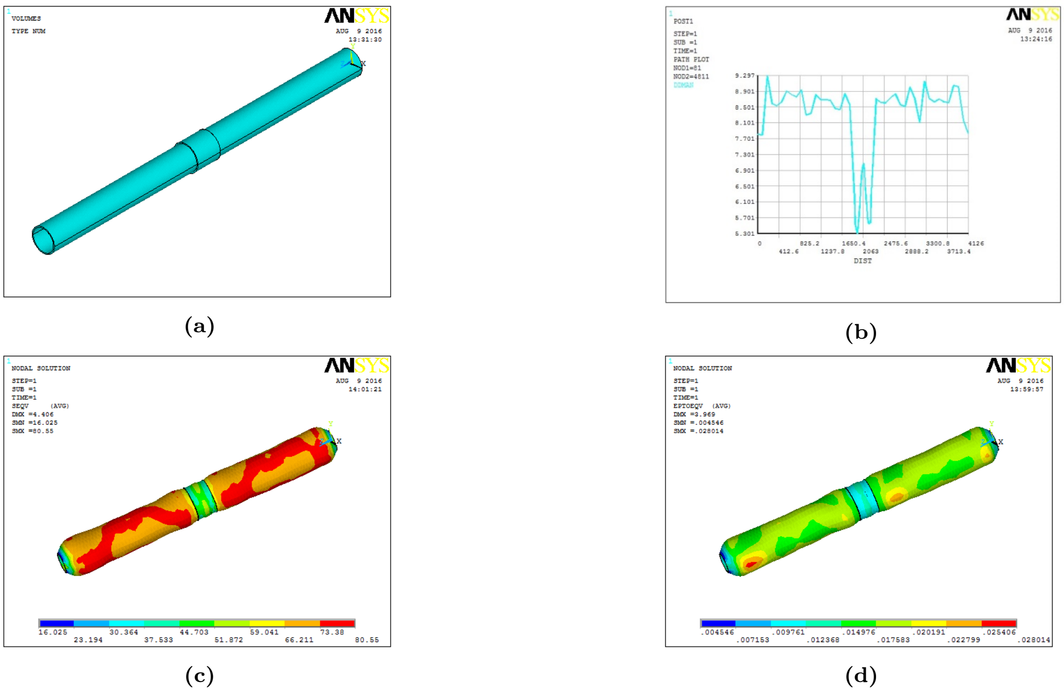


(a) (b) (c) (d)

Figure 3.4: ANSYS simulation of internal pressure onto pipelines without joints.



(a) (b) (c) (d)

Figure 3.5: ANSYS simulation of internal pressure onto pipelines with joints.

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