

RESEARCH PAPER

Numerical and experimental study of mechanical properties and hydrostatic behavior of PVC-O material for drinking water pipes

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ABSTRACT:

This study investigates the mechanical properties for oriented polyvinyl chloride PVC-O material from three different directions of stress application. A PVC-O 500 pipe material has been studied in terms of mechanical properties in three different directions (0°, 45°, 90°). Tensile strength at yield and percent elongation at fracture has been determined in all three directions. Two types of end caps (A and B) have been used to evaluate the pipe's hydrostatic strength. Results showed that molecular orientation has a significant impact on the pipe strength and ductility in different directions. Increasing the molecular orientation in the direction of the hoop (90° direction), the strength increased to 91 MPa compared with 0° and 45° direction, which were 49 MPa and 61 MPa, respectively. Results showed that the percentage of elongations was 200%, 76 %, and 61% for 0°, 45°, and 90° directions, respectively. The burst pressure for type A and B end caps was 6.22 MPa. Finite element analysis by SolidWorks 2018 simulation has been employed; the FEA has showed a good agreement with experimental results with a maximum difference of 5.16%. The FE results also showed that end caps affect stress distribution around the pipe during the hydrostatic test specially when using type B end caps. It's also concluded that both types of end caps cause stress concentration near the edges of the caps.

KEY WORDS: Oriented Polyvinyl Chloride; Hoop stress; Hydrostatic strength; Von Mises yield criteria; Finite element analysis.

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1. INTRODUCTION :

Pipe materials technology, market requirements, and demand for more potable and waste water supplies have enforced pipe makers to advance developments in the mechanical properties of water pipes. In the late nineteenth century, PVC plastic material has discovered and lead to numerous applications, among those plastic pipes. In the middle of the 1930s, engineers, and scientists in Germany produced a limited amount of PVC pipes (AWWA 2002).

Since then, extreme improvements and developments are made in the plastic pipe field, which includes producing un-plasticized polyvinyl chloride PVC-U, chlorinated polyvinyl chloride PVC-C, Modified polyvinyl chloride PVC-M, and recently oriented polyvinyl chloride PVC-O (Mulapeer et al, 2016).

PVC-O has the same constituents of PVC-U pipes, and both are produced by the extrusion process, but a further process is required to produce PVC-O pipes, off-line or in-line manufacturing processes, in which both processes aimed to activate the molecular orientation in a circumferential direction by increasing the pipe

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diameter during the manufacturing (ISO:16422, 2006) as shown in figure (1).

Increasing pipe diameter drives the molecules to orientate in the hoop direction and leads to substantial improvement in the mechanical properties, both strength, and toughness (Molecor 2017). PVC-O pipes also have significant resistance against surge pressures and water hammer and are quite capable of withstanding pressure transients over twice their rated working pressure (UK Water Industry 1999).

Since the product is an innovation and is not fully recognized by many academia, research centers, and even pipe manufacturers, there are limited published papers on this product. (Ferrante et al., 2015) presented the results of a study that investigate material rheology of PVC-O. Coupled measures of pressure and strain studied the viscoelastic effects in the strain-stress domain. They found that the rheological behavior of PVC-O is more predominant when pipes are subjected to transient pressure to a factor of 2 compared to UPVC pipes. (Bauer, 1994) studied the mechanical properties of oriented PVC pipes over traditional UPVC pipes, and it has been revealed that hoop stress of approximately 1.75 to 2.0 times higher is required to burst PVC-O that leads to PVC-O pipes requires less wall thickness than UPVC pipe at the same pressure and factor of safety.

Regarding fatigue resistance, studies found that PVC-O sustains more cyclic stress than UPVC; PVC-O demonstrates roughly 50 times greater strength (UK Water industry 1999).

(Purdue ECT Team, 2017) provided the market with the most eco-friendly pipes by eliminating many of the existing disadvantages of thermoplastic pipes. PVC-O provides greater hydraulic capacity between 15% - 40% higher than pipes made of other materials with the same outer diameter, and high chemical resistance, which does not require any coating of the pipes. Furthermore, the pipes can endure internal pressures about twice the nominal pressure of conventional pipes. Before the real emerging of PVC-O into the market, numerous studies have been conducted in order to improve the mechanical properties and hydraulic capacity of the available UPVC pipes. (Awham and Salih, 2011) studied some of the mechanical behavior,

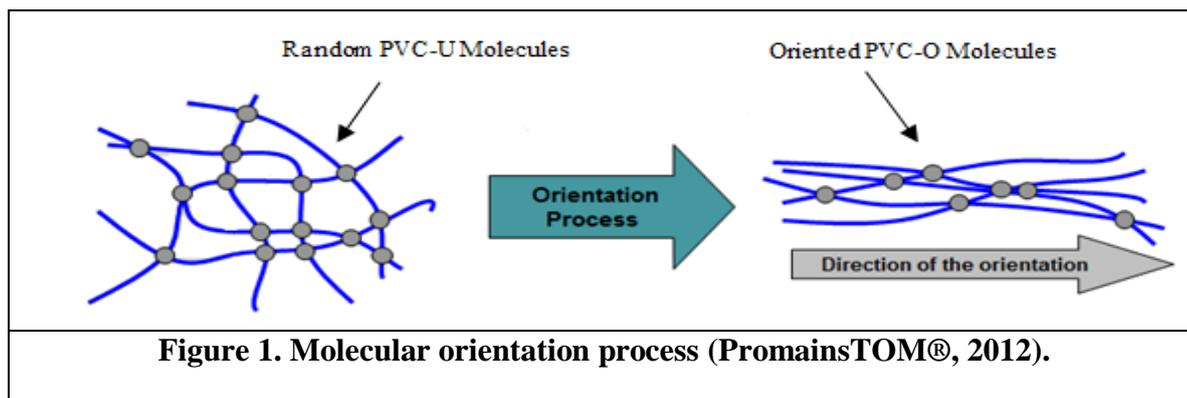
including impact, elastic modulus, flexural strength, and compression strength of PVC-U pipes. The results showed that PVC-U pipes have higher impact resistance and flexural strength as well as the compression failure considered suitable compared with other materials. Also, the results showed the presence of notches has a significant influence on such properties; as notch depth increased, the impact strength decreases.

Regarding the elastic modulus, it has been found that such material has a high elastic modulus compared with traditional PVC. (Ahmad et al., 2010) investigated the effects of rice husk and acrylic impact modifiers on the mechanical properties of PVC-U composites. Adding rice husk fillers from (10% - 40%) and 8% acrylic impact modifier has increased the flexural and tensile modulus of the unmodified and modified PVC-U composite. For 20% of rice husk, the flexural strength for both unmodified and modified PVC-U composite was increased. The scanning electron microscopy (SEM) showed that the rice husk fillers agglomerated and unevenly distributed throughout the matrix. The result showed that the impact strength of the filled PVC-U composites at 20% filler increased, but the tensile and flexural properties decreased with increasing impact modifier content. The formulation containing 8% of acrylic impact modifier and 20% of rice husk showed the best balance of stiffness and toughness properties. (Onitiri and Adeniyi, 2015) Studied the transverse compression loading under different temperature effects of recycled and extruded virgin PVC-U materials, the results showed recycled PVC-U exhibits better rigidity for all the temperatures considered except at 40°C where stress at yield of 59.19 MPa and 61.31 MPa for recycled and virgin PVC-U has been recorded respectively. Results also revealed that virgin PVC-U exhibits improved plasticity while recycled PVC-U showed improved rigidity from 85°C to 130°C. (Nirmala and Rajkumar, 2016) investigated the behavior of buried PVC-U pipes under the ground soil; several parameters were considered. It has been concluded that the depth of embedment of pipe, type of backfill, thickness of pipe and surcharge loads are the prime factors that affects the behavior of buried pipes.

This study aims to investigate the mechanical properties and hydrostatic strength of PVC-O

pipes using experimental and numerical tools to understand material behavior under different

loading conditions.

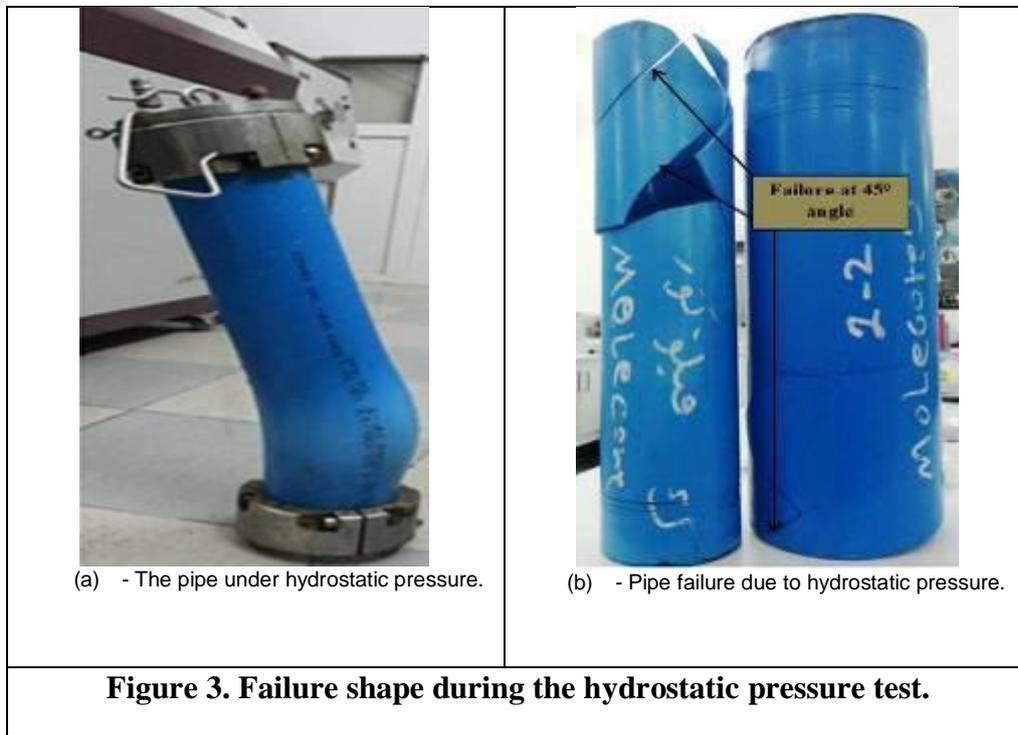
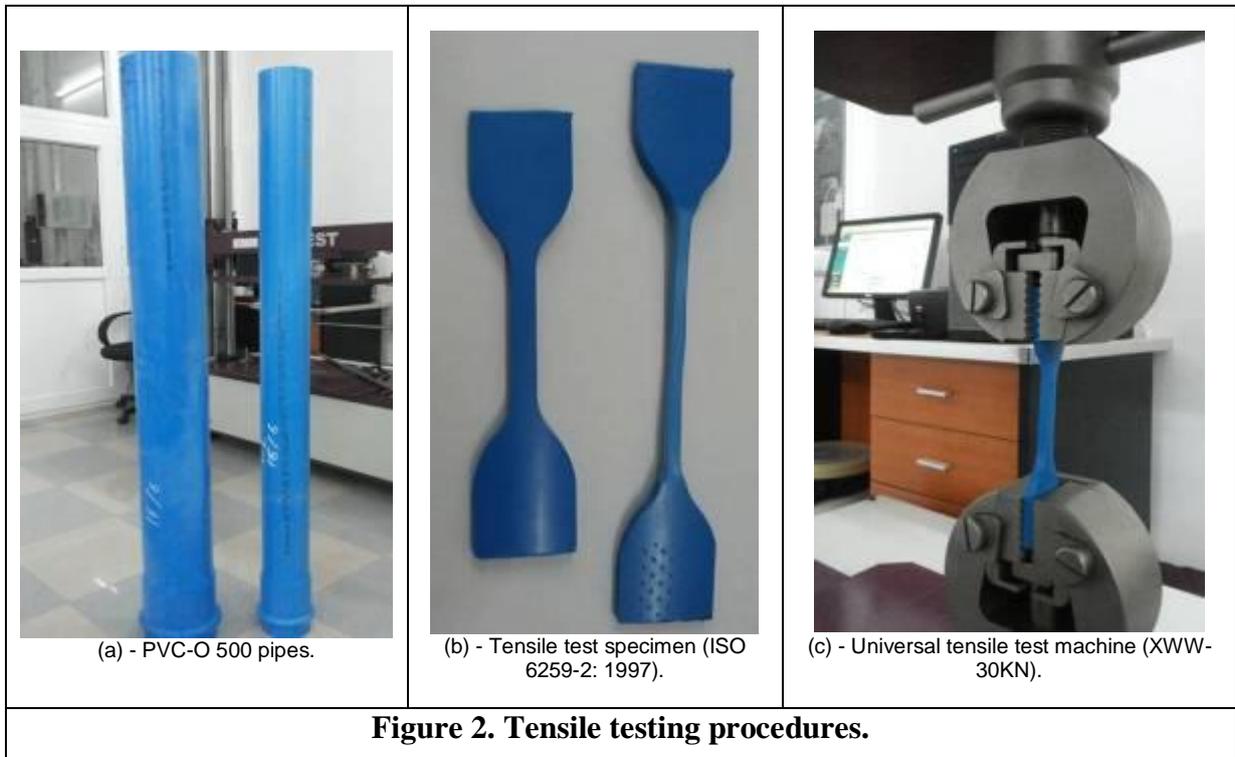


2. MATERIALS AND METHODS

In this work-oriented (PVC-O) with a minimum required strength (MRS) of 50MPa and design stress of 25MPa, usually designated as PVC-O 500 has been used as a pipe material with a size of 110 mm diameters and 3.8 mm thickness and nominal working pressure of 25bar as shown in figure (2a). The PVC-O 500 pipe is sourced from Molecor company-Spain, which is specialized in molecular orientated pipe materials. The pipe is sectioned to prepare tensile specimens and hydrostatic test. For the tensile test, nine specimens were machined according to ISO 6259-2: 1997, as shown in figure (2b) with a width of 6mm and a gauge length of 25mm. The samples were cut from three different directions with respect to the pipe axis (0°) (X-axis - longitudinal direction), (45°) (XY - plane), and (90°) (Y-axis - circumferential direction). The samples were

conditioned for 24hrs in the Lab at 23°C , according to ASTM D618. Then, the samples were tensile tested at a rate of 5mm/min using a computerized universal testing machine of 30KN capacity, as shown in figure (2c).

The hydrostatic test has been done according to ISO 1167-1, 2, and ASTM D1599 using a computerized hydrostatic testing machine capable of full monitoring and controlling water temperature and pressure rate during the test. The hydrostatic test has been performed in a water bath maintained at 20°C using two samples of the pipe with a length of 700 mm and two types of end caps [end closures] type (A and B) as presented in figure (3a). Both pipes are subjected to hydrostatic pressure gradually at a rate of 1MPa / second until the failure, as shown in figure (3b). The two samples burst at 6.2MPa.



2.1 Numerical analysis

For the numerical analysis, SolidWorks 2018, with a built-in simulation tool, has been employed based on Von Mises failure criteria theory (Kurowski, 2018). The pipes have been modeled with a length of 700 mm and dimensions similar to the samples of the experimental part and subjected to a uniform hydrostatic pressure of 6.2 MPa for both types of end caps. Type (A) end caps are gripped to the pipe body, which provides free movement in the longitudinal direction. While type (B) end caps, which are attached to

pipe ends through a steel bar passing inside the pipe, which restrict movement in the longitudinal direction. A linear elastic study was performed with solid curvature elements shown in figure (4) and with high-quality curvature mesh type of 39948 elements and 79644 nodes and with parameters shown in table 1. The FE analysis conducted using boundary conditions similar to the one observed or recorded during the experimental work and the resulted are tabulated in table 2.

Table 1. The mechanical property of PVC-O in different directions.

Angle with respect to the pipe axis	Modulus (MPa)	Poisson's ratio	Shear Modulus (MPa)	Mass Density (Kg/m ³)	Tensile Strength (MPa)	Compressive Strength (MPa)
0°	3000	0.35	1500	1410	49	66
45°	3500	0.35	1500	1410	61	66
90°	4000	0.35	2000	1410	91	66

Table 2. Experimental and numerical analysis of test results.

Properties	Exp. results	FE Stress analysis Results		ΔR (%) Experimental Vs FE	
	Measured value the average	End cap type A	End cap type B	End cap type A	End cap type B
Tensile strength at yield in the longitudinal direction MPa@23°C Direction 0°	49	46.57	26.66	4.96	45.6
Tensile strength at yield in the direction of 45°@23°C (MPa)	61	57.848	48.514	5.16	20.47
Tensile strength at break in the Circumferential direction MPa@23°C	91	91.057	90.149	0.06	0.93

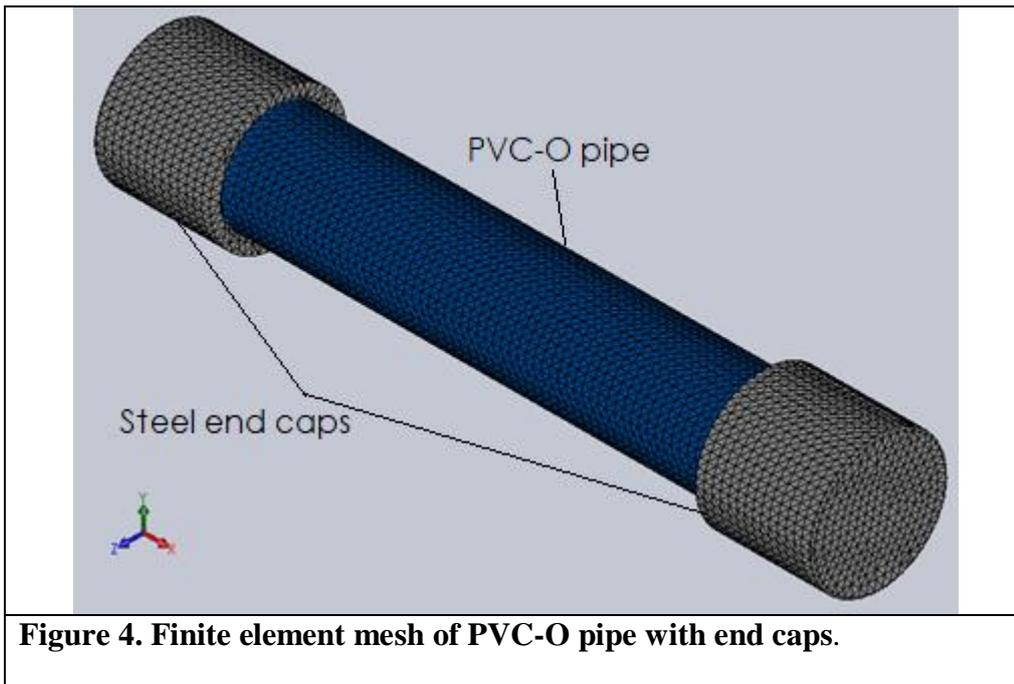


Figure 4. Finite element mesh of PVC-O pipe with end caps.

3.RESULTS AND DISCUSSION

3.1 Tensile Test

From the tensile test curves shown in figure (5), it's clearly shown that the material behavior and mechanical properties of PVC-O greatly depend on the test direction, i.e., the material is showing un-isotropy (William D. Callister). The tensile strength increases with increasing molecular orientation from the nearly zero orientation in the 0° direction (Longitudinal direction) to high orientation in the 90° direction (Hoop direction). This behavior is attributed to the fact that at an angle (0°) (longitudinal direction), the molecular are just tangled and can easily slip over each other and entangled (Mulapeer et al, 2016). So at 0° direction, the yield point is clearly visible due to the slip of the tangled molecular over each other, as in the case of metals where the yield point occurs due to the motion of freed dislocations of atoms in the crystal lattice (Hall.E.O, 1970). In polymers, yielding occurs due to molecular movement out of the entanglement (Bauer, 1994) as shown in figure 1. At angle (45°) (XY-plane) because of a certain amount of orientation, which is estimated to be around 50%, the yield point is higher but not clearly visible compared with the

yield point of (0°) direction. At angle (90°) (hoop direction), all the molecular are nearly 100% aligned and oriented, and therefore, the yield point is not clear at all since there is no more un-entanglement or slipping. The reason for showing the yield point is due to the un-entanglement of molecular chains and the orientation phenomena (Mulapeer et al, 2016). The results from figure 5 and more clearly from the figure (6 a & b) show that while the tensile strength at yield increases with increasing molecular orientation, the ductility or the percent elongation at fracture decreases. The tensile strength of 91MPa has been recorded at the direction of (90°), but the percent elongation is decreased to only 61%. While at (45°) and (0°), the tensile strength at yield was 61MPa and 49MPa, and the percent elongation was 76% and 200%, respectively. The elastic modulus significantly increased from 3000 MPa at (0°) to 4000MPa at (90°).

These results are very important and significant because the hydraulic capacity and hydrostatic strength of pipes depend mainly on the material strength in the hoop direction (Ahmad et al., 2010). Increasing hoop stress results in increasing the nominal working pressure of the pipes which saves material, and reduces the cost.

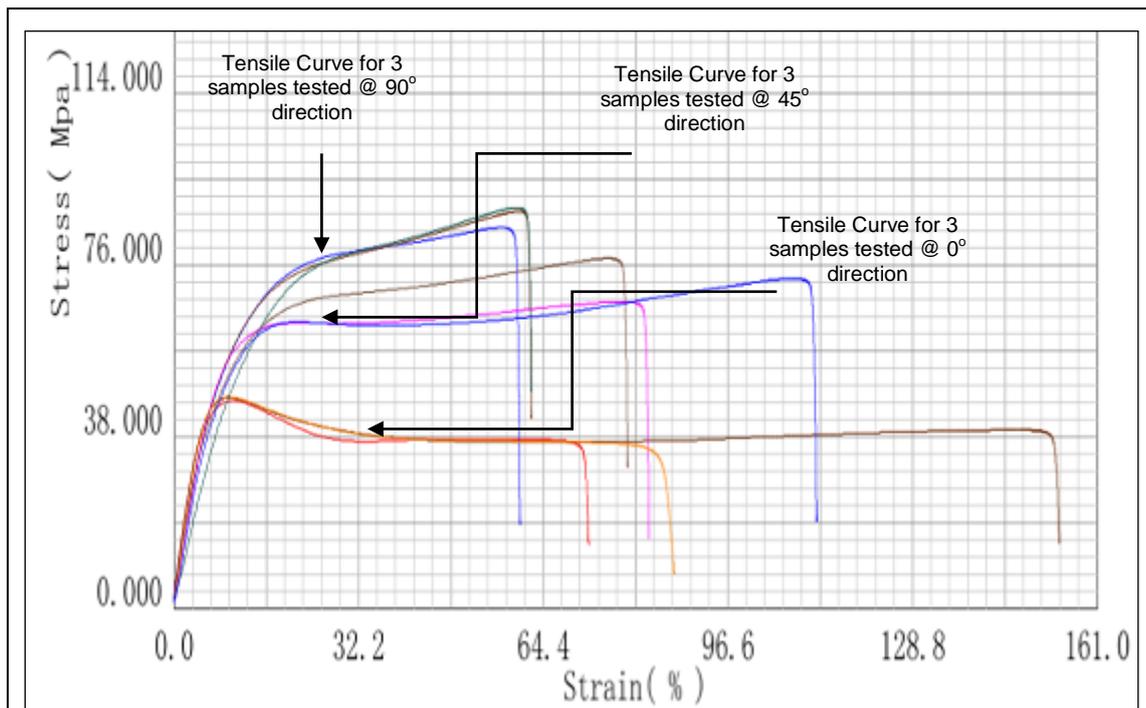


Figure 5. Stress-Strain diagram of (PVC-O) tested at (0°, 45°, 90°).

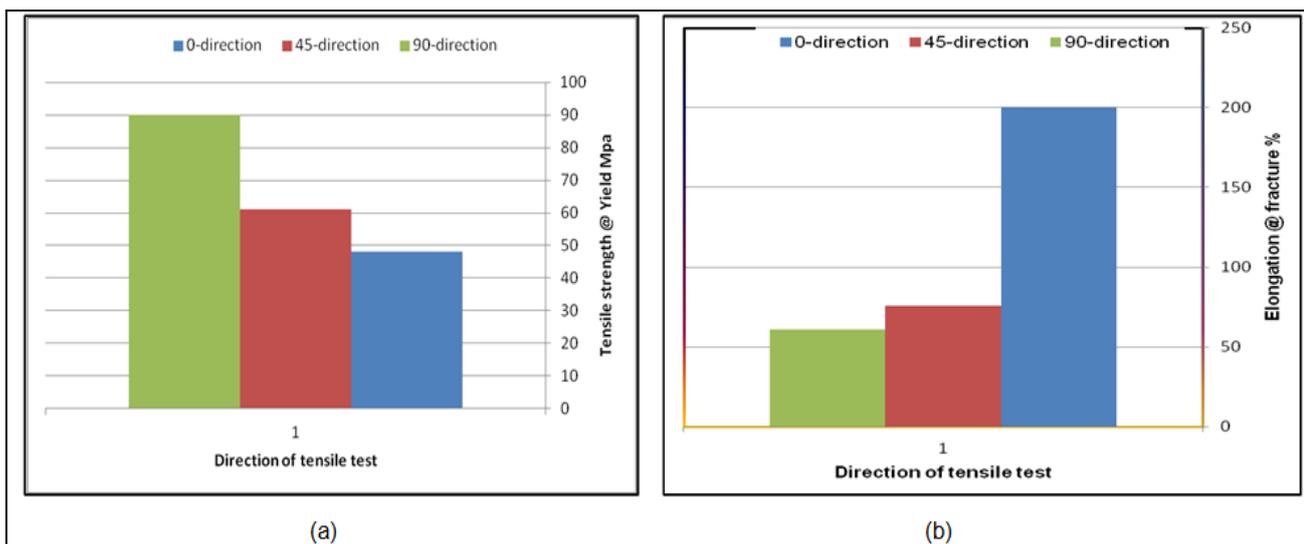


Figure 6. Variation of tensile strength at yield and Percent elongation as a function of test direction and molecular orientation

3.2 Hydrostatic Test

To experimentally characterize the effect of molecular orientation on hydrostatic of strength and behavior of PVC-O material, both pipes were individually and separately subjected to a gradually increasing hydrostatic pressure till the failure. Both pipes burst at the same pressure of

$$\sigma_H = \frac{Pd}{2t} \quad (1)$$

$$\sigma_L = \frac{Pd}{4t} \quad (2)$$

σ_H - Hoop stress in MPa

σ_L - Longitudinal stress in MPa

P – Internal pressure in Pa

d – Cylinder diameter mm

t – Wall thickness in mm

Increasing the design stresses from 12.5 MPa with a safety factor of 2 for PVC-U pipes to 25 MPa with the same safety factor for PVC-O pipes, led the plastic pipe technology a step forward to move to a higher design stress. From the hydrostatic test results shown in figures (3a) and (3b) it can be observed that in both pipes, failure has initiated in the areas close to the end caps because of the stress concentration from the sharp edges of the end caps that prevent the pipe in these areas from the expansion as well as the presence of scratches due to gripping effect of type A end cap. It was also observed that the failure due to hydrostatic pressure proceeds at 45° with respect to the pipe axis, and this is not the usual case of PVC-U pipes. This behavior may be attributed to the percent of molecular orientation. There is almost around 50% orientation in the 45° direction and is usually weaker than the hoop direction where the maximum stress occurs.

6.2MPa regardless of the type of end cap used. All thin-walled vessels, when subjected to hydrostatic pressure, undergo two types of static stresses longitudinal (axial) and circumferential (hoop) stresses (Shigley, 2011). Most of the failure occurs under the hoop stress since its magnitude is twice compared with axial stresses, as shown by the basic equations 1 and 2.

3.3 Finite Element Analysis

The objective of the numerical analysis was to investigate and visualize the effect of hydrostatic pressure on the PVC-O pipe material in the three directions (0°, 45°, and 90°) and the stress distribution along the pipe. The analysis evaluated according to the Von Mises stress failure criterion, also known as the shear-energy theory or the maximum distortion energy theory as expressed by equation (3) (Shigley, 2011) . Numerical results of stresses are tabulated in the table (2) and compared with the experimental results. From the results obtained, it is shown that the experimental results show a good agreement with the FEA results for both pipes of different end caps. The relative difference is expressed by equation (4) (Nazhad et al, 2020) at locations where the effect of end caps is not considered.

$$\sigma_v = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \geq \sigma_y \quad (3)$$

$$\Delta R = \left| \left(\frac{Exp. - FEA}{Exp.} \right) 100\% \right| \quad (4)$$

σ_v = Von Mises stress (MPa).

$\sigma_1, \sigma_2, \sigma_3$ = Principle stresses (MPa).

For thin wall cylinder $\sigma_3=0$.

σ_y = Yield stress (MPa).

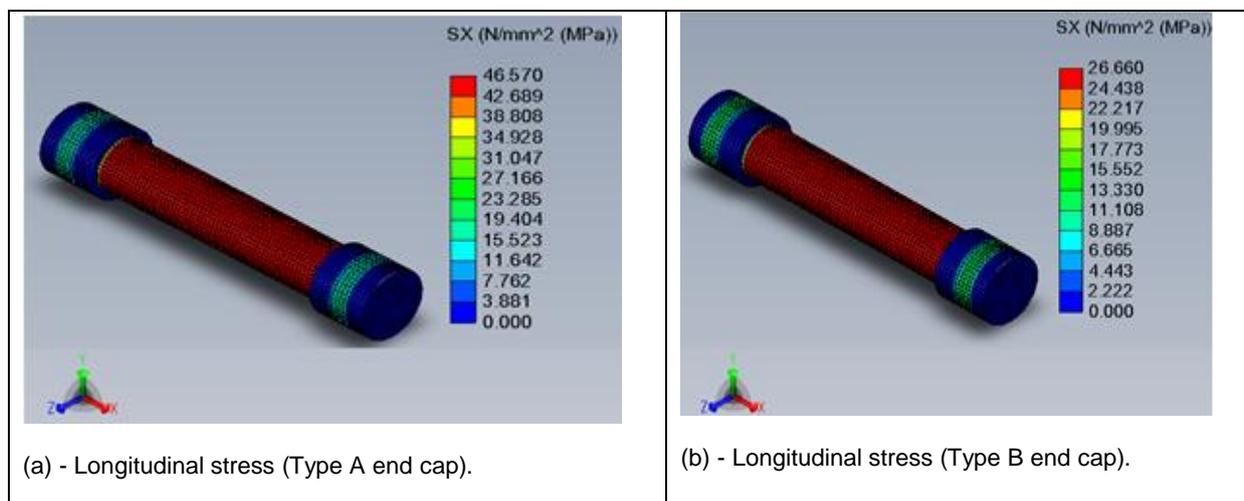
ΔR = Relative difference

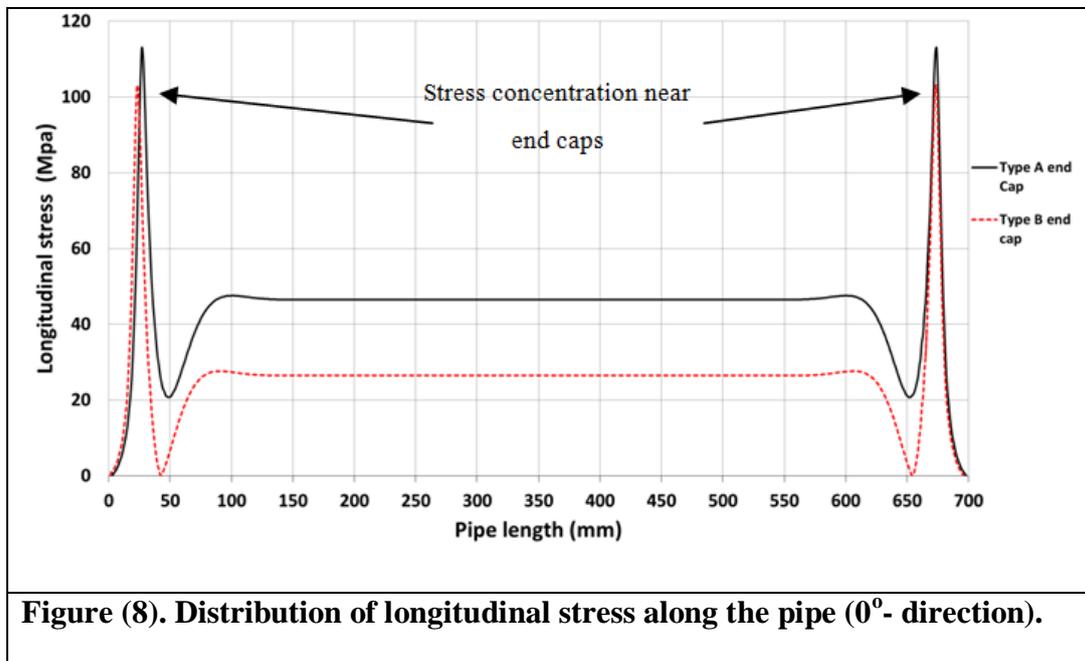
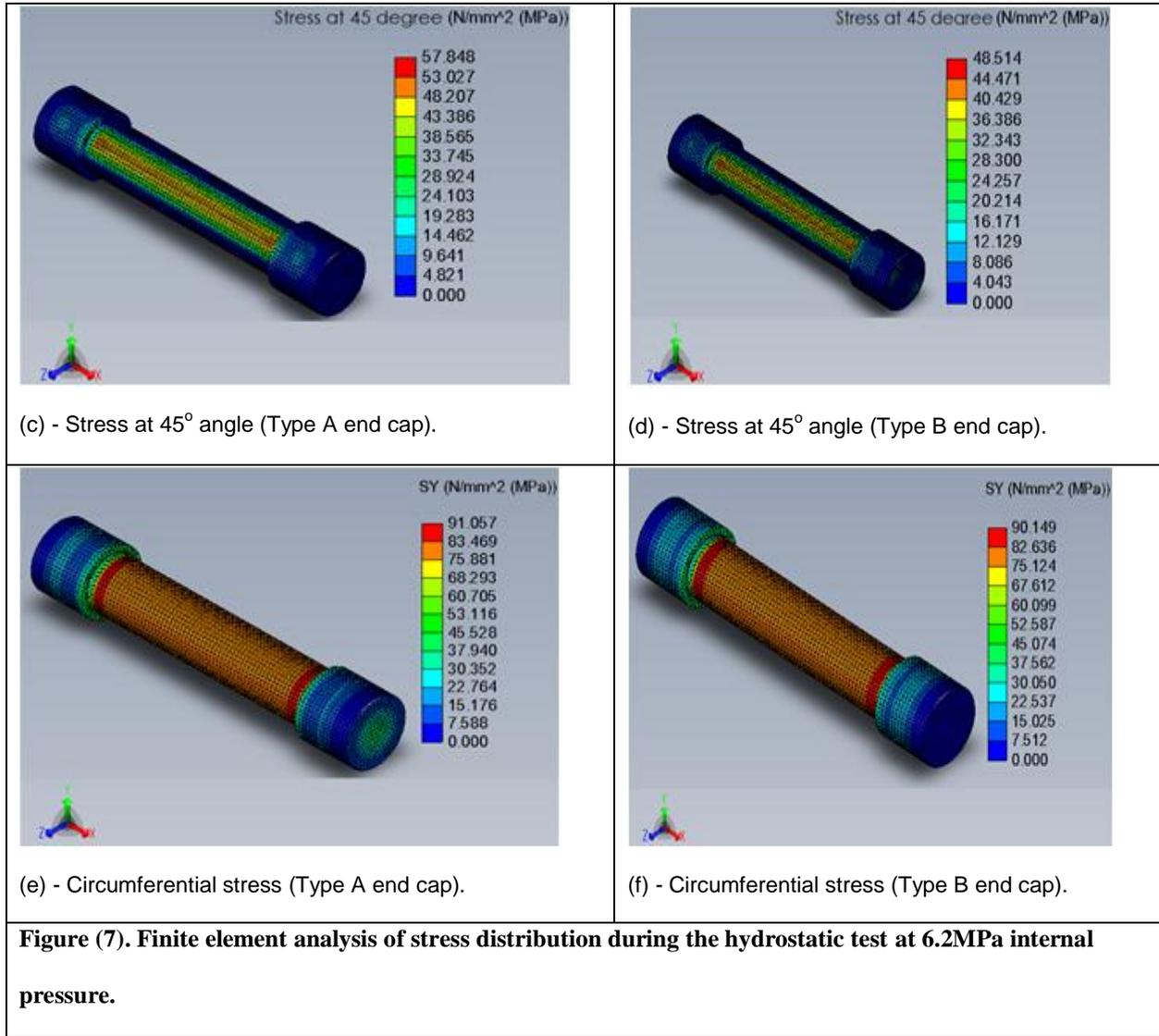
From the FE analysis of the hydrostatic test shown in figure (7), it can be seen that the type of the end cap has a great influence on the magnitude of stress in the 0° and 45° directions as shown in figure 7a through 7d except for the stress in hoop direction which remain very close to each other for both types of end caps as shown in figures (7e) and (7f). Comparing the longitudinal stresses in figures (7a) and (7b), it can be seen that for type (A) end cap, the longitudinal stress has increased by 42.75% compared with type (B) end cap since there is no longitudinal thrust involved in the type B end cap. Similar behavior is observed for figures (7c) and (7d), and the stress at angle 45° for type A end cap is greater by the amount of 16.13% compared with type B end cap. While for the circumferential direction, the magnitude of stress for type A end cap is larger by an amount of only 1% compared with Type B.

Stress distribution along the pipe length and the effect of stress concentration due to end caps can be clearly seen in figures (8), (9), and (10) in all the three directions. It's very obvious that end caps affect the stress intensity around the pipe, especially in the 0° and 45°. Pipe failure during the hydrostatic test shown in figure 3b is believed to

be initiated from the points of stress concentration near the edges of the end caps and propagated at angle of 45° with respect to the pipe axis.

There is a good agreement between FE stress analysis especially for type A end cap and the tensile test results as shown in table 2, the relative difference is 4.96, 5.16, and 0.06 in the 0°, 45°, and 90° respectively. While for type B end caps the relative difference is much higher except in the 90° direction which is almost near 1%. This is attributed to the fact that both types of end caps act differently on the pipe when it's under pressure. The restricted longitudinal movement of the pipe when using type B end cap has greatly affected stress distribution along the pipe body especially in the 0° and 45° direction and led to increase the relative difference when compared with experimentally determined tensile strength at those directions. While for Type A end cap, the pressure thrust acting on both ends of the pipe when its under its ultimate internal pressure capacity of 6.2MPa; resulted in the proper stress distribution and minimized the relative difference due the fact that the stress reached its maximum permissible value in all the directions.





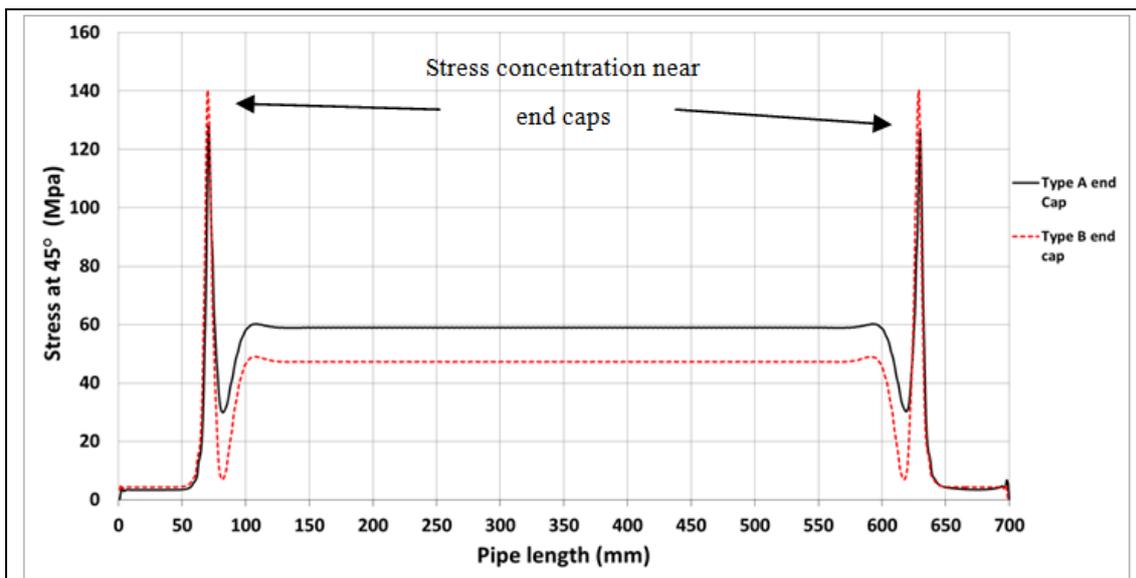


Figure (9). Distribution of Stress at an angle of 45° along the pipe.

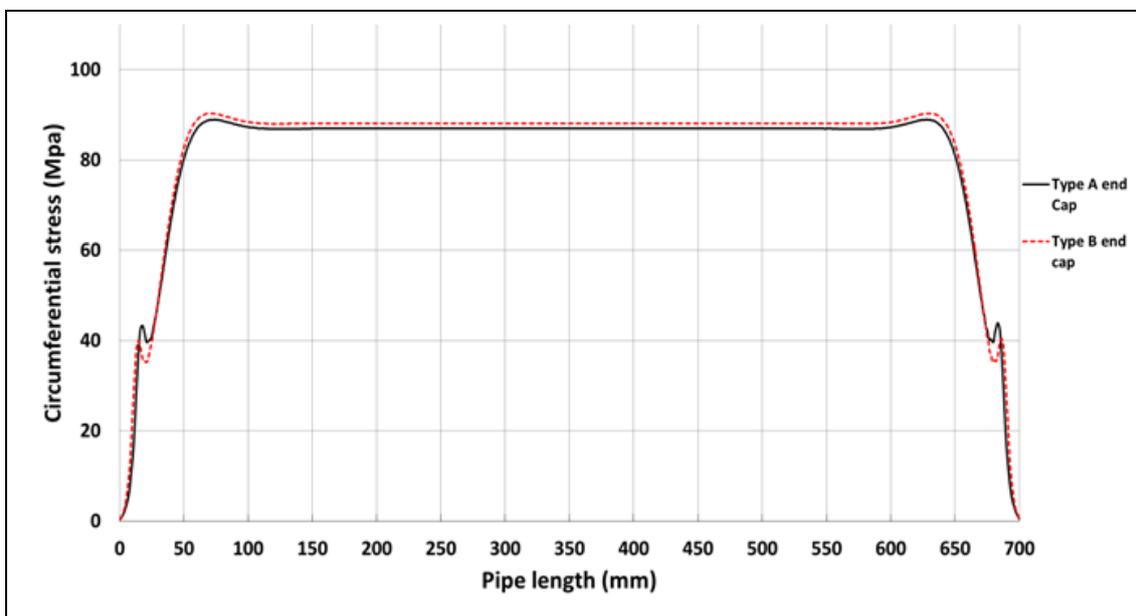


Figure (10). Distribution of circumferential (hoop) stress along the pipe (90°-direction).

4.CONCLUSIONS

Tensile properties and hydrostatic behavior of PVC-O 500 pipes with two different end caps types (A and B) have been investigated experimentally and numerically. The core of the present work is to examine the effect of molecular

orientation on the mechanical properties (tensile strength, circumferential resistance, and elongation). Numerical and experimental results exposed that:

- 1- Molecular orientation has a significant impact on the pipe strength. By increasing

the molecular orientation in the direction of the hoop, the strength increased to 91MPa compared with the traditional strength of PVC-U pipes of 49MPa.

- 2- The ductility has dropped dramatically with increasing the percent of molecular orientation.
- 3- The FEA has showed a good agreement with experimental results with a maximum difference of about 5.16% in the direction 45° angle for type A end cap.
- 4- The FE results also showed that end caps affect stress distribution around the pipe during the hydrostatic test with a maximum difference occurred when using type B end caps.
- 5- It's also concluded that both types of end caps cause stress concentration near the edges of the caps which may affect experimental results and the actual burst

pressure value of the pipe. Pipe failure during the hydrostatic test is believed to be initiated from the points of stress concentration near the edges of the end caps and propagated at angle of 45° with respect to the pipe axis.

Finally, further research is recommended to study the effect of pipe diameter and pipe thickness of such material on hydrostatic behavior.

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Conflict of interests

The author declares that they have no competing interests.

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