Weathering effects on mechanical properties of low and high density polyethylene pipes used in irrigation networks

A.M. Ollick and A.M. Al-Amri

Agricultural Engineering Department, King Faisal University, Saudi Arabia

The effect of outdoor weathering conditions on the mechanical properties of low and high Density Polyethylene (LDPE and HDPE) pipes used in irrigation networks have been studied. For LDPE, the test specimens were prepared from pipes exposed to outdoor weathering for different periods ranging from 2 years to 15 years. The obtained results showed that, the exposure to outdoor weathering conditions for periods equal to or less than 8 years increased the yield stress while it decreased for an exposure periods more than 8 years. The modulus of elasticiy increaed for exposure periods equal to 10 years and less while it decreased for exposure period of 15 years. The elongagtion to break decreased due to the exposure to outdoor weathering regardless the exposing periods. The decrement rate is small up to an exposure periods of 8 years while a dramatic decrease occurred for an exposure periods equal to 10 years and higher. For HDPE, test specimens were prepared from, a new pipe, a pipe used under outdoor weathering for 5 years and a pipe stored indoors inside unconditioned store for 5 years. The obtained results showed that, both the exposure to outdoor weathering conditions or the storage indoor increased the yield stress and the modulus of elasticity while the elongation at break decreased for the two pipe conditions.

تستخدم أنابيب البولي اثيلين ذات الكثافة المنخفضة (LDPE) بشكل واسع في تمديد شبكات الري و تستخدم أنابيب البولي اثيلين ذات الكثافة العالية (HDPE) لتمديد الخطوط الرئيسية في شبكات الري. و لحساب قيمة التغير فى الخواص الميكانيكية فقد تم اختبار أنابيب جديدة مماثلة تماما للأنابيب المستخدمة من حيث القطر وسمك الجدار. و قد أثبتت النتائج أن إجهاد الخضوع لأنابيب البولي اثيلين ذات الكثافة المنخفضة يزداد خلال العامين الأولين من التعرض للظروف المناخية الى أقصى قيمة له حيث يبلغ معدل الزيادة ٠,٨١% ميجابسكال/سنة ثم تبدأ القيمة الجديدة في النقصان بمعدل ٠,١٤% ميجابسكال/سنة و ذلك لفترات تعرض بين سنتين و حتى ثماني سنوات و لكن قيمة اجهاد الخضوع تستمر أعلى منها للأنابيب الجديدة و يبدأ اجهاد الخضوع فى النقصان عن قيمته للأنابيب الجديدة لفترات تعرض أكبر من ثمانى سنوات و حتى ١٠ سنوات حيث يبلغ معدل التناقص في هذه المرحلة ١,١% ميجابسكال/سنة و يظل اجهاد الخضوع ثابت تقريبا لفترات الاستخدام الأعلى من عشر سنوات . و قد وجد أن النسبة المئوية للاستطالة تقل كلما زادت فترة الاستخدام حيث يبلغ معدل التناقص ١٥% خلال الثمانى سنوات الأولى و لكن هذا التناقص يزداد زيادة كبيرة لفترات الاستخدام بين ثماني سنوات و حتى عشر سنوات حيث يبلغ معدل التناقص خلال هذه الفترة ١٧٢% ثم يظل ثابت تقريبا لفترات الاستخدام الأعلى. أما معاير المرونة فقد وجد أنه يزداد الى أقصى قيمة له خلال الثلاث سنوات الأولى من الاستخدام حيث يبلغ معدل الزيادة في هذه الفترة ٧,١ ميجابسكال/سنة ثم تبدأ القيمة الجديدة في النقصان بمعدل ١,٢ ميجابسكال/سنة و ذلك لفترات استخدام أعلى من ثلاث سنوات و حتى ١٠ سنوات و لكنه يتناقص بحده لفترات استخدام أكثر من ١٠ سنوات حيث يبلغ معدل التناقص ٨,٤% ميجابسكال/سنة . بالنسبة لأنابيب البولي اثيلين ذات الكثافة العالية فقد وجد أن عملية التخزين تؤدي الى زيادة اجهاد الخضوع بنفس القيمة مثل الاستخدام تحت الظروف المناخية الخارجية حيث بلغت النسبة المئوية للزيادة ١١% لكلتا الحالتين. بينما يكون النقص في النسبة المئوية للاستطالة عند الكسر للأنابيب المستعملة خارجيا أكثر من ثلاث أضعاف تلك النسبة للأنابيب المخزنة حيث يبلغ مقدار النقص ١١% و ٣,٢% للأنابيب المستعملة خارجيا و الأنابيب المخزنة على الترتيب. و قد بلغت النسبة المئوية للزيادة في معاير المرونة ١٩% و ١٦,٨% للأنابيب المستعملة خارجيا و الأنابيب المخزنة على الترتيب و هي نسبة متقاربة.

Keywords: HDPE pipes, LDPE pipes, Outdoor weathering, Mechanical properties, Irrigation networks

1. Introduction

The properties of many polymers are significantly influenced by the exposure to outdoor or indoor weathering [1]. In many applications specially irrigation networks, PE pipes are subjected to outdoor weathering conditions. So, it is very important to study the changes of the engineering properties of PE pipe material due to the effect of outdoor weathering conditions. A two-year study was undertaken to quantify the effects of UV radiation on the properties of PVC pipes [2]. The results obtained showed that, the exposure to UV radiation resulted in change in pipe's surface color and reduction in impact strength, while other properties such as tensile strength and pipe stiffness are not adversely affected. The effect of outdoor weathering conditions in Al-Hasa, on the fracture toughness of PVC pipe material was studied [3]. The results obtained showed that, the fracture toughness decreases by 50% due to the exposure to outdoor weathering conditions. Also, the material became more brittle. The effect of outdoor weathering in Jeddah, Saudi Arabia, on the mechanical properties and residual stresses in injection molded semi-crystalline polymers was investigated [1]. PolyproPylene (PP), Poly OxyMethylene (POM) and Nylon6.6 (N6.6) were used for this study. The test specimens were exposed to outdoor weathering conditions for different periods up to three years. The test results showed that, the exposure to weathering conditions created tensile residual stresses near the surfaces of the three polymers. For N6. 6, the exposure to outdoor weathering for 1.5 year decreased the yield stress by 35% while the upper yield stress for both PP and POM remained approximately constant after three years of outdoor weathering. Furthermore, for the outdoor weathered N6. 6 and PP specimens, the elongation at break remained approximately unchanged through the first year and decreased dramatically to 10% of its original value through the second year while it decreased about 10% for POM. For the specimens weathered in the shade, the elongation to break remained constant for POM and decreased about 35% for both PP and N6. 6. The effect of the weathering on fracture toughness and yield strength of unreinforced and short glass-fiber reinforced thermoplastic polyester was investigated using CT test specimens naturally weathered for 11 months outdoors in Pert, West of Australia [4]. It was found that the weathering induced a percentage reduction of 15-35% in the fracture toughness. The yield stress of unreinforced polyester increased by 9% while it decreased by 11% for short glass-fiber reinforced polyester. Furthermore, the elongation to break of the weathered specimens decreased. The effect of the environment on the fracture toughness of PVC and PVC-CPE was studied [5]. The results obtained from this study showed that, the environment affected the fracture toughness and crack growth for both PVC and PVC-CPE, where the fracture toughness and crack growth resistance decreased in the presence of benzene vapor. The effect of weathering on the residual stress in polypropylene and polystyrene was studied [6]. The obtained results showed that, the exposure to outdoor weathering changed the residual stresses near the surface from compressive to tensile ranging between 2 to 3 MPa. The effect of humidity on the time to breakdown of Polyethylene Terephthalate was investigated [7]. The results of this study showed that, increasing humidity increased then lifetime until a critical value of relative humidity after which the lifetime decreased dramatically.

Low-Density PolyEthylene pipes (LDPE) are more flexible than those, which are, made from High-Density PolyEthylene (HDPE), so, they are used in irrigation net works as sublines while HDPE pipes are used as main lines. The goal of this work is to quantify the effect of the outdoor weathering conditions on the yield stress, modulus of elasticity and the elongation to break for LDPE and HDPE pipe materials when used in irrigation networks under outdoor weathering conditions.

2. Experimental procedure

The test specimens of the exposed LDPE pipes were prepared from pipes that were used for different periods in irrigation network under outdoor weathering conditions in Al-Hasa, Saudi Arabia. Table 1 shows the pipes diameter d, the wall thickness t and the in use periods of these pipes.

In order to study the change in mechanical properties due to the exposure to outdoor weathering, specimens made from new LDPE pipes having the same dimensions as those in table 1 must be tested. HDPE pipes are used in the irrigation networks as main lines; so, it was difficult to cut parts from pipes used in networks for different periods. The only used pipe segment that can be obtained was a pipe used for five years under outdoor weathering conditions and a segment from the same pipe stored for the same period inside unconditioned store. So, the study of HDPE will be restricted to make a comparison between the mechanical properties of these two pipes and the new one regarding that the three pipes have 63 mm outer diameter and 3.8 mm wall thickness. The dimensions of the test specimens for both LDPE and HDPE pipes were chosen according to ASTM standard D 396-84[8]. Uniaxial tensile tests were conducted on a hydraulic testing machine. Fig. 1-a shows a photograph for the test specimen while fig. 1-b is a photograph for the experimental setup. The specimen load was measured using a load cell having 2500N capacity. The load cell was connected to the specimen through the specimen upper grip and a load indicator was connected to the load cell to monitor the specimen load. The specimen elongation was measured by fixing a ruler, having 0.5-mm divisions to the moving head of the testing machine. The crosshead speed was adjusted at 50 mm/min [8]. The reading of the load indicator and the motion of the ruler were recorded using a video camera connected to a video. The recorded video tapes were played back at speed equal to 1/16 of the normal running speed using special video. The picture of the load indicator and the ruler was monitored using 32 inch TV

Table 1
The dimensions and the using periods for the LDPE pipes that were used to prepare the test specimens

Pipe dimensions mm								
	d	17		25		15	20	
	t	1.4		1.6		1.2	1.5	
Exposure period (years)		5	15	7	10	2	3	8

Fig. 1-a. Photograph for the test specimen.

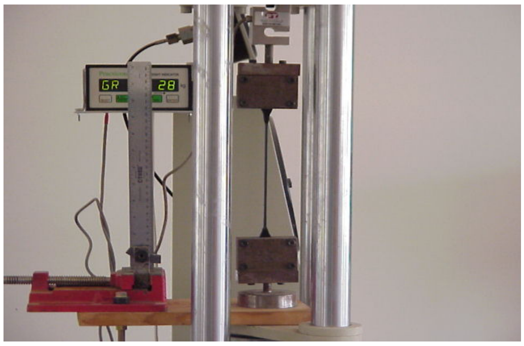

Fig. 1-b. Photograph for the experimental setup.

that allows getting 15 times magnification. The motion of the ruler divisions relative to a selected fixed line and the corresponding reading of the load indicator were listed. The data of each specimen was analyzed separately to get the yield stress, the modulus of elasticity and the elongation to break. In order to increase the results accuracy four specimens were tested for each pipe condition. The final values of the mechanical properties were taken as the average of these four specimens.

3. Results and discussions

Fig. 2-a shows the stress-strain relation for pipes used for 3, and 8 years. Also, the similar new pipe is presented. The data are displaced along the strain axes by 8 and 16 as shown in the figure. To obtain the yield stress and the modulus of elasticity of the pipes, the regions in the stress strain relations which are corresponding to the first 8 mm elongation were expanded and displaced along the strain axis as shown in fig. 2-b (noting that, 8 mm is an elongation suggested by the authors). The presented data represent a selection for one specimen for each pipe condition. The data over the first 2.5 mm was found to fit straight line with an average coefficient of determination of 0.94, so, the data over the first 2.5 mm will be fitted linearly to obtain the modulus of elasticity. The yield stress was taken as defined in [8]. Table 2 presents the average values of the yield stress, the modulus of elasticity and the elongation to break. Each value represents the average of 4 specimens.

The data in table 2 shows that, the exposure to outdoor weathering for 3 and 8 years increased the yield stress by 14% and 4%, respectively. The modulus of elasticity increased by 12% and 6% for the same periods while, the elongation to break

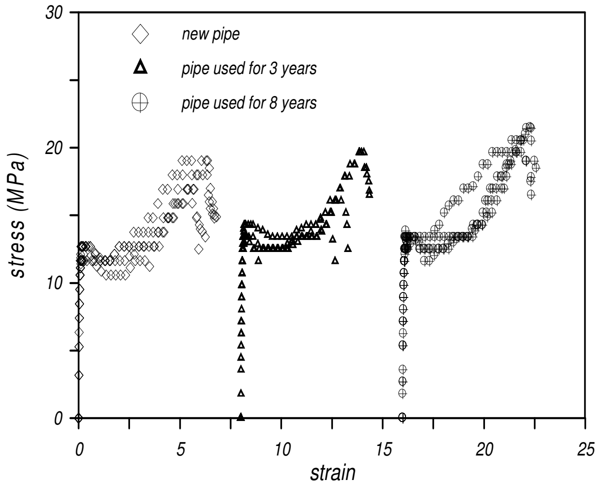

Fig. 2-a. Stress-strain relation for LDPE pipes used in irrigation network under outdoor weathering conditions for 3 and 8 years and the corresponding new one.

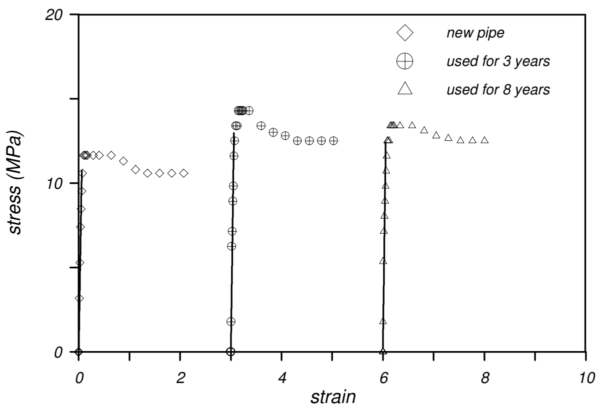

Fig. 2-b. Expansion for the first regions in the stress-strain relation in fig. 2-a. the presented data represent one specimen each pipe.

Table 2
Mechanical properties of used LDPE pipes and the similar new one, with 20 mm outer diameter and 1.6 mm wall thickness

Pipe condition	Average of 4 specimens		
	S_y (MPa)	E (MPa)	%elongation to break
New	12.2	187	641
Used for 3 years	13.9	210	565
Used for 8 years	12.7	199	549

Table 3
Mechanical properties of LDPE pipes used in irrigation net works for different periods and the similar new one with 15 mm outer diameter and 1.2 mm wall thickness

Pipe condition	Average of 4 specimens		
	S_y (MPa)	E (MPa)	% elongation to break
New	12.9	201	688
Used for 2 years	14.6	212	662

decreased by 12 % and 14.5 %. Fig. 3 shows stress-strain relation for a pipe used for 2 years and the similar new one. The data of the used pipe displaced along the strain axes. To calculate the values of the yield stress and the modulus of elasticity, the first regions from the stress-strain relations are expanded and fitted using the same method as that in fig. 2-b. Table 3 presents the average mechanical properties of the pipes of fig. 3.

The data presented in table 3 shows that, the exposure to outdoor weathering for 2 years increased the yield stress and the modulus of elasticity respectively by 13% and 5.5% while decreased the elongation to break by 4%. Fig. 4 presents the stress-strain relations for pipes used for 7 and 10 years and the similar new one. The data of the used pipes are displaced along the strain axes as shown in the figure. It is obvious that, the elongation to break for the pipe which was used for 10 years, is much smaller than that for the new pipe. To obtain the yield stress and the modulus of elasticity, the data of the first regions from the stress strain relation were expanded and fitted using the same method as that used in fig. 2-b. Table 4 presents the average values for the yield stress, the modulus of elasticity and the elongation to break for the pipes in fig. 4.

The data presented in table 4 shows that, for the pipe, which was used for 7 years, the yield stress and the modulus of elasticity increased respectively by 13% and 4% while the elongation to break decreased by 23%. For the pipe which was used for 10 years, the yield stress and the elongation at break decreased respectively by 5.5% and 66% while, the modulus of elasticity increased by 5%. Fig. 5 shows the stress strain relation for a new pipe, a pipe used for 5 years and a pipe used for 15 years. It is obvious that, the elongation to break for the pipe which was used for 15 years is much smaller that those for the other two pipe conditions. The mechanical properties were obtained by expanding the first stage of the stress-strain relation and fitting the first 2.5 elongation as used previously. The average values of the mechanical properties are listed in table 5.

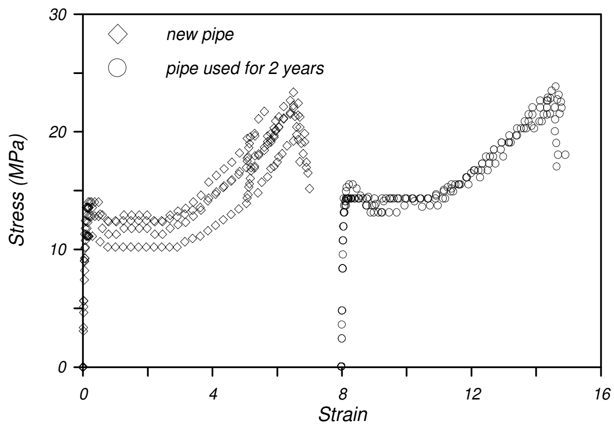

Fig. 3. Stress-strain relation for LDPE pipes used in irrigation network under outdoor weathering conditions for 2 years and the corresponding new one.

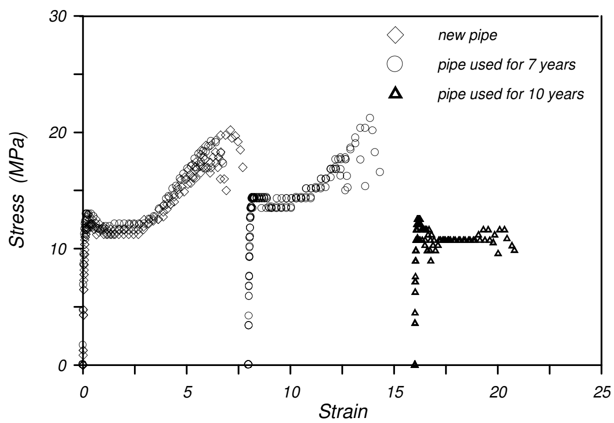

Fig. 4. Stress-strain relation for LDPE pipes used in irrigation network under outdoor weathering conditions for 7 and 10 years and the corresponding new one.

Table 4
Mechanical properties of LDPE pipes used in irrigation net works for 7 and 10 years and the similar new one with 25 mm outer diameter and 1.7 mm wall thickness

Pipe condition	Average of 4 specimens		
	S_y (MPa)	E (MPa)	%elongation to break
New	12.5	192	699
Used for 7 years	14.1	200	536
Used for 10 years	11.8	202	237

The data in table 5 shows that, for the pipe that was used for 5 years the yield stress and the modulus of elasticity increased by 7% and 3%, respectively while the elongation to break decreased by 6%. For the pipe which was used for 15 years, the yield stress, the modulus of elasticity and the elongation to break decreased respectively by 12%, 16% and 65%. Fig. 6 shows the stress-strain relation for HDPE pipes. It is obvious that, the yield stresses of a pipe used under outdoor weathering for 5 years and a similar pipe stored inside unconditioned store for the same period are equal and both of them is higher than that for the new pipe. Table 6 presents the average values of the mechanical properties.

The data listed in table 6 shows that, the yield stress and the modulus of elasticity of the pipe, which was used under outdoor weathering increased by 13.3% and 19% respectively while the elongation to break decreased by 11%. For the stored pipe, the yield stress and the modulus of elasticity increased by 12.8%, and 16.8%, respectively, while the elongation at break decreased by 3.2%.

From tables 2-5 the yield stress of new LDPE pipes has an average value of 12.3 MPa and standard deviation of 0.32 MPa. The mean value of the yield stress matches very well with the values presented for LDPE in [10] (S_y= 7- 16 MPa). The modulus of elasticity of

Table 5
Mechanical properties of LDPE pipes used in irrigation net works for different periods and the corresponding new one with 17 mm outer diameter and 1.5 mm wall thickens

Pipe condition	Average of 4 specimens		
	S_y (MPa)	E (MPa)	% elongation to break
New	11.6	187	631
Used for 5 years	12.4	193	592
Used for 15 years	10.2	157	220

Table 6
Mechanical properties of HDPE pipe used in irrigation net works for 5 years, a pipe stored indoor for the same period and the corresponding new one. The outer diameter is 63 mm and the wall thickness is 3.8 mm

pipe condition	Average of 4 specimens		
	S_y (MPa)	E (MPa)	%elongation to break
New	20.3	322	682
Used for 5 years	23	383	606
stored for 5 years	22.9	367	660

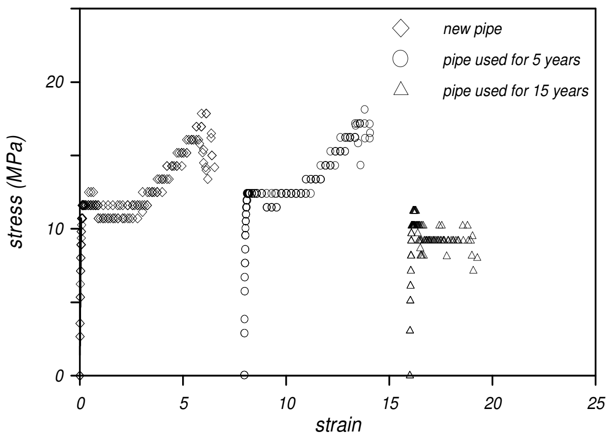

Fig. 5. Stress strain relation for LDPE pipes used in irrigation network under outdoor weathering conditions for 5 and 15 years and the corresponding new one.

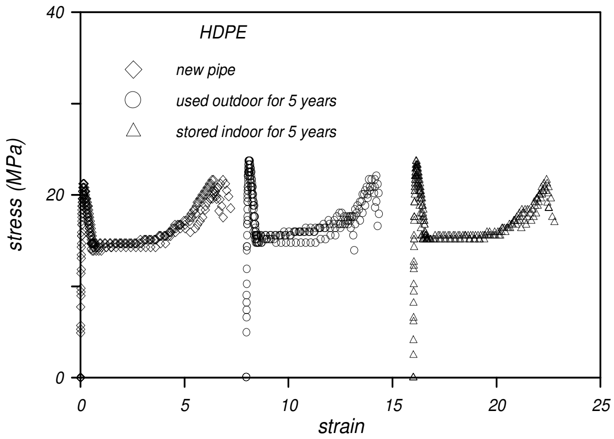

Fig. 6. stress strain relation for HDPE pipe used in irrigation network under outdoor weathering conditions for 5 years, a pipe stored indoor for the same period and the corresponding new one.

the new LDPE pipes has an average value of 192 MPa and standard deviation of 5.7. This value agree very well the data presented in [10] for LDPE (E = 120-240 MPa). The elongation to break for the new LDPE pipes has an average value of 665% and a standard deviation of 23%. This elongation is in acceptable matching with the data presented for LDPE in [10] (elongation%= 90-650). The obtained values of the yield stress for unused HDPE pipes (table 6) are in a good agreement with the values presented in [10] (Sy = 22-38 MPa). The elongation to break for new pipes agree very well with the values presented in [10] (elongation %=50- 800). But, the obtained values for the modulus of elasticity is less than that presented in [10] (E = 550-1050 MPa). This decrement in the modulus of elasticity of HDPE pipes may be occurs due to adding some Linear Low Density PolyEthylene (LLDPE) during manufacturing process to increase pipes flexibility.

The exposure to weathering changes some of the engineering properties of polymers [1,2,3,4,6,7,9]. These properties may increase, decrease or remain unchanged depending on polymer type. For example, the exposure to outdoor weathering increased the yield stress of unreinforced short glass fiber polyester and decreased it for both reinforced short glass fiber polyester and Nylon6.6 while for POM and PP the yield stress remained approximately unchanged. Further more, for N6.6 the total change of the yield stress occurred in the first 1.5 year of exposure and the new value remained unchanged for the an exposing periods of three years. i.e, for the same polymer, there is not a unique rate of change for yield stress over the total exposing period, it may be a decreasing rate, increaring rate or zero rate depending on the ability of polymer to resist the effect of weathering paramters such as ultra violet radiation, humidity and temperature [1,4,7]. For the sake of comparison between LDPE ans HDPE pipes, the data of the used pipes in tables 2-6 are normalized by deviding the values of the used pipes by the values of the correspondung new pipes. Fig. 7 represents a relation between the normalized yield stress and the using periods for both LDPE and HDPE. For LDPE the maximum change in the yield stress occurred in the first 2 years of expousre where, the yield stress increased at an average rate of 0.81 MPa/year. For exposing periods between 2 and 8 years the increased value of the yield starts to decrease at an average rate of 0.14 MPa/year. Between 8 and 10 years the yield stress decreased dramatically at an average rate of 1.1 MPa/year. For exposing periods more than 10 years the yield stress remained approximatly constant. In fig. 7 the data of the of HDPE pipes shows that, the increase in the yield stress of HDPE pipes due to the exposure to outdoor weathering or storing inside unconditioned room is within the increase of that for LDPE pipes. This change in the yield stress can be explained as follow. Unused polyethylene pipe wall contains a compressive residual stresses, $\sigma_{residual}$ [11], after a certain period of weathering, this compressive stresses will be change to a tensile residual stresses [1,4]. The actual stress, σ_{actual}, required to broke the test specimen can be expressed as:

$$\sigma_{actual} = \sigma_{applied} + \sigma_{residual}.$$

This equation shows that, if the actual stress is constant, as the residual stress changes from compressive to tensile stress, the applied stress, $\sigma_{applied}$, ($\sigma_{applied}$ is the stress measured by the load indicator) will decrease. Also, the molecular weigth of the pipe material may be changed due to weathering and the change in molecular weigth will affect the mechanical properties of the pipe material [12,13]. The previous studies of the weathering effects on polymers concluded that, the exposure to weathering decreased the elongation to break regardless the polymer type [1,4], i.e. the material becomes more brittle when exposed to weathering. It was also concluded that, for the same polymer the rate of decrement of the elongation to break is not constant over the whole exposing period. For example the elongation to break for PP did not change through the first year of exposing to outdoor weathering and decreased to 10% of its original value through the second year and remained approximately unchanged for exposing periods more than two years [1]. Fig. 8 is

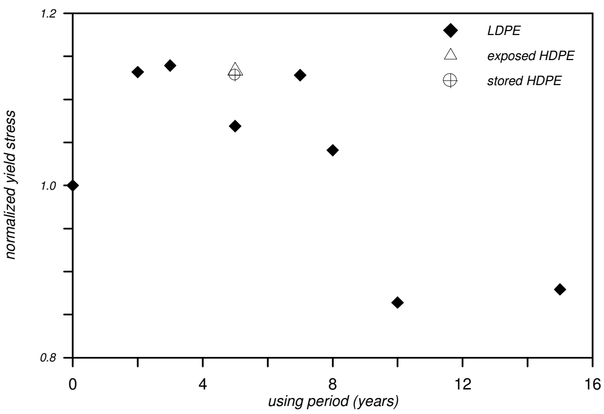

Fig. 7. Relation between the normalized yield stress and the using period for LDPE and HDPE.

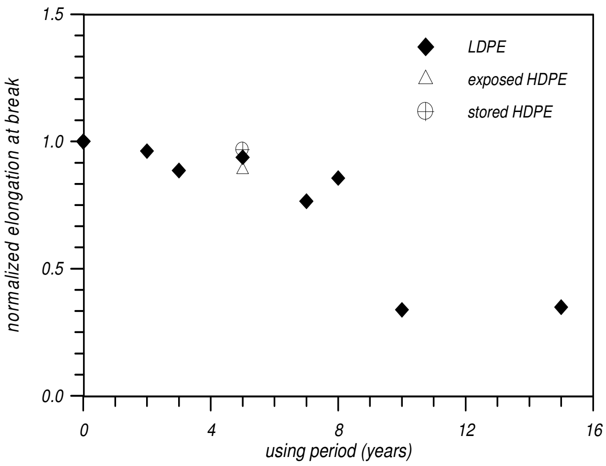

Fig. 8. Relation between the normalized elongation to break and the using period for LDPE and HDPE pipes.

a relation between the normalized elongation to break and the exposing period. It is obvious from this figure that, the elongation to break decreasees as the exposing period increases which means that, the pipes material became more brittle. The average decreasing rate of the elongation to breake is small for a using periods of 8 years and less where it reaches 15%/year, while it increased dramatically for a using period between 8 and 10 years where the decreasing rate reaches 172%. For a using period more than 10 years the elongation to break remained approximatelly unchanged which agree very well with PP and N6.6 data [1]. For HDPE, the elongation to break for the pipe which was stored indoor for 5 years decreased at an average rate of 4.4%/year while the average decrement rate the pipe which was exposed to outdoor weathering conditions is 15.2%/year, i.e. the decrement rate for a pipe weathered under outdoor conditions is more than three times of that for a pipe weathered indoor, which agree very well with POM, PP and N6.6 data [1]. The presented data for both the exposed and the stored HDPE pipes show that, the percentage elongation to break fits with that for LDPE pipes. Fig. 9 is a relation between the normalized modulus of elasticity and the using period. It is obvious that, for LDPE, the total increase in the modulus of elasticity occurred through the first three years of exposure where, the average increasing rate

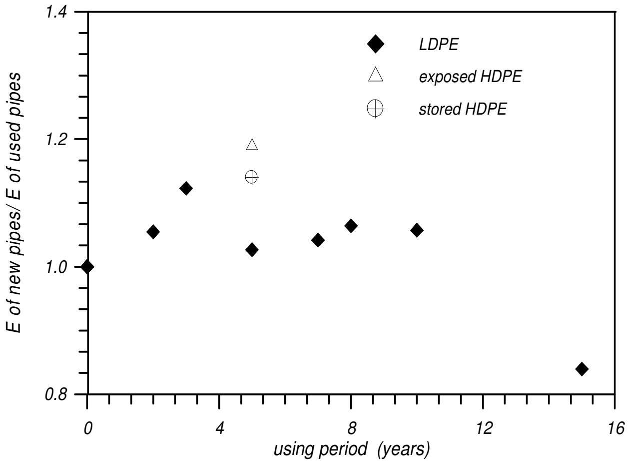

Fig. 9. Relation between the normalized modulus of elasticity and the using period for LDPE and HDPE pipes.

reaches 7.1 MPa/year. After three years and up to an exposing periods of 10 years the increased value strats to decrease at a small rate of 1.2 MPa/year. After ten years and through the next five years of exposure the modulus of elasticity decreased dramatically at a rate of 8.4 MPa/year. For HDPE pipes, the percentage increase in the modulus of elasticity of both the stored and the exposed pipes is higher than that for LDPE pipes which exposed to outdoor weathering for the same period.

5. Conclusions

From the previous results the following conclusions are obtained.

1. The yield stress of LDPE pipes increased when used in irrigation network under outdoor weathering for using periods up to 8 years. While for a using periods more than 8 years, the yield stress decreased.
2. For LDPE pipes, the elongation to break decreased when used under outdoor weathering conditions for any period. But the percentage decrease increases as the using period increases.
3. The modulus of elasticity of LDPE pipes increased when used in irrigation network under outdoor weathering for using periods up to 10 years. While for a using periods more than 10 years, the modulus of elasticity decreased.
4. For HDPE, exposing to outdoor weathering or storing inside unconditioned rooms for the same period gives the same effect on the yield stress.
5. For HDPE, the outdoor weathering increased the modulus of elasticity more than the storing indoors.
6. For HDPE, the outdoor weathering decreased the elongation to break more than the storing indoors.

References

[1] M.M. Qayyum and J.R. White, “The Effect of Weathering on Residual Stresses and Mechanical Properties in Injection-Molded Semi-Crystalline Polymers”, J. Mater. Sci., Vol. 21, pp. 2391-2401 (1986).

[2] The uni-Bell PVC Pipe Association, "The Effect of UV Aging on PVC pipe", Uni-Bell's UNI-TR-5, 2655 villa Creek drive, Suite 155, Dallas, Texas 75234 (1986).

[3] A. Ollick and A.M. Al-Amri, “The Effect of Outdoor Weathering Conditions on the Fracture Toughness of PVC Pipes”, Alexandria Engineering Journal, Vol. 39 (6), pp 837-846 (2000).

[4] N.S. Choi, K. Takahashi, D. Oschmann, J. Karger-kocsis and K. Friedrich, "Influence of Weathering on Unreinforced and Short Glass Fiber Reinforced Thermoplastic Polyester", J. Mater. Sci., Vol. 33, pp. 2529-2535 (1998).

[5] J. Breen, "Environmental Stress Cracking of PVC and PVC-CPE ", J. Mater. Sci., Vol. 30, 5833-5840 (1995).

[6] Li Tong and J.R.White, “Residual Stress Distribution Modification Caused by Weathering in Polypropylene and Polystyrene”, Polymer Engineering and Science, Vol. 37 (32), pp. 321-328 (1997).

[7] F. Gauastavino and P. Tiemblo, “The Effect of Humidity on the Time to Breakdown of Polymers Subjected to Partial Discharge”, Polymer Engineering and Science, Vol. 38 (8), p. 119 (1998).

[8] Annual Book of ASTM Standard ASTM D638-84, “Standard Test Method for Tensile Properties of Plastics), pp. 227-241 (1985).

[9] K.M. Jansen, "Analytical Approximation of Degradation Profiles in Polymer Products", Polymer Engineering and Science, Vol. 34 (21), p. 1619 (1994).

[10] M.F. Ashby and D. R. Jones, Introduction to Engineering Materials, Edward Arnold (Publishers) Ltd, 41 Bedford Square, London WC1B 3DQ UK (1986).

[11] K.Chaoui, A. Chudnovesky and A. Moet, "Efeect of Residual Stress on Crack Propagation Resistance in MDPE Pipes", J.Mater. Sci. 22 pp. 3873-3879 (1987).

[12] S. Hillmansen, S. Hobeika, R.N. Haward and P.S. Leevers, "The Effect of Strain Rate, Temperature and Molecular Mass on the Tensile Properties of Polyethylene", Polymer Engineering and Science, Vol. 40 (2), p. 481 (2000).

[13] C.Y. Hui and E.J. Karmer, " Molecular Weight Dependance of the Fracture Toughness of Glassy Polymers Arising from Crack propagation Through a Craze, Polymer Enguneering and Science, Vol. 35 (5), p. 419 (1995).

Received June 16, 2002
Accepted August 14, 2002