The effect of outdoor weathering conditions on the fracture toughness of PVC pipes

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The effect of the outdoor weathering conditions on the fracture toughness, K_c, of PVC water pipes were studied using an arc segment test specimens made of PVC water pipe used for ten years in outdoor weathering conditions in Al-hasa at the east of Saudi Arabia. The specimens were notched at their inner surfaces using razor blades. Different values for the notch length were used to obtain different distances between the initial notch tip and the outer surface of the pipe. The results obtained showed that as the distance between the initial notch tip and the pipe outer surface decreased, K_c decreased with a rate of 0.81 $MPa.m^{1/2}/mm$ and 0.38 $MPa.m^{1/2}/mm$ for the pipe side which was exposed to the direct sunrays and the shadow side, respectively. Furthermore, K_c of the test specimens that were exposed to the direct sunrays was found to be lower than that for the shadow side by about 40%. The examination of the fracture surfaces showed that, as the distance between the initial notch tip and the outer surface of the pipe decreased, the stress whitening area ahead the crack tip decreased. Also, it was found that, for the same notch length, the stress whitening area for the test specimens that were exposed to the direct sunrays were smaller than that for the shadow side.

يهدف هذا البحث إلى دراسة تأثير الظروف المناخية الخارجية فى منطقة الإحساء شرق المملكة العربية السعودية علــى متانــة الكسر لأنابيب عديد كلوريد الفينيل. وقد تمت الدراسة باستخدام عينات إختبار على شكل قطع قوسيه تم تحضيرها مــن أنبوبــة أستخدمت لمدة عشر سنوات تحت ظروف مناخية خارجية. وقد تم عمل شرخ إبتدائى باستخدام شفرة حادة من الصلــب. حيــث أستخدمت أطوال مختلفة للشرخ الإبتدائى وذلك للحصول على مسافات مختلفة بين مقدمة الشرخ الإبتدائى والســطح الخــارجى للأنبوبة. وقد أثبتت الدراسة أنه كلما زاد طول الشرخ الإبتدائى كلما نقصت متانه الكسر حيث بلغ معدل النقصان للعينات التــى عرضت لأشعة الشمس المباشرة ٠,٨ ميجا باسكال متر ^٠,٥^/مم بينما بلغ حوالى٠,٣٨ ميجا باسكال متر ^٠,٥^/مم للعينات المجهزة من ناحية الظل. أيضا وجد انه لنفس طول الشرخ الإبتدائى تقل متانة الكسر للعينات التى عرضت لأشعة الشــمس المباشــرة بحوالى ٤٠ % عن العينات المجهزة من ناحية الظل. وبفحص سطح الكسر وجد أن منطقة التشكل اللدن عنــد مقدمــة الشــرخ الإبتدائى تقل كلما زاد طول الشرخ وايضا كلما زاد التعرض لأشعة الشمس المباشرة وهو ما يدل على أن مرونه أنابيب عديــد كلوريد الفنيل تقل بالتعرض لأشعة الشمس.

Keywords: PVC, Weathering conditions, Fracture toughness, Plastic zone, Ultraviolet degradation

1. Introduction

Like many polymers, PVC pipe material is liable to degrade when subjected to natural weathering conditions specially sunrays. When PVC pipes exposed to ultraviolet (UV) radiation from sunrays, they can suffer from surface discoloration. This is commonly termed "UV degradation or sun burning". UV degradation affects PVC when energy from the UV radiation causes excitation of the molecular bonds in plastic. The resulting reaction occurs only on the exposed surface of the pipe and to extremely shallow depths of 0.025 to 0.075 mm [1].

In many applications PVC pipes are subjected to outdoor weathering conditions, so, it is very important to study the degradation of the engineering properties of PVC pipe material due to the effect of weathering, specially, the solar UV radiation.

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 were not adversely affected. The effect of outdoor weathering in Jeddah, Saudi Arabia, on the mechanical properties and residual stresses in injection molded semi-crystalline polymers was investigated [3].

Three polymers used in this study, which were polypropylene (PP), polyacetal (POM) and nylon6.6 (N6.6). 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. After three years of weathering it was found that, the upper yield stress for both PP and POM remained approximately constant and decreased with about 35% for N6.6. Furthermore, for the outdoor weathered specimens, the elongation at break decreased with about 85% for both N6.6 and PP and with about 10% for POM. For the specimens weathered in the shade, the elongation at break remained constant for POM and decreased with about 35% for both PP and N6.6.

The effect of the weathering on fracture toughness and yield strength of 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 and little increase in the yield stress (about 9%). 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.

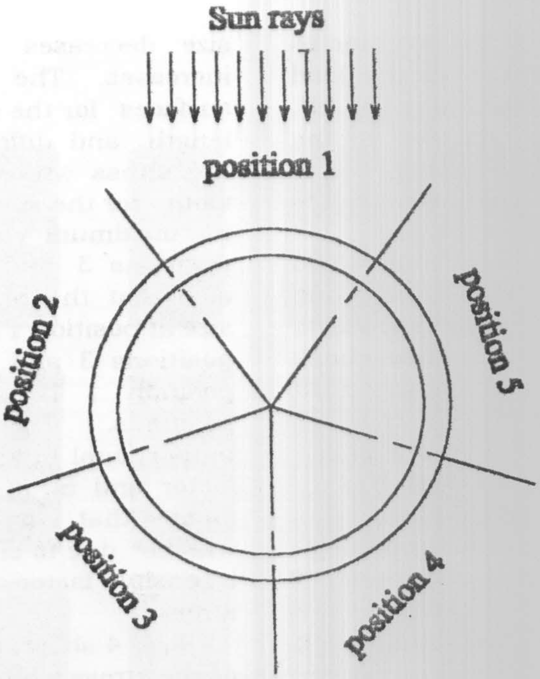
The examination of PVC water pipe used for ten years in outdoor weathering conditions in Al-hasa, Saudi Arabia, showed that, the surface discoloration in the pipe side which was exposed to the direct sunrays penetrated through the pipe wall for about 70% of its thickness. This did not agree with the data presented in [1]. The degree of discoloration decreases with increasing the distance from the pipe outer surface of the pipe. This deep penetration is related to the high temperature most of the year in Saudi Arabia. The aim of this paper is to quantify the effect of the outdoor weathering conditions, specially the sunrays in Al-hasa, Saudi Arabia, on the fracture toughness, Kc, of PVC pipes.

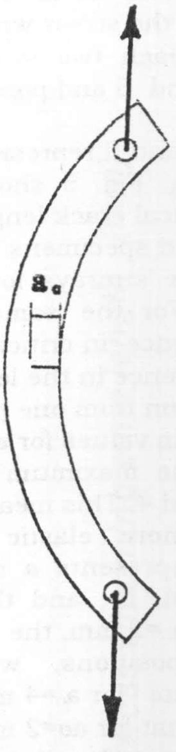
2. Experimental procedure

The test specimens were prepared from a PVC water pipe used for ten years in outdoor weathering conditions in Al-hasa, Saudi Arabia, where the temperature in summer reaches about 50 °C. The pipe has 160 mm outer diameter and 12 mm wall thickness, t. The test specimens were classified according to their positions relative to the direction of the sunrays. These positions were denoted from 1 to 5, where, position 1 denoted to the specimens that were exposed to the direct sunrays as shown in Fig. 1. The test specimen was designed as an arc segment as shown in Fig. 2-a. The specimen's dimensions were chosen according to ASTM standard E399-81 [6]. The test specimens were notched to an initial depth of a_o from their inner surfaces using a razor blade.

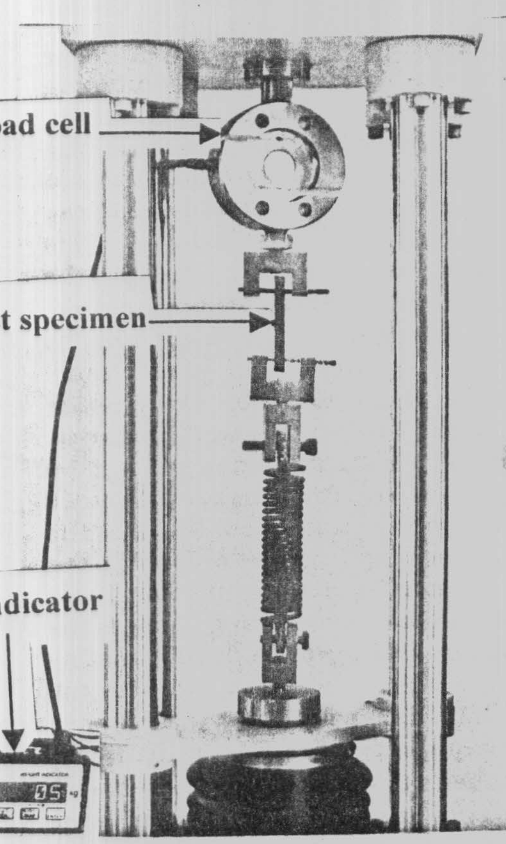
The effect of the weathering conditions is excepted to increase as the distance from the outer surface of the pipe decreases, so, to study the weathering effect, different distances between the initial notch tip and the outer surface of the pipe were used by using different values of a_o. Nine test specimens were prepared from each position. The specimens of the same position were divided to three groups, each group had three test specimens.

The length of the initial razor notches, a_o, were a_o= 2 mm, 4 mm and 6 mm for the first group, the second group and the third group respectively. The specimens were tested using a hydraulic static testing machine. Where,


Sun rays
position 1
position 2
position 5
position 3
position 4


a_o

2-a


load cell
test specimen
load indicator

2-b

the test specimen was fixed to the machine as shown in Fig. 2-b. The range of the load measuring system of the machine is 100 kN, which is very large with respect to the expected load required for testing, so,. a modified load measuring system was used to increase the measuring accuracy

The modified system depends upon a load cell having a maximum capacity of 2500N and a load indicator connected to the load cell to read the specimen load. To reduce shock loads on the test specimen a spring was used between the machine head and the test specimen. The test specimens were loaded monotonically at a loading rate of 40 N/s up to fracture, then, the failure load was recorded. The fracture surfaces morphology of the tested specimens was examined to measure the critical crack length and the stress whitening area ahead the initial crack tip.

3. Results and discussion

PVC material that is gray in the undeformed state, exhibit stress whitening effect when subjected to plastic deformation. Plastic deformation takes place around the crack tip in order to keep a finite stress at this region, the deformed region ahead of the crack tip is called the plastic zone. This deformation will create a white area on the fracture surface called stress whitening zone. The size of the stress whitening zone is proportional to the size of the plastic zone. Fig. 3 shows a photograph for the fracture surfaces of some broken tested specimens. The photographs were arranged in the form of a 3x5 matrix, where, the number 3 denotes to the three different notch lengths and the number 5 denotes to the different five positions. Region I represents the razor notch, region II (stress whitening zone) is the region of stable crack growth during loading before ultimate failure, while region III is the region of unstable crack growth.

The examination of the fracture surfaces for the specimens of the same position shows that, the size of the stress whitening zone decreases as the initial notch length increases, this means that, the plastic zone size decreases as the initial notch length increases. The examination of the fracture surfaces for the specimens of the same notch length and different positions. shows that. the stress whitening zone has its minimum value for the specimens of position 1 and has its maximum values for the specimens of positions 3 and 4. Consequently, this means also that the plastic zone has its minimum size at position 1 and has its maximum size at positions 3 and 4. i.e.. the pipe material at position 1 is more brittle than the other positions. The plastic zone length is proportional to K^2/S_y (K is the stress intensity factor and S_y is the yield stress) [7], which means that, the decrease in plastic zone size will be due to either decreasing in the stress intensity factor or increasing in the yield stress.

Fig. 4 shows the relation between the size of the stress whitening zone and the ratio a_o/t for the five different positions. In this figure the lines represent a linear fit to the data. This figure shows that the stress whitening zones are equal for each two symmetric positions (positions 2 and 5 and positions 3 and 4).

The size of regions I and II represents the critical crack length. a_c. Fig. 5 shows the relation between the critical crack length and the position of the tested specimens relative to the direction to the sunrays for three different values for a_o. For the same initial notch length, the difference in critical crack length is due to the difference in the length of the stress-whitening region from one position to the other. The minimum values for a_c occur at position 1, while the maximum values occur at positions 3 and 4. This means that the pipe material is more elastic at the shadow side. Fig. 6 represents a relation between the failure load, F_c, and the test specimen position. For a_o=2 mm, the force is constant for different positions, while, it changes with a small rate for a_o=4 mm and a_o= 6 mm. This means that for ao=2 mm, the exposure to sunrays has no effect close to the inner surface of the pipe. The values of a_c (Fig. 5) and failure loads (Fig. 6) were used to calculate the fracture toughness. K_c, using the following Equation [6]:

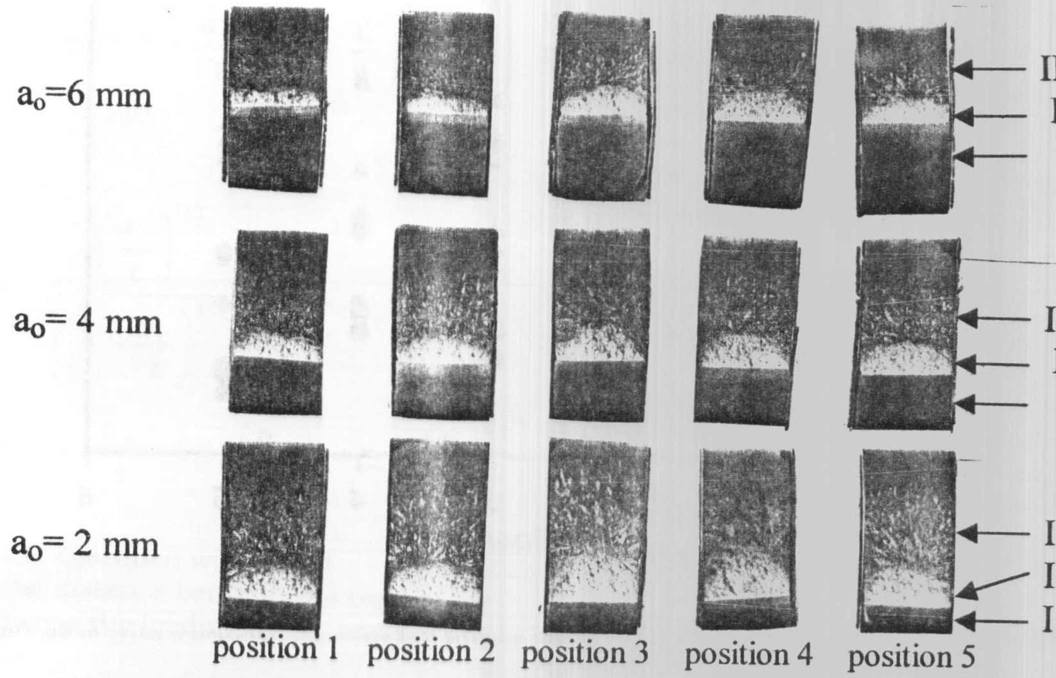


Fig. 3.

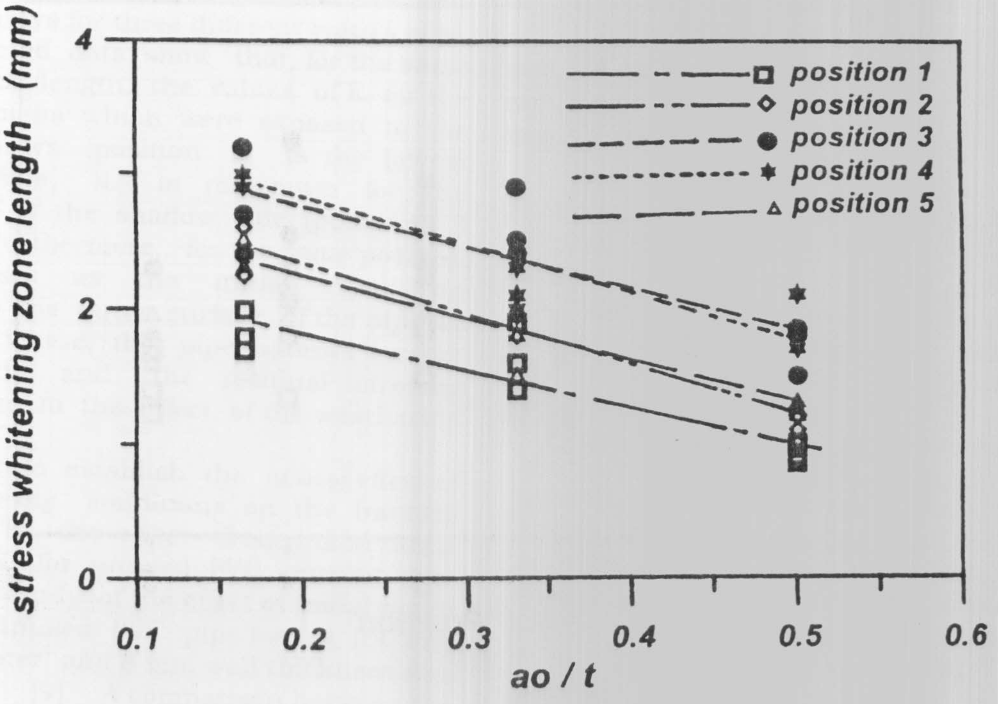


Fig. 4. The relation between the stress whitening zone length and the ratio ao/t for the five different positions.

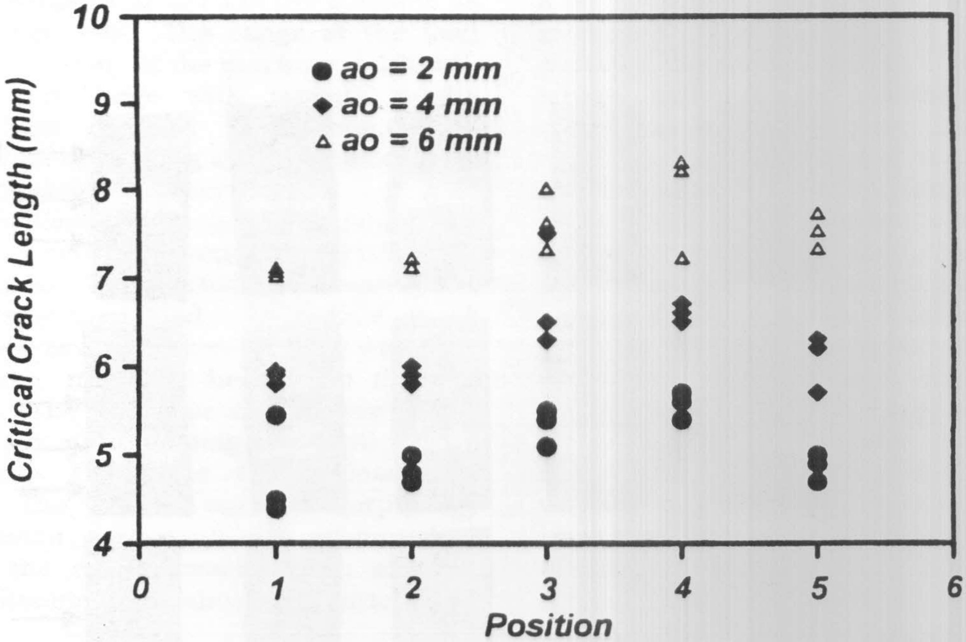


Fig. 5. Relation between the critical crack length and the test specimens position relative to the sunray direction.

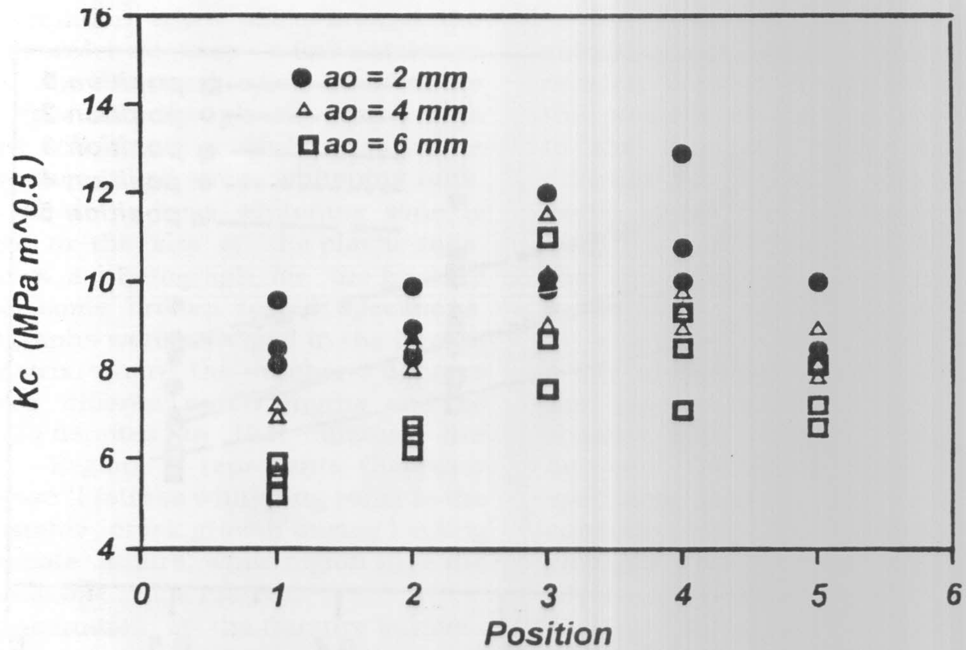


Fig. 6. Relation between the specimens position relative to the sunrays direction and the breaking load.

$$K_c = \left(\frac{F_c}{Bt^{1/2}}\right)\left[\frac{3x}{t} + 1.9 + 1.1\frac{a_c}{t}\right]$$

$$\left[1 + 0.25\left(1 - \frac{a_c}{t}\right)^2\left(1 - \frac{r_1}{r_2}\right)\right] f\left(\frac{a_c}{t}\right),$$

where;

$$f\left(\frac{a_c}{t}\right) = \left[\frac{\left(\frac{a_c}{t}\right)^{1/2}}{\left(1 - \frac{a_c}{t}\right)^{3/2}}\right],$$

$$\left[3.74 - 6.3\frac{a_c}{t} + 6.32\left(\frac{a_c}{t}\right)^2 - 2.43\left(\frac{a_c}{t}\right)^3\right]$$

B is the specimen width, and
X is the distance between the center line between the loading holes and the crack edge

Figure 7 shows the relation between K_c and the position of the test specimens relative to the sunrays for three different values of a_o. The presented data show that, for the same initial notch length, the values of K_c for the test specimens which were exposed to the direct sunrays (position 1) is the lowest values, while, K_c is maximum for the specimens of the shadow side (positions 3 and 4). Furthermore, for the same position K_c decreases as the initial crack tip approaches the outer surface of the pipe (a_o increases), where, the pipe material became more brittle and the residual stresses changes due to the effect of the weathering conditions [3].

In order to establish the actual effect of the weathering conditions on the fracture toughness, K_c, the effect of the initial notch length on K_c for unused PVC pipe must be known. A study of the effect of initial notch length for unused PVC pipe having 160 mm outer diameter and 8 mm wall thickness was investigated [9]. A comparison between the data of the unused pipe and the data obtained for the pipe which was exposed to the direct sunrays (position 1 of the used pipe) is shown in Fig. 8, where the horizontal axis is the normalized initial notch length, a_o/t. For the unused pipe, as a_o increases, K_c increases with a rate of dK_c/da_o = 0.9 MPa. $m^{1/2}$/mm, while for the used pipe, as a_o increases, K_c decreases with a rate of dK_c/da_o= 0.8 MPa. $m^{1/2}$/mm. To explain this phenomena, let us consider the effective stress intensity factor, $K_{eff.}$ [9]:

$$K_{eff.} = K_{app.} + K_{resid.}$$

Where,

K_{eff} is the effective stress intensity factor
K_{app} is the applied stress intensity factor
K_{resid} is the stress intensity factor due to residual stress.

For the unused pipe the residual stress changes from tensile stress having its maximum value at the pipe inner surface to compression stress having its maximum value at the outer surface of the pipe [10]. At a certain point close to the inner surface of the pipe there is a transition from tensile residual stress to compression residual stress. So, as a_o increases K_{resid} decreases and will have negative values at compression residual stress locations. As a result K_{app} will increases to keep K_{eff} constant.

For the used pipe, the weathering conditions creates a tensile residual stress [3], so, K_{resid} will be more than that for the unused pipe, consequently, K_{app} will decrease to keep K_{eff} constant. Furthermore, the increase of brittleness of the pipe material due to the weathering conditions will affect the fracture toughness.

Figure 9 shows a relation between K_c and the initial notch length a_o for five different positions relative to the sunrays. As explained before, the fracture toughness K_c decreases as a_o increases. The rates of decreasing of K_c with respect to a_o , dK_c/da_o, is equal to the slope of the fitting lines which are 0.81, 0.64, 0.39, 0.38 and 0.67 MPA.$m^{1/2}$/mm for positions 1, 2, 3, 4 and 5, respectively.

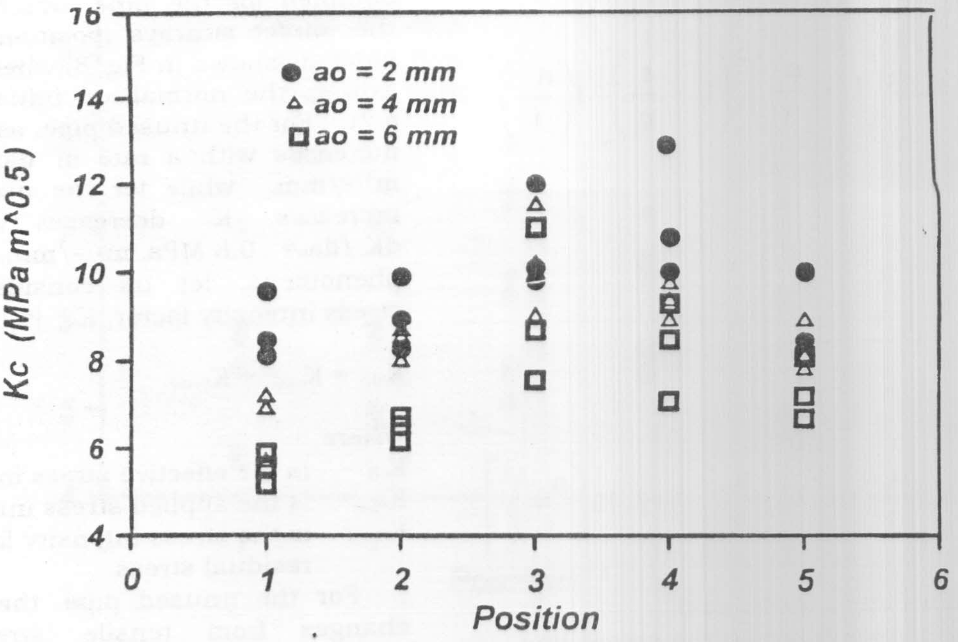


Fig. 7. Relation between the fracture toughness and test specimen position for different initial notch length.

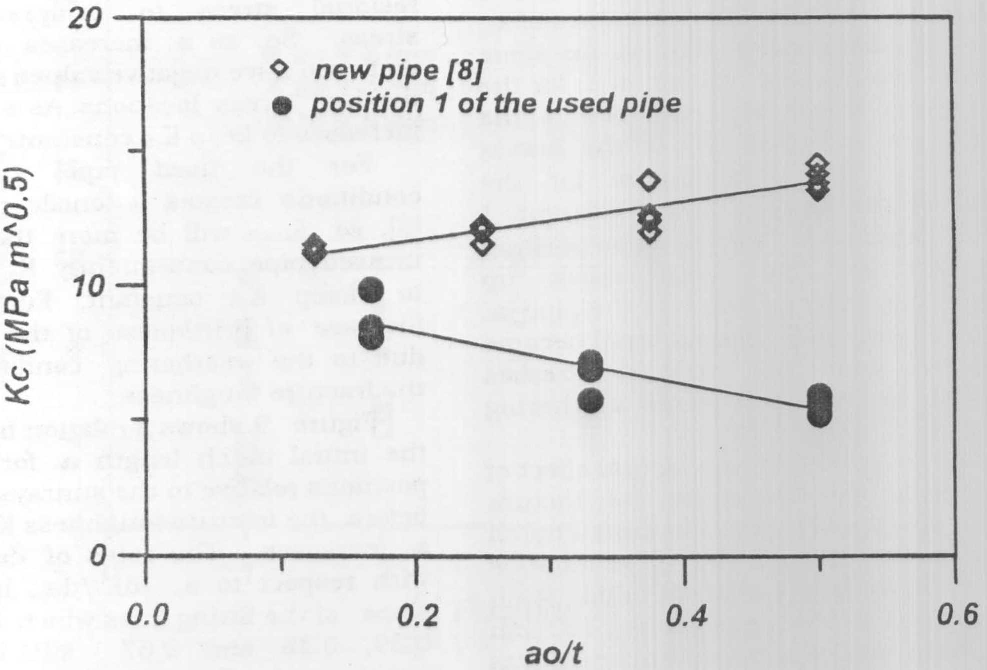


Fig. 8. Comparison between the fracture toughness of used pipe and new pipe for different a_o/t values.

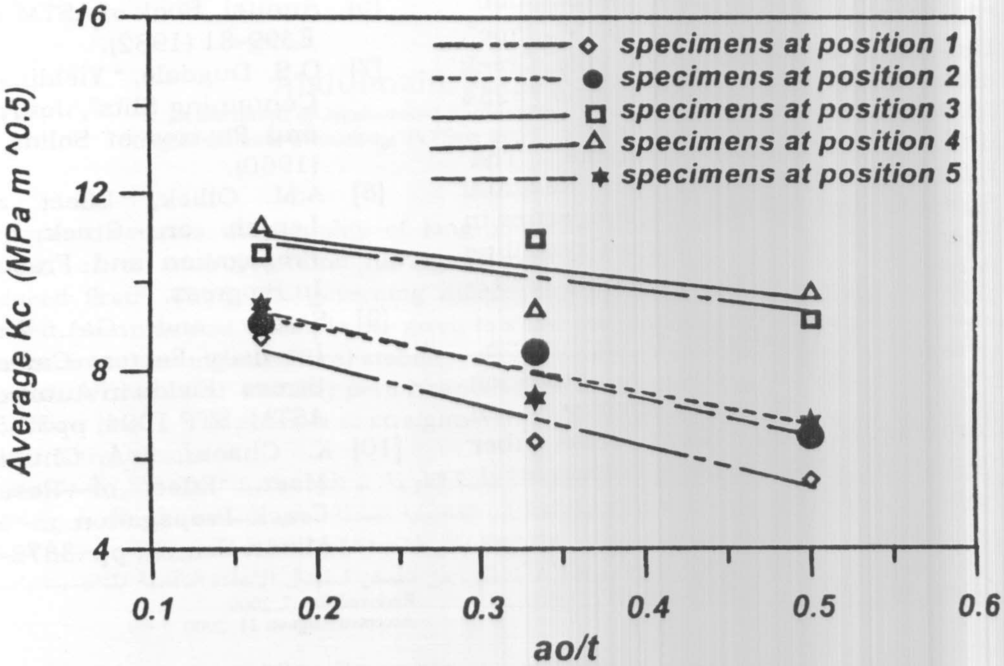


Fig. 9. Relation between the fracture toughness and the ratio ao/t for five different positions (each data point represents the average of three values).

The maximum decreasing rate occurs for the specimens of position 1, which is subjected to the solar UV radiation from sunrays. The minimum decreasing rate occurs for the specimens of positions 3 and 4. The effect of the weathering conditions changes the rate dKc/da_o from an increasing rate for the unused pipes to a decreasing rate the used pipe.

4. Conclusions

The fracture toughness, K_C, of PVC pipes is affected by the exposure to outdoor weathering conditions especially the sunrays.

1 The exposure to direct sunrays decreases the fracture toughness by about 25% and 65% at a_o/t = 0.17 and a_o/t= 0.5, respectively
2 For both new and used pipes K_C is affected by the initial notch length, but, for new pipe K_C increases as a_o increases while for used pipe K_C decreases as a_o increases. The rate of change of K_C due the exposure to sunrays is dK_C/da_o=-1.7Mpa $m^{1/2}$ /mm.
3 For the used pipe, K_C for the pipe side that is exposed to direct sunrays decreases by about 40% than that for the shadow side.
4 The stress whitening area ahead the initial crack tip is reduced by about 50% due to the exposure to the direct sunrays. This means that PVC material becomes more brittle.

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