

The Temperature Effects On High Density Polyethylene (HDPE) Pipes

MAHIR H.H. ES-SAHEB

*Mechanical Engineering Department, College of Engineering,
King Saud University, Riyadh, Saudi Arabia*

ABSTRACT. The mechanical characteristics and properties of HDPE pipes are highly affected by the environmental conditions. In this investigation the influence of temperature on the mechanical characteristics (*i.e.*, stress-strain) curves as well as the viscoelastic properties of these tubes is examined. A range of testing temperatures of 23 to 80°C is covered for HDPE pipes of both classes (3) and (5) with working pressures of 4 and 10 bars respectively. Various pipe sizes ranging from 16 to 32 mm are investigated. In this investigation, mainly, the standard Japanese axial tensile test (JIS K6761) is employed.

The results of this investigation show that all pipes tested exhibit temperature sensitivity to varying degrees (*i.e.*, decreased resistance to deformation as the temperature is increased) regardless of the pipe size and class. All the mechanical properties of these tubes except for ductility are decreased non-linearly as the testing temperature increases. The values of the yield stress, tensile strength, modulus of elasticity, and specific work are found to be degraded by about 45 to 60% over the tested range of temperatures. Generally, the pipes of class (5) are found to be superior to pipes of class (3) in all their mechanical properties over the whole testing range of temperatures. Finally, polymer degradation problem is discussed, including its principles, causes, mechanisms and factors affecting this phenomena. Also, the thermal and mechanical degradation types of HDPE pipes in particular are discussed and presented.

1. Introduction

Several types of pipes are used in different fields, where the selection of the pipe material depends on the application to be used for. But after manufacturing the plastic pipes many of them have been substituted in different applications^[1,2], such as

food processing, water distribution, irrigation and sewerage where the resistance of a piping material to corrosion is an important factor which must be balanced against the cost of replacement. With the extraordinary advances in the chemical industry there have appeared on market numerous additions in the field of piping materials^[3-5]. Notable of these materials are polyvinyl chloride (PVC) and polyethylene. Traditionally, however, in the polyethylene there are two main grades widely used^[5,6]. These are the low density polyethylene (LDPE) which has branched chains, and high density polyethylene (HDPE) which is predominantly linear.

In the last few years, however, high density polyethylene pipes are becoming increasingly used and rapidly replacing the conventional metal (steel) and polyvinyl chloride pipes in many areas of water distribution. The main reasons are that the HDPE pipes are attractive due to their competitive cost, corrosion resistance properties, flexibility and relative ease of installation and handling. However, the applications of the wide ranges of polyethylene pipes depend on their physical, chemical, thermal and mechanical properties. But since there are many sources for the polyethylene pipes, as is the case with the various types of plastic pipes, their properties are varying somewhat from one manufacturer to another. This may be due to the method of manufacturing, the use of filler materials, to bring down the cost ... etc. As a result of this, it is necessary to check with the manufacturer of the particular pipe being used about its various properties and the allowable pressure rating. Contrary to the case of ferrous pipe, there is still considerable standardization of these materials to be desired^[1]. This is particularly important in the case of the mechanical properties of HDPE pipes and their 'fits' specially at relatively high working temperatures, where there is considerable actual theoretical and practical (experimental) information still lacking in this area.

It is well known that the mechanical characteristics and properties of HDPE pipes and other polymeric products are highly affected by the environmental conditions, such as the sunlight (UV), moisture, oxygen and nitrogen gases and temperature^[5,11-16]. But for the HDPE pipes used in water distribution and irrigation net works, the particular effects of temperature and temperature variation (*i.e.*, cyclic temperature) of the atmosphere and the water, are serious in 'degrading' the general properties of these pipes, especially the mechanical properties. This aspect to date has not been systematically investigated in most of the polymeric (plastic) materials in general and in polyethylene in particular:

In this paper, a summary of an extensive research program on the influence of temperature on the characteristics and mechanical properties of HDPE pipes, including the stress-strain curves, tensile strength, elongation percent, ... , etc., is presented. The investigation involves the systematic testing of five different pipe sizes ranging from 16 to 32 mm of both classes (3) and (5) of HDPE tubes under thermal environmental conditions similar to those which exist in the Kingdom of Saudi Arabia. The temperature range covered for all pipes investigated lies between 23 to 80°C.

2. Materials

The experimental program is carried out on two types of HDPE pipes produced locally. These are (i) HDPE pipes of Class (3) with working pressure of 4 bars, manufactured by Saudi Plastic Products Co. Ltd., SAPPCO (Dammam, Saudi Arabia). The two pipe sizes investigated of this class are 16 and 25 mm nominal diameters, (ii) HDPE pipes of Class (5) with working pressure of 10 bars, manufactured by Mais Co., (Riyadh, Saudi Arabia). In this class three pipe sizes of 20, 25 and 32 mm nominal diameters are investigated. For further details on these pipes and material properties including some physical, thermal, and manufacturing see References [5,7]. Meanwhile, for some chemical analysis of these tubes including the carbon content and distribution employing the X-ray diffraction analysis as well as electron scanning microscope photographs and loading rate effects References [8,9] may be consulted. It is found that, the carbon content in all the samples is within the standard value of 3%. But the carbon distribution across the sample is found to be relatively homogeneous with maximum variation in concentrations less than 5%^[8].

3. Testing Equipment and Methods

As recommended by the Japanese standard^[10], which has been adopted in this work, two types of tensile samples are prepared as shown in Fig. 1. Type (a) samples are prepared from pipes of 25 mm size and less nominal diameters, and type (b) samples are prepared from pipes of 30 mm size and over nominal diameters. Table 1 below displays the characteristic dimensions of the pipes investigated. Thirty samples of each pipe size are made. These samples are made in two steps: First, pieces of the pipe of about 105 mm axial length and with an approximate circumferential arc length of about 30 mm are prepared by cutting. Then these pieces are brought to the final shapes and dimensions, see Fig. 1, by milling according to the standard dimension specifications of JIS B 7502 and JIS B 7507.

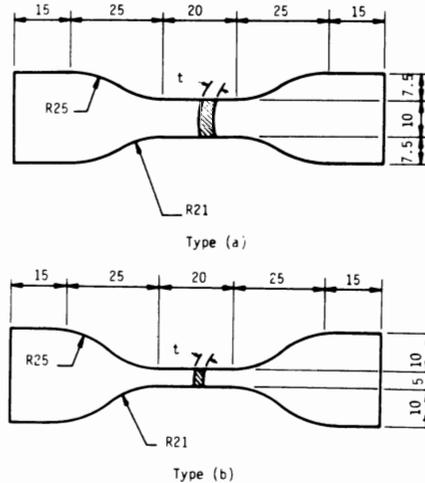


FIG. 1. The dimensions of standard types of test samples used for tensile test. (Note: All dimensions are in mm).

TABLE 1. Heat reversion test results.

No.	Pipe size (mm)	Pipe thickness (mm)	$\bar{\epsilon}$ %	Pipe class
1	16	1.3	0.79	(3)
2	25	1.5	0.77	(3)
3	20	2.0	0.81	(5)
4	25	2.5	0.80	(5)
5	32	3.0	0.65	(5)

Uniaxial tensile tests at standard constant speed of 200 mm/min are carried out on all samples prepared of these pipes according to the Japanese standard JIS K6761 and procedures^[10]. All tests were carried out until failure using the universal Instron machine. Also an auxiliary standard Instron oven is used, in all tests, to provide and maintain the necessary constant testing temperatures during the test. The test temperatures investigated are 23, 40, 50, 60, 70 and 80°C. For each pipe size and testing temperature conditions the tensile test is repeated five times to ensure the results consistency. In each test, the load versus displacement was plotted and the temperature was measured and later the results were processed. Typical load-displacement curve for sample of pipe size 16 mm (class, 3) tested at constant temperature of 40°C is shown in Fig. 2.

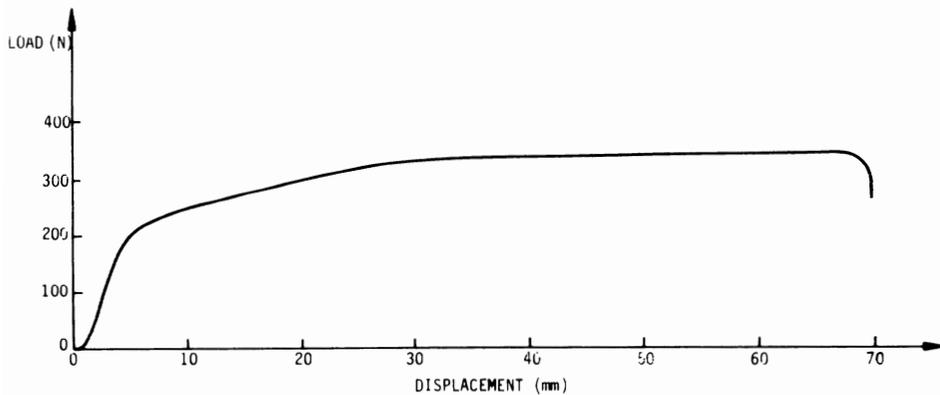


FIG. 2. Typical load-displacement curve for a tensile sample of 16 mm pipe size, Class (3), performed at a temperature of 40°C.

Also, to assess the behavior of these pipes materials and to help in understanding the temperature effect on their properties and to give insight into the problem of 'degradation'^[11,12] of these polymeric materials, two other standard tests are carried out on samples of all pipes. These are the standard Heat Reversion Test, DIN/8075,^[17] and Carbon Black Content Test (or Ash Test), JIS K6761,^[10]. The standard procedures of these tests were followed for all samples and pipe sizes investigated in this study.

In the heat reversion test^[17], five complete sections of pipe, approximately 200 mm long are taken as test pieces for each pipe size. A mark is scribed around the whole circumference on the external surface approximately 50 mm from each end of the test pieces. The distance between the two marks, l_o (reference length), is approximately 100 mm and is measured to the nearest 0.25 mm at $(23 \pm 2)^\circ\text{C}$. To ensure that any changes in length may take place unimpeded, all test pieces are placed on a glass plate previously dusted with talcum.

The glass plate with the test pieces are placed in an oven heated to test temperature of $(110 \pm 2)^\circ\text{C}$ and capable of maintaining continuous forced air circulation (as described in DIN 50 011) for a period of (60 ± 1) min. After the test pieces have been removed from the oven and left to cool in air to a temperature of $(23 \pm 2)^\circ\text{C}$, the minimum distance between the two marks, l_{min} is measured. Consequently, the relative change in length, ε , in % is calculated according to the German standard (DIN/8075) using the following equation

$$\varepsilon = [(l_o - l_{min}) / l_o] \times 100 \quad (1)$$

The arithmetic mean value of the relative changes in length, ε , calculated from the above equation, is taken as the mean relative change in length $\bar{\varepsilon}$, for each pipe size. These values together with the specifications of the samples tested are presented in Table 1.

From this table it is noticed that as the pipe diameter and thickness are increased the percentage change in the length, $\bar{\varepsilon}$, decreases. But in all the samples tested it is found that these percentage changes are well below the standard allowable limit of 3%.

For the carbon black content, ash test^[10], is employed. Five standard samples of each pipe size are used. The test carried out as follows: Each standard sample is taken in porcelain crucible and weighed (w_i) precisely. All the samples are then placed in an oven heated to 500°C and ignited for about 15 minutes, after which each sample (*i.e.*, the ash left) is weighed (w_f). However, to insure complete burning of the carbon content of the samples, the above procedure (*i.e.*, the reburning and weighing of the samples) is repeated till no change in the final samples weight w_f is recorded (*i.e.*, constant final mass of the ash is obtained). Then the percentage loss in the weight, which presents the carbon content in the sample is calculated using the equation

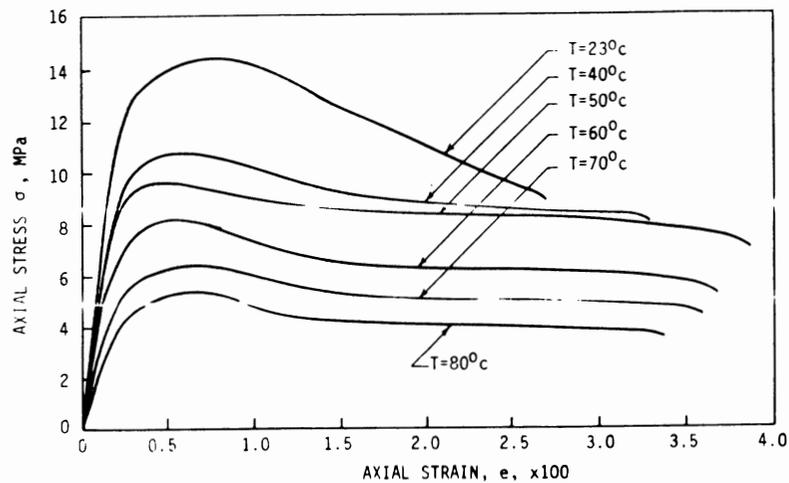
$$C = [(w_i - w_f) / w_i] \times 100$$

It is found that, in all samples tested, the percentage of the carbon content is between 2.8-3% which is within the allowed standard value of 3%. For more details on this test and the measurements of the carbon distribution in the samples, using the X-ray diffraction analysis, see Ref. [8]. It is useful, however, to mention that though the carbon black is usually added during production to increase resistance to weathering and aging, the presence of higher percentages of it (*i.e.*, above 3%) in the HDPE reduces its ductility and increases the failure tendencies of these tubes under the

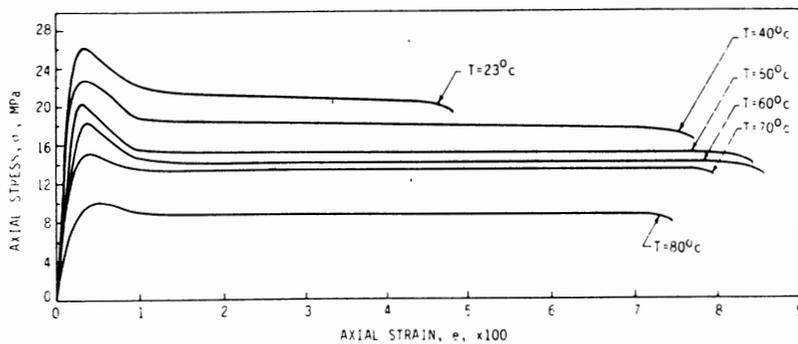
mechanical stressing and shock.

4. The Tensile Test Results

For each test, at selected points on the load-displacement curve, (see Fig. 2), the load, F , (N) and displacement, ΔL , (mm) are measured. Knowing the initial sample dimensions (*i.e.*, the cross-sectional area, A , and the gauge length L_0) it was possible to calculate the stress, σ , and the strain, e , by following the well known normal procedure. Then from the five tests carried out at the same conditions (*i.e.*, speed and temperature) a mean representative stress-strain curve is obtained. These representative curves are, then, displayed on common axes for each tube size. Figure 3 shows typical stress-strain curves obtained at the different testing temperatures for samples of the pipe size 25 mm of both classes (3) and (5) respectively.



(a)



(b)

FIG. 3. The stress-strain curves for HDPE pipes obtained at different temperatures for: (a) Pipe size 25 mm, Class 3 and (b) Pipe size 25 mm, Class 5.

From the stress-strain curve obtained for each test the following properties were derived: (i) The tensile strength (*i.e.*, the ultimate stress); (ii) The yield stress, measured at 15% strain^[7]; (iii) The elongation percent *El%*; (iv) The specific work (*i.e.*, the work per unit volume), calculated by dividing the total area under the load-displacement curve ($\text{N} \cdot \text{mm}$) by the sample volume (mm^3); and finally (v) The modulus of elasticity, measured from the tangent of the stress-strain curve at about zero strain. The variation of these parameters with the temperature for all pipes of both classes (3) and (5) are shown in Fig. 4 to 8 respectively.

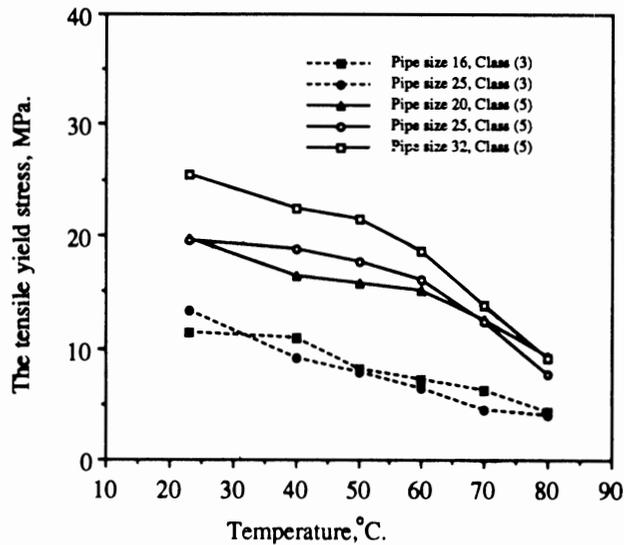


FIG. 4. The variation of tensile yield stress with the temperature for HDPE pipes.

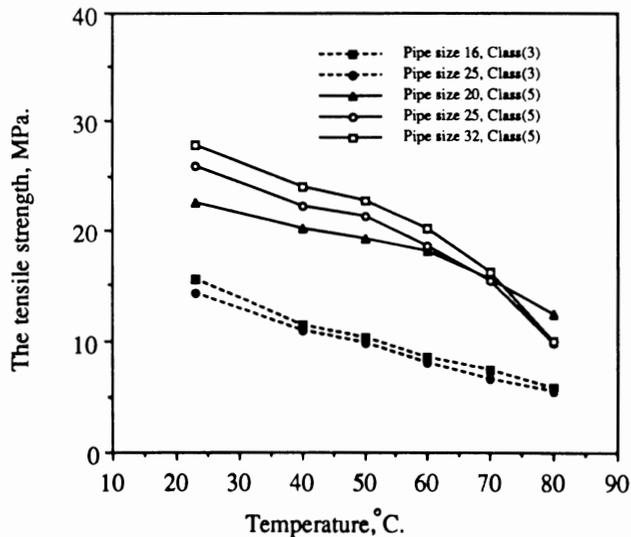


FIG. 5. The variation of tensile strength with the temperature for HDPE pipes.

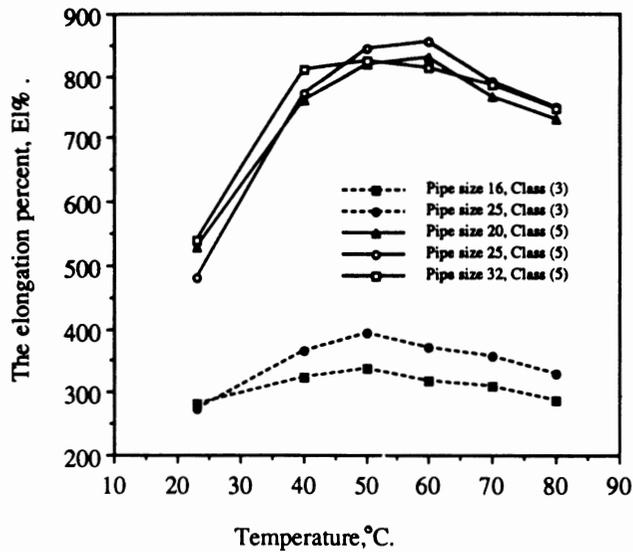


FIG. 6. The variation of elongation percent with the temperature for HDPE pipes.

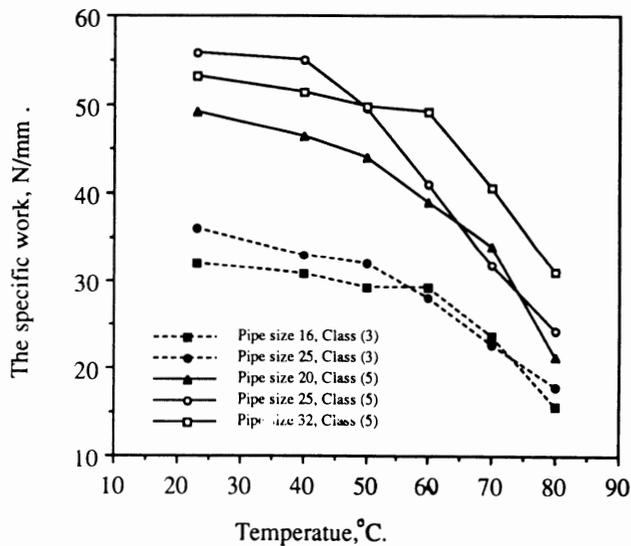


FIG. 7. The variation of specific work with the temperature for HDPE pipes.

5. Discussion

The most important mechanical property of a plastic is its tensile stress-strain curve, (see Fig. 3). It provides information about the, modulus of elasticity which is related to the polymer's stiffness and rigidity, yield point, tensile strength and elongation at break which is a measure of the polymer ductility. The curve, also, helps to

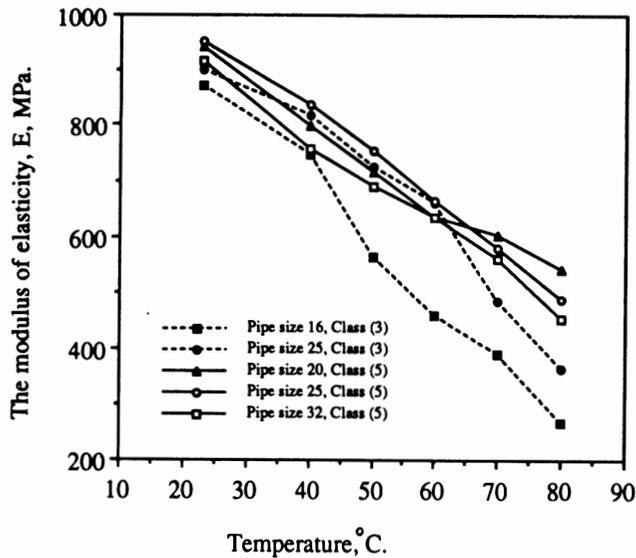


FIG. 8. The variation of modulus of elasticity with the temperature for HDPE pipes.

define toughness and the specific work required for forming the polymer. Furthermore, since plastics show viscoelastic behavior, which is highly sensitive to temperature and loading rate, the stress-strain curves obtained at low and high temperatures as well as different loading and forming speeds are essential in evaluating and understanding the thermal, viscoelastic characteristics and the mechanical properties of these materials^[5].

Polymer materials including polyethylene are non-homogeneous mixtures of different materials, such as the resin, fillers, additives, ... , etc. However, each of these materials possesses different mechanical characteristics and properties. Consequently, the combined mechanical characteristics of these varying components are complex. This is clearly revealed and manifested in all stress-strain curves obtained, which displayed non-linear behavior over the whole ranges of strain and temperature tested as shown in Fig. 3. This in turn imposes some difficulties in analyzing and assessing the results, which implies the tediousness of obtaining highly accurate and reliable quantitative measurements of most of the mechanical properties, such as the yield stress, modulus of elasticity, specific work, ... , etc. Hence, in the literature, most of the polymers properties are reported in a range form rather than precise single value^[3,7,18], particularly for the mechanical properties. Each sample of these materials, due to the non-homogeneity, could be treated as if it is a different material. This is noticed from the slightly different stress-strain curves obtained for the various pipes samples, which indicated as reported above, the presence of some variation in the material composition of these tubes even within the same pipe size samples, see Fig. 3. This can be clearly seen in Fig. 3-8 where some differences in the stress-strain curves and consequently other values of mechanical properties exist for the different pipe sizes even at the same testing conditions. In spite of this, however,

collectively it is noticed that the behavior of both pipe classes is non-linear and they follow almost similar general trend which characterizes this range of HDPE materials tested^[5,19].

The degradation of properties of polymers under certain conditions, is one of the most important practical features of these materials. Because of the importance of this aspect in polymers and its strong relevance to the present investigation; this phenomena will be discussed briefly below.

Generally, polymer degradation which is the collective name given to various processes which degrade polymers (*i.e.*, deteriorate their properties or ruin their outward appearance), is a harmful process which is to be avoided or prevented. In order to do this suitably, with maximum efficiency, we must understand the mechanism of polymer degradation, and we must identify the factors causing it.

In this paper we deal primarily, with the problems related to the damaging character of degradative processes of this phenomena. But from the great variety of polymer degradation processes only the most relevant important types will be treated here, demonstrated in connection with the HDPE polymers.

Degradation may happen during every phase of a polymer's life, *i.e.*, during its synthesis, processing, and use. Even after the polymer has fulfilled its intended purpose, its degradation may still be an important problem. During processing, the material is subjected to very high thermal and mechanical stress. These high stresses may initiate a variety of polymer degradation processes leading to a deterioration of properties even during processing. On the other hand, the damaging of the material may result in the introduction of various defects in the polymer which will work as degradation sources during its subsequent service life. For example, in the presence of traces of oxygen during processing or/and usage, carbonyl groups can be formed in polyolefins^[13,14]; these will later absorb UV light during outdoor applications, as is the case with the water distribution and irrigation pipes, and thus will function as built-in sensitizers for photodegradation processes. The best known appearance of polymer degradation is connected with the use of these materials. Some kinds of polymer degradation are, aging, stiffening, discoloration, ... , etc. It can be concluded that degradation plays an important role in every life phase of a polymer. Thus the importance of studying the degradation mechanism, relationships, ... , etc., is essential.

Macromolecules are composed of monomeric units which are joined by chemical bonds to each other. The monomeric units contain chemical bonds which either are in the main chain of the macromolecule or connect various atoms or side groups to it. Side groups, if they are present, contain additional chemical bonds. All of these bonds may be reaction sites in polymer degradation, and various energy sources may be effective in supplying the energy necessary to break the bonds. The bond energies are manifold and depend not only on the kind of atoms connected by the bond but also on the chemical and physical characteristics surrounding the bond. The most important types of energy that cause polymer degradation, generally and HDPE in par-

ticular, are heat, mechanical energy, and radiation. Thermal and mechanical degradation of polymers may occur during thermo-mechanical processing, installation and subsequent usage conditions (*e.g.*, as the case with HDPE pipes used for water distribution and irrigation). An extreme case of heat damage is burning. Also, the most common form of radiant energy which causes degradation is that of the UV component of sunlight^[14,15]. Not only is the role of temperature important when the heat necessary for bond dissociation is supplied by thermal motion of the atoms, it can also activate various chemical and biological processes. Reactions of polymers with oxygen and moisture, generally present in various applications, such like water distribution and irrigation, are very important in polymer degradation^[8]. However, the factors generally are not separated; various combinations of damaging components (*e.g.*, heat, mechanical stress, moisture and oxygen) may initiate very complex processes. As a result of degradation processes, initiated and completed by the above factors or their combination, the internal properties as well as the external appearance of the polymers may change. This is clearly noticed in our case for all HDPE pipes tested, where the mechanical properties including the mean tensile strength, yield stress and modulus of elasticity values are deteriorated (*i.e.*, reduced) by about 50% over the testing temperature range as displayed in Fig. 4, 5 and 8 respectively. Also this combined effect of degradation is manifested and shown clearly in the reduced mean values, obtained in all samples, of the elongation percent and specific work which decreased by about 45-60% over the tested temperature range. Chain scission and cross-linking lead to a change of molecular weight distribution, oxidation and other chemical reactions, in the side chains too, cause changes in chemical composition result in discoloration, ... , etc. These primary alterations in the polymer usually cause the deterioration of mechanical and other technically important properties; as a result, the material loses its value and becomes a useless waste. In conclusion, polymer degradation is a very complex process because of the numerous causes and the changing response and degradation mechanisms of the different polymers under the various working conditions. For more details on the thermal "degradation" and other types of polymer degradation, classifications and the different degradation principles and mechanisms involved in each type see the works of Schanabel^[11] and Kelen^[12] whose work is mainly concentrated on the PVC materials.

As far as the effect of temperature is concerned it is obvious from the results of tensile tests (see Fig. 3 and 4-8 that as the testing temperature is increased the mechanical properties are decreased. This decrease in mechanical properties could be due to thermal degradation effects discussed above, in addition to the softening effect of the temperature on the HDPE and the possible melting or near melting of some smaller molecules or chains especially at the higher testing temperatures of the range (*i.e.*, near 70 and 80°C testing temperatures).

It is important, here, to mention that the effect of high temperature is to encourage the viscoelastic behavior of these pipe's materials. Consequently, it is not surprising that, at higher temperatures (*e.g.*, 60-80°C) and longer durations of time (*e.g.*, of about 620 to 860 min.^[8,9] observed during some tests), the effect of these temperatures is more pronounced in the decrease of both the yield stress and the flow stress

as well as the other mechanical properties. For all samples tested the viscoelastic effect is displayed more clearly in the smaller pipe sizes and thicknesses of both classes. For more details on the viscoelastic properties of this material and the effect of strain rates (*i.e.*, speeds) of testing and other experimental techniques and analysis used see Ref. [8,9]. The heat reversion test results given in Table 1 supports these findings and provide strong evidence on the viscoelastic nature of these materials which is a temperature sensitive property, see Fig. 3-5. It is found that the percentage change in the length, $\bar{\epsilon}$, is increasing as the pipe size (diameter) and thickness are decreased. Hence, the ductility of the pipes of class (5) is found to be higher than that of pipes of class (3), see Fig. 6.

Generally, from Fig. 3-8 it is noticed that, all mechanical properties and characteristics of the pipes of class (5) are found to be superior (*i.e.*, higher) to those of class (3) over the whole testing range of temperatures. For example the highest degradation in the tensile yield stress of pipes in class (5) is found to be about 63% compared with 66% for pipes in class (3), see Fig. 5. Finally, it is found that pipes with bigger thicknesses possess higher mechanical properties. This indicates the importance of the pipe thickness in the selection procedures and decision stages of the pipe usage.

6. Conclusion

From all the tests carried out on the various sizes of HDPE pipes of both classes (3) and (5), a number of conclusions can be drawn. These are :

1. The mechanical characteristics and properties of all pipes tested of both classes except elongation are degraded, by about 50%, as the testing temperature increases in a non linear manner. The most temperature sensitive pipe is found to be the 16 mm pipe size of class (3).
2. Generally, the tensile stress-strain curve is useful for characterizing the HDPE polyethylene pipes. Pipes of class (5) show superior mechanical properties than those of class (3). Thus, the thickness of the pipe is important in degradation and should be included in the selection criteria of HDPE pipes.
3. All pipes tested display some viscoelastic behavior with varying degrees. In the heat reversion test, the percentage change in length is found to be below the allowable standard limit of 3% in all samples tested.

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تأثير درجات الحرارة على أنابيب متعدد الإثيلين عالي الكثافة

ماهر حمدي الصاحب

قسم الهندسة الميكانيكية ، كلية الهندسة ، جامعة الملك سعود

الرياض - المملكة العربية السعودية

المستخلص . تتأثر الخواص والمميزات الميكانيكية لأنابيب متعدد الإثيلين عالي الكثافة بالظروف البيئية بصورة كبيرة . ويهدف هذا البحث إلى دراسة تأثير درجات الحرارة على منحنيات الخواص الميكانيكية (الإجهاد ، والانفعال) واللزوجة المرنة لهذه الأنابيب ، فقد تمت تغطية مدى من درجات الحرارة (٣٣-٨٠م) في اختبارات أنابيب متعدد الإثيلين عالي الكثافة لدرجتيه الثالثة (٣) والخامسة (٥) ذوات ضغوط عمل ٤ بار ، و ١٠ بار على التوالي . حيث درست مقاسات مختلفة من هذه الأنابيب تتراوح أقطارها بين ١٦-٣٢ مم ، واستخدم في هذه الدراسة بشكل رئيس اختبار الشد ، وذلك حسب المواصفات القياسية اليابانية .

بيّنت نتائج هذا البحث أن جميع الأنابيب التي تم اختبارها قد أبدت حساسية لدرجات الحرارة بنسب متفاوتة (حيث قلت مقاومتها للتشكيل كلما ارتفعت درجة الحرارة) بغض النظر عن درجة الأنبوب أو مقاسه . كذلك تبين بشكل عام أن جميع الخواص الميكانيكية لهذه الأنابيب قد قلت بصورة غير خطية مع زيادة درجة حرارة الاختبار . وقد أظهرت قيم إجهاد الخضوع وقوة التحمل القصوى ، ومعامل المرونة والشغل اللازم لكل وحدة حجم إنخفاضاً أضعافاً يتراوح بين ٤٥-٦٠٪ على مدى درجات الحرارة التي تم اختبارها . وعموماً فقد أبدت الأنابيب من الدرجة الخامسة (٥) تفوقاً في الخواص الميكانيكية على الأنابيب من الدرجة الثالثة (٣) لكل مدى درجات الحرارة التي تم اختبارها . وأخيراً تمت مناقشة مشكلة التفكك في اللدائن ، بما في ذلك مبادئها وأسبابها وآلياتها والعوامل التي تؤثر على هذه الظاهرة ، وأيضاً نوقشت أنواع التفكك الحراري. والميكانيكي في أنابيب متعدد الإثيلين عالي الكثافة على وجه الخصوص .