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Effect of Temperature and UV on Some Mechanical Properties of PVC Pipes

A Thesis

Submitted to the College of Engineering of Babylon University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Materials Engineering
(Polymers Engineering)
by

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جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة

تأثير درجة الحرارة والأشعة فوق البنفسجية (UV) على بعض الخواص الميكانيكية لأنابيب مصنوعة من PVC

رسالة

مقدمة إلى كلية الهندسة في جامعة بابل وهي جزء من متطلبات نيل درجة
ماجستير علوم في هندسة المواد
(تخصص/لدائن)

أعدت من قبل

محمد رزاق محمد

إشراف

د. نجم عبد الأمير سعيد د. محمد حمزة المعموري

1430 هـ 2009 م

بسم الله الرحمن الرحيم

((يَرفَعِ اللهُ الذين امنُوا مِنكُم والذين
أُوتُوا العِلمَ دَرَجاتٍ واللهُ بما تَعمَلُونَ خَبيرٌ ٠))

صدق الله العلي العظيم

سورة المجادلة

الآية
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Abstract

For water and sewer pipes, PVC competes with other materials due to its good properties.

This work was conducted to study some mechanical properties of two PVC pipes material under different conditions.

The samples were prepared by cutting the pipe to rings which were softened by using an oven to obtain flat specimens. The samples of tensile, impact and fatigue tests were prepared from the flat specimens according to standard specifications.

In this work, effect of strain rate (crosshead speed) and temperature and UV radiation on tensile properties of PVC pipes material were investigated. Also, effects of temperature and UV radiation on impact strength and fatigue behavior of PVC pipe material were investigated.

In tensile test, the results showed that the yield stress and modulus of elasticity increased with increasing strain rate and they decreased with increasing temperature, whilst the fracture strain increased with temperature and decreased with strain rate, the yield stress and modulus of elasticity were (38.34 MPa) and (2916.66 MPa) at 28°C while they were (13.62 MPa) and (2258.06 MPa) at 70°C respectively. The yield stress and modulus of elasticity increased and then decreased with increasing time of UV.

Results of impact test showed that the impact strength increased with temperature and decreased with notch depth and UV radiation. The impact strength was (34.21kJ/m^2) at 26°C whilst it was (65.38 kJ/m^2) at 48°C. The impact strength was (34.21kJ/m^2) for unexposed sample to UV while it was (29.18 kJ/m^2) for exposed sample to UV for (17 days).

Results of fatigue test illustrated that the cycles to failure decreased with increasing of stress. Also it was observed that the fatigue life decreased with increasing temperature, the cycles to failure were (334218) at 6°C while they were (4671) at 50°C. As well, the results showed that the cycles to failure increased largely when the samples exposed (17) days to UV but after this period, the cycles to failure decreased so much. The cycles to failure were (392022),(18224) and (48818) for exposed sample to UV for 17 days, 45 days and for unexposed sample to UV at the same stress (5.58 MPa) respectively.

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ABBREVIATIONS

Symbol	*Description*
ASTM	*American standard for testing material*
$CaCo_3$	*Calcium carbonates*
CRB	*Cracked round bar*
DAP	*Di-alphanyl phthalate*
DBTT	*Ductile-Brittle Transition Temperature*
DIOP	*Di-isooctyl phthalate*
DOP	*Di-ethyl hexyl phthalate*
DP	*Degree of polymerization*
ESC	*Enviromental stress cracking*
EVA	*Ethylene–vinyl-acetate*
FCG	*Fatigue crack growth*
FNCT	*Full notch creep test*
HDPE	*High-Density Polyethylene*
LEFM	*Linear Elastic Fracture Mechanics*
IFWI	*Instrumented falling weight impact test*
PA 6	*polyamide 6*
PB	*Polybutylene*
PEEK	*polyether ether ketone*
PEX	*Cross-linked polyethylene*
PMMA	*Poly(methyl methacrylate)*
PP	*Polypropylene*

PPS	*polyphenylene sulfide*
PVC	*Polyvinyl chloride*
PVC-P	*Plasticized Polyvinyl chloride*
PVC-U	*Unplasticized Polyvinyl chloride*
rpm	*Revolutions per minute*
T_g	*Glass transition temperature*
TiO_2	*Titanium dioxide*

Table (1): Results of tensile tests at (28°C) for different crosshead speeds for the gray pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	38.34	2916.66	2.1
50	40.25	3181.81	1.95
100	41.78	3233.31	0.96

Table (2): Results of tensile tests at (50°C) for different crosshead speeds for the gray pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	31.27	2692.30	2.39
50	34.13	2916.66	2.25
100	35.77	3043.47	2.11

Table (3): Results of tensile tests at (70°C) for different crosshead speeds for the gray pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	13.62	2258.06	2.94
50	16.13	2413.79	2.72
100	18.72	2500.00	2.69

Table (4): Results of tensile tests at (28°C) for different crosshead speeds for the white pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	25.31	3076.923	1.21
50	28.20	3636.36	0.81
100	29.7	4000	0.63

Table (5): Results of tensile tests at (50°C) for different crosshead speeds for the white pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	22.21	2666.66	1.61
50	24.21	2913.52	1.53
100	26.51	3334.31	1.03

Table (6): Results of tensile tests at (70°C) for different crosshead speeds for the white pipe.

Crosshead speed (mm/min)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
5	11.38	2221.20	1.81
50	13.81	2666.61	1.63
100	17.22	3076.92	1.37

Table (7): Results of tensile tests at different time of exposure to UV radiation for the gray pipe material.

The time of exposure to UV(days)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
0	38.34	2916.66	2.1
7	39.12	3013.32	1.91
17	41.67	3332.312	1.68
30	39.37	3225.8	1.85
45	37.15	3043.48	1.76

Table (8): Results of tensile tests at different time of exposure to UV radiation for the white pipe material.

The time of exposure to UV(days)	Yield stress (MPa)	Elastic modulus (MPa)	Fracture strain (%)
0	25.31	3076.92	1.21
7	25.90	3332.31	1.13
17	26.51	4000	0.94
30	25.3	3773.58	0.91
45	22.74	3637.45	1.03

Table (9): Results of impact tests at different temperatures for the two pipe materials.

Temperature (°C)	Impact strength (kJ/m^2)	
	The gray	the white
7	12.23	9.73
15	24.32	22.38
26	34.21	31.78
35	44.67	40.07
40	51.32	46.15
45	60.1	51.54
48	65.38	62.63

Table (10): Results of impact tests at different times of exposure to UV for the two pipes material.

The time of exposure to UV(days)	Impact strength (kJ/m^2)	
	The gray	the white
0	34.21	31.28
7	33.46	29.63
17	29.18	27.16
30	29.37	27.3
45	29.82	28.29

Table (11): Results of impact tests at different crack depth for the two pipe materials at room temperature.

Crack depth (mm)	Impact strength (kJ/m^2)	
	The gray	The white
0	34.21	31.78
0.25	29.51	27.32
0.5	24.34	20.11
0.75	20.51	17.21
1	16.28	12.33
1.25	12.63	9.81

Table (12): Results of fatigue test for PVC pipe material.

Stress amplitude (MPa)	Cycles to failure (N_f)
2.7949	92527
5.5898	48818
8.3848	20730
11.179	5048

Table (13): Results of fatigue test for PVC pipe material at different temperatures and constant stress (5.58 MPa).

Temperature (°C)	Cycles to failure (N_f)
6	334218
24	48818
40	21373
50	4671

Table (14): Results of fatigue test for PVC pipe material at different times of exposure to UV at constant stress (5.58MPa).

Exposure time to UV (days)	Cycles to failure (N_f)
0	48818
7	49435
17	392022
30	93463
45	18224

CERTIFICATION

We certify that this thesis, titled **” Effect of Temperature and UV on Some Mechanical Properties of PVC Pipes”** was prepared by “***Mohammed Razzaq Mohammed***” under our supervision at Babylon University in partial fulfillment of the requirements for the degree of Master of Science in Materials Engineering.

Signature:

Name: ***Asst. Prof. Dr.*** **Najim A. Saad**
(Supervisor)
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Date: **/ 3 / 2009**

In view of the available recommendation, I forward this thesis for debate by the examination committee.

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Chapter One
Introduction

1-1 Introduction

The introduction of the plastic pipe early in the 20th century brought revolutionary changes in piping system engineering and material specification. Selecting suitable piping materials depends on the substance being transported and on the specific service conditions. Some of the characteristics of plastics may be favourable or unfavourable, depending on the particular service conditions and the type of plastic. The effect of some unfavourable attributes can be reduced or eliminated through proper design and installation of the pipes. Choosing the right material therefore requires a thorough knowledge of the physical features of various plastics [1].

The dominance in the versatility of polymers used for industrial piping is disappearing in importance when the status of polymers in the ranking of all possible materials used in piping systems is considered [2].

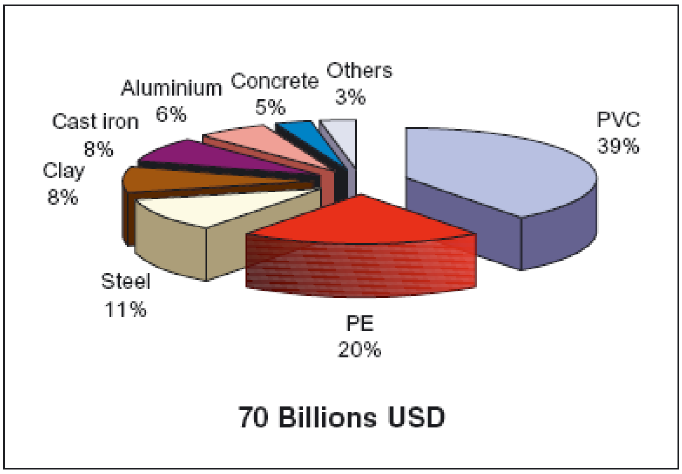


Fig.(1-1): Global piping market 2002 / Ranking of materials[2].

1-2 Materials for pipes industry

1-2-1 Copper and Stainless Steel Piping

Copper and stainless steel are “passive” metals. Passive metals corrode rapidly but quickly form a tight, protective corrosion layer that serves as a thin film to protect the metal from the environment and prevent further corrosion. The dull coating that forms on a shiny penny is a good example. In the right environments, pipes made from passive metals can have very long lives. For this reason, copper has long been a preferred material for residential water supply piping. However, pitting corrosion on the inside of the pipes and the resulting pinhole leaks in copper piping have become widespread problems in many areas of the United States, coinciding with the introduction of requirements for cleaner drinking water. The more aggressive corrosive features of cleaner water, the use of chemicals to flush water systems, particles that are freed and then deposited on the pipe walls by the flushing, or a combination of these factors are generally thought to contribute to the corrosion.

In any case, the end result is randomly spaced corrosion cells where the protective film on the pipe wall is breached. These corrosion cells rapidly progress into pinhole leaks [3].

1-2-2 Galvanized Steel Piping

Galvanized pipe has been popular because of its low cost and relatively long life in most, but not all, water supplies. Galvanized piping relies on a zinc coating that corrodes before the pipe base material. Ultimately, however, the base material will corrode once the zinc coating is consumed. Selective corrosion of the zinc coating produces thick layers of loose deposits that can reduce the inside diameter of the pipe, sometimes to the point of obstructing the flow through the pipe [3].

1-2-3 Cast iron piping

The corrosion of cast iron pipe in drinking water distribution system will cause many problems such as clogging , offering habit for pathogen or opportunity pathogen , bringing unpleasant color, lowering the pressure resistance, engendering water supply accident and so on, thereby accelerating water quality deterioration and aggrandizing the threat to human health. Consequently cast iron, especially grey cast iron, is prohibited in many developed countries. However, grey cast iron pipes have been widely used for decades and for economic reason it is difficult to substitute them with plastic or stainless steel pipes immediately. Thus, their usage in drinking water industry will still last for some years, and the research about the corrosion of cast iron pipes is still of great importance [4].

Nowadays two types of cast iron are found on the market: the gray- and ductile cast iron. Both are one and the same alloy of less than 1.7% C in iron. In gray cast iron the carbon is present in a flaky form, whereas it is spheroidal in the ductile type, which improves the elongation and impact resistance of the material. The corrosion properties of the casts are similar[5].

1-2-4 Polybutylene Piping

Polybutylene (PB) piping was popular for residential use 10 to 20 years ago. This piping was easy to install, less bulky than PVC piping, and suitable for both hot and cold water service. The piping was installed with barbed fittings and compression rings that were crimped onto the piping to secure (or “swage”) it to the fittings.

The plastic fittings used with this piping system degraded over time and frequently resulted in leaks and consequent property damage. The later PB systems used metal fittings, but leaks at fittings persisted. PB piping has been taken off the market because of the leak problems, and homes with this piping are being repiped [3].

1-2-5 Polyethylene Piping

HDPE pipes are used to carry potable water, wastewater, slurries, chemicals and hazardous waste. They are also used in cables and for the transportation of oil and compressed gases. It is, therefore, most probable that small pieces of these pipes are recovered from scenes of pipe burst, explosions and also in theft cases [6].

Cross-linked polyethylene (PEX) piping is a relatively new product that is gaining popularity for water supply systems. It is formulated by several different processes that result in piping that consists of only one long, crosslinked molecule. Cross-linked polyethylene piping is installed in a similar method to PB piping and is suitable for both hot and cold water use. Unlike other plastic piping, PEX piping is not as readily damaged when the water in the piping freezes. The earlier PEX piping was translucent and would degrade in UV light, making it unsuitable for prolonged exposure to sunlight or strong artificial light. The newer PEX piping has added carbon black to increase resistance to UV light.

The carbon black makes the pipe opaque. The pipe is now available in several different colors (red pipes for hot water and blue pipes for cold water). There is some documentation indicating that PEX piping can become brittle over time due to chlorine additions to water or other contaminants that come in contact with the pipe. It is too early, however, to judge the effective service life of this type of piping [3].

1-2-6 composite pipes

Instead of conventional carbon steel pipes, composite pipes are increasingly used in the oil and gas industry. This is due to their better

corrosion resistance compared with steel pipes. The first composite alternatives to steel pipelines were composite pipes based on thermoset matrices. The properties of thermoset composites are well known and documented. On the other hand, filament wound composite pipes made of fiber-reinforced plastics have many potential advantages such as high specific stiffness and strength, good corrosion resistance and thermal insulation. With the development of manufacturing technology to product filament- wound pipes, there has been a growing interest in the application of the FW fiber-reinforced cylindrical composite structures.
A common requirement of such products is that they must safely bear a certain working pressure [7].

1-2-7 Concrete pipes

Most sewer pipes are gravity pipes, there the wastewater is flowing without internal pressure in the pipe. There are no shear stresses in the pipe wall, but the pipe wall has to resist the pressure stresses originating from the external soil pressure. In 1986 87 % of wastewater pipes was made of concrete material, which is able to resist pressure stresses. In sewage pipes there the wastewater is pumped the choice of materials is the same as for water distribution pipes. The rate of corrosion of concrete pipes depends on the strength and density of concrete, the degree of acid penetration, the acid value and the circulation of hydrogen sulfide in the atmosphere. An important influence on the rate of corrosion is exerted by the geometry of the pipes and the filling capacity [8,9].

1-2-8 Polyvinyl chloride pipes

Polyvinyl chloride (PVC) piping systems are some of the oldest plastic piping systems and are well known for significantly reducing the cost of plumbing [3].

By 1932, the first tubes made from a PVC copolymer were produced. Nearly three years later the first PVC pipes were produced using a roll mill and hydraulic extruder. This two step process involved melting the PVC powder on a roll mill and rolling the sheet produced up to a billet. The PVC could then be processed in a discontinuously working ram extruder to make pipe. This process was adapted from that used for celluloid and was really ill-fitted for PVC. As a result, the products were often of dubious quality.

Nevertheless, these early PVC pipes were deemed suitable for drinking water supply piping and waste water piping because of their chemical resistance, lack of taste or odor and smooth interior surface [10].

PVC offers a host of properties that have made it the dominant water and sewer utility pipe material [11]:

●Corrosion Resistance / Durability

PVC is invulnerable to underground external corrosion as well as internal pipe corrosion. This eliminates the need to specify corrosion protection methods that have become standard procedure for metal piping. For sanitary sewers, PVC pipe is resistant to virtually all the chemicals found in domestic and industrial wastewater. In addition, PVC pipe is highly resistant to erosion or abrasion wear [11].

●Strength

When properly designed and installed, PVC pipes can handle external loads up to 75,000 kg/m^2 (about 40 meters of ground cover) and are available with internal pressure ratings up to 2,100 kPa (305 psi). PVC pipes also are able to bend or flex without breaking, making them better suited to handle ground movements caused by unstable, shifting soils and earthquakes [11].

●Water Quality

PVC water pipe delivers water as clean and pure as it receives. It imparts no taste or odor to the water it transports, isn't a source of lead or other chemical contaminants associated with metal pipe, and does not react with even the most aggressive water [11].

●Superior Flow

PVC's resistance to internal corrosion also eliminates tuberculation – the build-up of corrosion by-products that can reduce hydraulic capacity and increase pumping costs. PVC pipe's smoother internal wall surface minimizes fluid friction and flow resistance. The need for cleaning and maintenance are reduced, thereby lowering operating costs [11].

●Superior Strength-to-Weight Ratio

Fewer pounds of material are required to manufacture a foot of PVC pipe versus a foot of metal or concrete pipe. That weight advantage is quite significant. Not only does it make PVC more economical on a per-foot basis, it also conserves resources, lowers shipping costs, simplifies and reduces the time needed for installation, and decreases the number and severity of injuries for installation crews. Collectively, these advantages result in lower installed costs [11].

1-3 Failure of a PVC Pipe

Failures of PVC pipes and fittings are quite common. The causes of failure that we have identified are summarized in Table (1-1)[12].

Table (1-1): Causes of pipe failure [12].

Type of failure	Root Cause of Failure
Resin Defects	MW too low
	crystallinity too low
	filler content too high
Manufacturing Defects	incomplete fusion of resin particles
	voids or particulates in pipe/fitting
Improper Installation	excessive glue inside pipe
	clamps too far apart
	clamps too tight
	wrong clamps/contact with other pipes
	no allowance for thermal expansion
	wrong antifreeze
	pipes not aligned
	ESC due to contamination
	short insertion
	over-insertion overbelling
Improper Operation	water hammer
	over pressurization
	area contamination
Abuse by Distributor	stored in sun
	damaged during handling/transport

1-4 Literature Review

Haleem (1999) studied the effects of temperature (0-70°C) and notch depth on the impact strength of araldite, vinyl ester and polyester without or with reinforcement through the glass fibers (woven roving) and hybrid composite materials contained two types of fibers and the other contained three types of fibers (glass, Kevlar and carbon). It was found that the impact strength increased with temperature and decreased with notch depth for all composite materials and reinforced with glass fiber, showed the higher impact strength than the others [13].

Parsons et al (2000) studied the effects of R-ratio (0.1 to 1.0) and temperature (21 to 80 °C) on the mechanism and kinetics of slow crack propagation in a medium density polyethylene pipe material. It was found with increasing R-ratio and decreasing temperature, the fracture mode changed from stepwise crack propagation, i.e. crack growth by the sequential formation and breakdown of a craze zone, to a ”quasi-continuous” mode of crack growth through the preexisting craze [14].

Wang et al (2002) studied tensile properties of extruded short E-glass fiber reinforced polyamide-6 composite sheet at different temperatures (21.5°C, 50°C, 75°C, 100°C) and different strain rates (0.05/min, 0.5/min, 5/min). It was found that the elastic modulus and tensile strength of the composite increased with strain rate and decreased with temperature [15].

Cheng and Chen (2004) studied the mechanical properties and strain-rate effect of neat PMMA and EVA/PMMA blends. They found that while the EVA/PMMA blends are investigated at room temperature over the strain rates of four decades (from $1.6x10^{-4}$ to $0.16\ s^{-1}$). It has an obvious transition, whereas the neat PMMA remains brittle over the entire range of strain rates[16] .

Kanny and Mahfuz (2004) studied the effects of frequency on the fatigue behavior of S2 glass fiber–vinylester reinforced sandwich composites with two different PVC cores. It was found that the fatigue strength increased with core density, and the number of cycles to failure, N_f, increased with increase in frequency and crack growth rate decreased with increase in loading frequency [17].

***Lara et al* (2004)** studied the kinetics and mechanism of fatigue crack growth in poly(vinyl chloride) (PVC) compounds of different molecular weight. It was found that the fatigue crack propagation resistance improved with increasing molecular weight of the resin. Fatigue crack growth followed the Paris law with a power (m= 2.7) for all compounds at all fatigue rates and temperatures. Stepwise fatigue crack propagation through a crack-tip craze zone was observed in all the compounds studied[18].

Tanniru and Misra, (2005) investigated the micromechanism of plastic deformation during impact loading of 20% calcium carbonate-reinforced polyethylene micrometric composite through scanning electron microscopy and atomic force microscopy and the behavior compared with the un-reinforced polyethylene under identical conditions of processing. It was found that the addition of calcium carbonate to polyethylene increases impact strength in the investigated temperature range of (−40 to +70 ◦C) and alters the primary micromechanism of plastic deformation from crazing–tearing and brittle behavior in neat polyethylene to particle-induced cavitation and fibrillation in the composite[19].

Ferreira et al (2005) studied the fatigue properties of aluminized glass fiber composite with epoxy and polyester matrix and its comparison to conventional glass fiber composites. The tensile strength of aluminized composite is lower than uncoated composites. This is associated with the fabrication defects and the much lower strength of the aluminum interface when compared to uncoated glass fibers. The potential drop values were enough accuracy to quantify fatigue damage, presenting a well defined increasing tendency with the number of cycles and with the fatigue stress level. During the subcritical fatigue process potential drop presents an almost linear relationship with the loss of rigidity [20].

Mohammadian et al (2006) studied the effects of blending and processing conditions, such as sheet temperature and strain rate on the hot tensile properties and rheological properties of ternary blends of PP/HDPE/EPDM. It was found that the elastic modulus, load at yield and the post yield modulus decreased in comparison with original PP [21].

Hassan and Haworth (2006) investigated the effect of temperature on the impact strength of acrylate rubber-modified PVC-U using the instrumented falling weight impact test (IFWI) method. It was found that all the acrylate rubber-toughened PVC blends have successfully shifted the ductile–brittle transition points to a lower temperature and the findings from the SEM study showed that the fibrous yielding phenomenon observed is an indication of the transition of the brittle stage to ductile stage and correlates well with the large increases of the impact strength[22].

Khalid (2006) studied the effect of fiber volume fraction and testing temperature on the impact energy of the woven roving aramid and glass/epoxy composite specimens by using Charpy impact tests. the impact tests were conducted for a temperature range of 40 to -40°C in intervals of 10. Results showed that a slight increase on the impact energy of composite specimens with temperature increase for the range of -40 to -10°C. It was found that the aramid/epoxy support higher impact energy than the glass/epoxy at all the tested temperatures and the increase in fiber volume fraction decreases the impact energy absorbed for both of glass and aramid/epoxy[23].

Merah et al (2006) studied the combined effects of temperature and frequency on FCG properties of commercial HDPE pipe material. It was found that the crack growth resistance decreased with increase in test temperature and decrease with frequency[24].

Shindo et al (2006) studied the tension–tension fatigue behavior of woven glass fiber reinforced polymer laminates at cryogenic temperatures. Tension–tension fatigue tests at frequencies of 4 and 10 Hz with a stress ratio of 0.1 were conducted at room temperature, 77 and 4 K. The observed S–N curves showed the usual trend that as the maximum applied stress increases, the fatigue life decreases[25].

Kultural and Eryurek (2006) investigated the fatigue behavior of polyproylenes filled with three different percentages of $CaCO_3$ (0%, 20%, and 40%) by using the tensile–tensile cyclic loading at different frequencies of 23 and 50 Hz . It is reported that filler content influences the fatigue performance. Increasing the filler content reduces the fatigue performance of PP from pure to PP40, respectively, if normalization effects are not included [26].

Fiedler et al (2007) studied UV degradation of polychloroprene through testing tensile bars exposed to UV radiation at 350 nm for different lengths of time. They found that the elongation of the tensile bars decreased significantly with increasing duration of UV radiation. As they found that the tensile strength of polychloroprene specimens decreases with increasing radiation [27].

Alcock et al (2007) studied the mechanical performance of all-PP composites by measuring the mechanical properties of highly oriented PP tapes and subsequent all-PP composites at a range of temperatures by static and dynamic testing methods. They found that the tensile strength of all-PP decreases with increasing temperature in two linear regions, with a transition at 90°C [28].

Shan et al (2007) investigated the effects of the draw temperature and the strain rate on the tensile deformation of polyamide 6 (PA6) using three PA6 samples with different initial shapes and physical dimensions[29].

Khojin et al (2007) studied the impact strength sandwich composites with Kevlar/hybrid and carbon facesheets subjected to different temperatures. They found that the impact performance of these composite sandwiches changed over the range of temperature and that testing at ambient temperature is not sufficient in the development and full understanding of composite sandwich damage properties[30].

Pinter et al (2007) presented a method to characterize crack growth resistance of PE pipe using fatigue loading of cracked round bar (CRB) specimens. The method was applied to five commercially available PE pipe materials and the results were compared with the full notch creep test (FNCT). The same ranking was found with both methods, but it was obvious that fatigue crack growth (FCG) experiments were faster by up to two orders of magnitude, especially when characterizing modern (bimodal) PE types [31].

1-5 Aim of study

Because of using the PVC pipes over and under the ground and water supply systems, they will be suffered different conditions, that will be led to the failure.

The objectives of this study are:

1- Investigation of the effects of strain rate (crosshead speed) and temperature on tensile properties of PVC pipe material. Also

Investigation of the effect of temperature on impact strength and fatigue behavior of PVC pipe material.

2- Investigation of the effect of UV radiation on tensile properties, impact strength and fatigue behavior of PVC pipe material.

Chapter Two
Theoretical part

2-1 Introduction

Polymer is a large molecule built up by the repetition of small, simple chemical units. In some cases the repetition is linear , much as a chain is built up from its links. In other cases chains are branched or interconnected to form three dimensional networks. The repeat unit of polymer is usually equivalent or nearly equivalent to the monomer, or starting material from which the polymer is formed. The repeat unit of poly (vinyl chloride) is-CHCHCl-; its monomer is vinyl chloride, CH=CHCl.

The length of the polymer chain is specified by the number of repeat units in the chain. This is called the degree of polymerization (DP). The DP is also defined as the number of repetitions of mers in a polymer chain.

Mathematically ,

$$DP= \frac{\text{Molecular weight of polymer}}{\text{Molecular weight of a single monomer}} \quad \ldots\ldots\ldots\ldots\ldots\ (2\text{-}1)$$

The molecular weight of the polymer is the product of the molecular weight of the repeat unit and the DP. As an example, poly (vinyl chloride). A polymer of DP 1000 has a molecular weight of 63 X 1000 = 63,000. Most high polymers useful for plastics, rubber, or fibers have molecular weight between 10,000 and 1,000,000. The molecular weight increases with the size of the molecule. The molecules having low DP are called oligomers, the oligo meaning few. Usually, the term polymer is used for macromolecule, i.e. a large size molecule [32].

The first polymers used were natural products, especially cotton, starch, proteins, and wool. Beginning early in the twentieth century, synthetic polymers were made. The first polymers of importance, Bakelite and nylon, showed the tremendous possibilities of the new materials[33].

Polymers can be made that contain more than one type of repeat unit. Such polymers are called copolymers. The presence of more than one type of repeat unit opens up many possibilities for variation in the structure of the polymer, or chain architecture as it is sometimes called. If the two monomers of a bi-component copolymer are perfectly alternating, an alternating copolymer results, as shown in Figure (2-1a). If the monomer units alternate in a random fashion, a random copolymer results, as in Figure (2-1b). Figure (2-1c) shows a block copolymer, in which the different monomers prefer to add to each other, resulting in large segments of one type of monomer, followed by large segments of the other type of monomer. Finally, a second type of monomer can be added as a branch to a polymer backbone, as shown in Figure (2-1d), resulting in a graft copolymer. These different types of copolymers can have markedly different physical properties and are the basis for many important materials in the healthcare and consumer products industries [34].

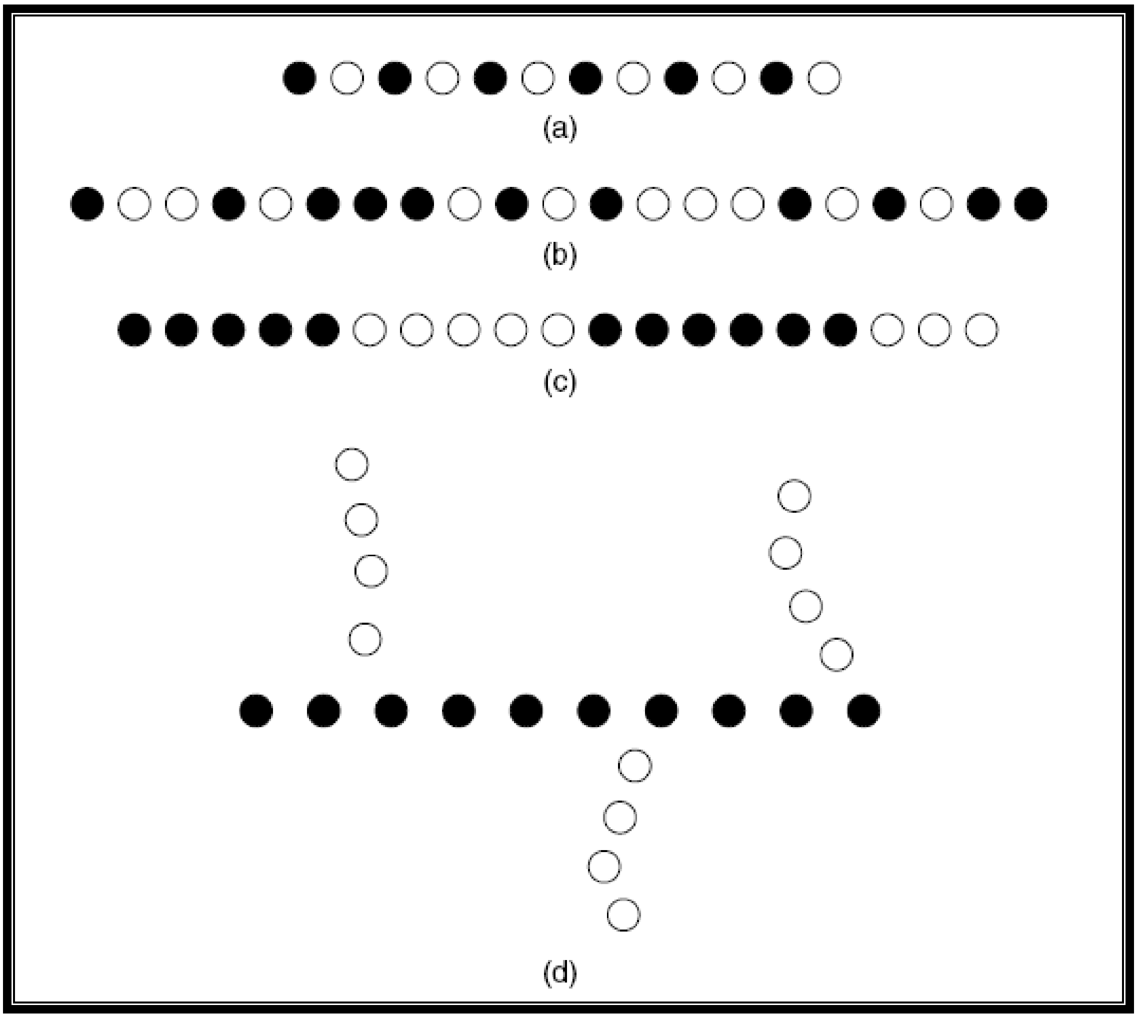


Fig. (2-1): Summary of copolymer classifications: (a) alternating, (b) random, (c) block, and (d) graft [34].

2-2 Classification of polymers

There are many possible classifications of polymers. One is classifications based on structure: linear, branched or network polymers. Figure (2-2) shows these types of polymer schematically. It should be noted that the real structures are three-dimensional, which is particularly important for networks [35].

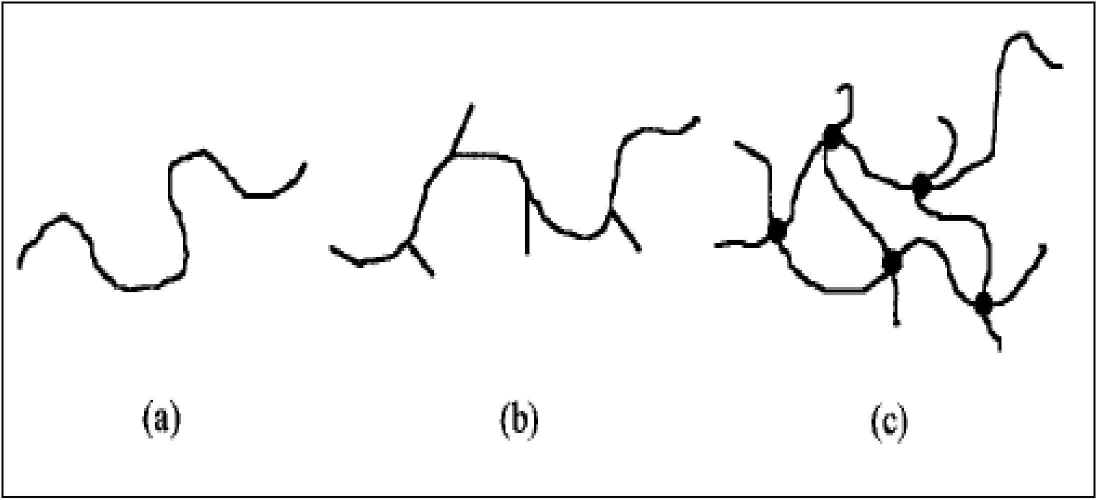


Fig. (2-2): Schematic representations of (a) a linear polymer, (b) a branched polymer and (c) a network polymer [35].

Polymers are broadly classified in three categories[32]:

i) Plastics

ii) Elastomers

iii) Fibers

2-2-1 Plastics

These are the organic material that can easily shaped or moulded by mechanical or chemical action, with or without the application of heat. Plastic materials may further be classified as thermoplastic or thermosetting[36].

2-2-1-1 Thermoplastics

The plastics which soften on heating and harden on cooling in a reversible fashion are called thermoplastics. No chemical reaction occurs during the heating cycle. Thus heating and cooling cycles can be repeated any number of times to obtain a desired shape. The transformation can represented by:

$$\text{Thermoplastic} \xrightarrow{\text{Heat}} \text{softens} \xrightarrow{\text{cool}} \text{Hard}$$

This characteristic of the thermoplastics is attributed to their linear chain structure and absence of cross-bonding between the molecules. The linear chain molecules are held together by weak secondary bonding. In the soft or molten state, linear polymers behave as rubber-like liquids with distinct viscoelastic properties. They display features of elastic materials as well as liquids. The above characteristic has made it possible to recycle the waste thermoplastic products. In the solid state they may exist as glassy material such as polymethyl methacrylate (PMMA) or partially crystalline material such as nylon.

The most common commodity thermoplastics are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS) [34,36].

2-2-1-2 Thermosets

Thermosets are network polymers that are heavily cross-linked to give a dense three-dimensional network. They are normally rigid. They cannot melt on heating and they decompose if the temperature is high enough.

The most common types of thermosets are the phenolformaldehydes (PF), urea-formaldehydes (UF), melamine-formaldehydes (MF), epoxies (EP), and polyurethanes (PU) [34,36].

2-2-2 Elastomers

ASTM D1566 defines elastomers as “macromolecular materials that return rapidly to approximately the initial dimensions and shape after substantial deformation by a weak stress and release of the stress.

Elastomers, when compared with other engineering materials, are characterized by large deformability, lack of rigidity, large energy storage capacity, nonlinear stress-strain curves, high hysteresis, large variations in the stiffness, temperature, and rate of loading, and compressibility of the same order of magnitude as most liquids. Certain of the elastomeric materials possess additional useful characteristics to a relative degree, such as corrosive chemical resistance, oil resistance, ozone resistance, temperature resistance, and resistance to other environmental conditions. The common elastomers are natural rubber, styrene butadiene rubber, acrylonitrile butadiene rubber, chloroprene [32,37].

2-2-3 Fibers

These consists of long molecular chains and all the chains are aligned in the direction of length of the fiber. The directional properties are improved by alignment, i.e. the strength of fibers are greatly enhanced in the direction parallel to the fiber length. These provide strength to the molecular units.

The fiber polymer are quite capable of being drawn into long filaments having at least a 100:1 length to diameter ratio. Some polymers used as fibers, such as nylon and cellulose acetate, serve equally well as plastics[32].

2-3 Polyvinyl chloride (PVC)

Polyvinyl chloride (PVC) is one of the most widely used plastics in the vinyl family. Poly(vinyl chloride) (PVC) has been, for more than 70 year, one of the most important polymers, and it is the second most produced thermoplastic resin, placing after polyolfins and before styrene polymers, with a worldwide capacity of more than 31 million tons (i.e.,ca.20% of the total plastic production) [38].

Sodium chloride (salt) and natural gas or oil are the resources necessary to make polyvinyl chloride (Figure 2-3). Electricity is passed through a salt solution to produce chlorine, while the oil or gas undergoes a cracking process to produce ethylene. The next step involves causing a reaction between the two gases to produce ethylene dichloride, which then undergoes another cracking process to produce vinyl chloride monomer. This is then polymerized- the molecules joined together – to produce a sludge which is centrifuged and dried to achieve polyvinyl chloride in the form of a white powder [39].

PVC is prepared by the polymerization of vinyl chloride in a free radical-addition polymerization reaction. The polymer can be made by suspension, emulsion, solution, or bulk polymerization methods. The polymer is essentially linear, but a low number of short chain branches may exist. The structure of the PVC repeating unit is represented as $(CH_2CHCl)_n$.

PVC is self-extinguishing and, therefore, has applications in the field of flame resistant wire and cable. PVC’s good flame resistance results from removal of HCl from the chain, releasing HCl gas. Air is restricted from reaching the flame because HCl gas is denser than air. PVC also has excellent resistance to acids, bases, alcohol, oils, and many other hydrocarbons. It thus finds applications in parts for the chemical processing industries.

There are two basic forms of PVC: rigid and plasticized. Rigid PVC is an unmodified polymer and exhibits high rigidity. It is stronger and stiffer than polyethylene (PE) and polypropylene (PP). Plasticized PVC is modified by the addition of low-molecular-weight plasticizers to flexibilize the polymer.

Plasticized PVC can be formulated to give products a rubbery behavior. PVC resins are generally heavily compounded with additives to improve properties. A wide variety of applications for PVC exist because one can tailor the properties by the selection of additives.

Rigid PVC can be processed using most conventional processing equipment. Because HCl is given off in small amounts during processing, corrosion of metal parts is a concern. PVC joints can be solvent- or heatwelded.

Plasticized PVC can be processed by methods such as extrusion and calendering into a variety of products.

Rigid PVC is used in products including house siding, extruded pipe, and thermoformed and injection-molded parts. Rigid PVC is calendered into credit cards.

Plasticized PVC is used in applications such as flexible tubing, floor mats, garden hose, shrink wrap, and bottles[37].

Table (2-1) shows the general physical, mechanical and thermal properties of PVC [1].

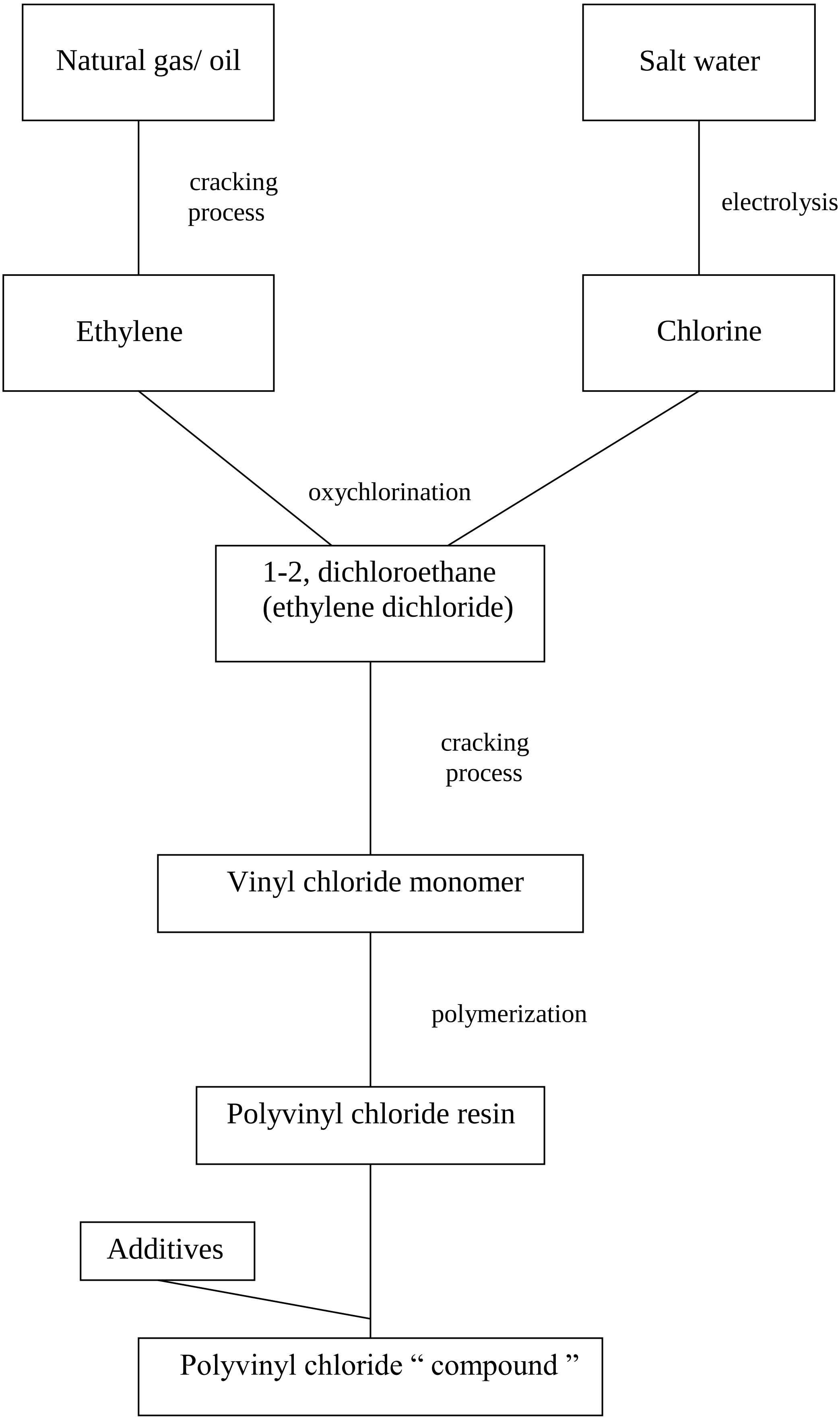

Natural gas/ oil
Salt water
cracking process
electrolysis
Ethylene
Chlorine
oxychlorination
1-2, dichloroethane (ethylene dichloride)
cracking process
Vinyl chloride monomer
polymerization
Polyvinyl chloride resin
Additives
Polyvinyl chloride " compound "

Fig. (2-3): The PVC production process [39].

Table (2-1): Properties of PVC [1].

Property	Unit	Value
Physical properties		
Molecular weight		14000
Relative density		1.42
Water absorption	%	0.12
Mechanical properties		
Ultimate tensile strength	MPa	52
Elongation at break	%	50-80
Short term creep rupture	MPa	44
Long term creep rupture	MPa	28
Elastic tensile modulus	GPa	3.0-3.3
Elastic flexural modulus	GPa	2.7-3.0
Long term creep modulus	GPa	0.9-1.2
Shear modulus	GPa	1.0
Bulk modulus	GPa	4.7
Impact strength: 20 ℃	kJ/m^2	20
Impact strength: 0 ℃	kJ/m^2	8
Coefficient of friction		0.4
Poisson's ratio		0.4
Thermal properties		
Softening point	°C	80-84
Max continuous service temperature	°C	60
Coefficient of thermal expansion	/k	$7x10^{-5}$
Thermal conductivity	W/[m.k]	0.16
Specific heat	J/[kg.k]	1000
Thermal diffusivity	m^2/s	$1.1x10^{-7}$

2-3-1 Applications of PVC

Window frames, drainage pipe, water service pipe, medical devices, blood storage bags, cable and wire insulation, resilient flooring, roofing membranes, stationary, automotive interiors and seat coverings, fashion and footwear, packaging, cling film, credit cards, synthetic leather and other coated fabrics[40].

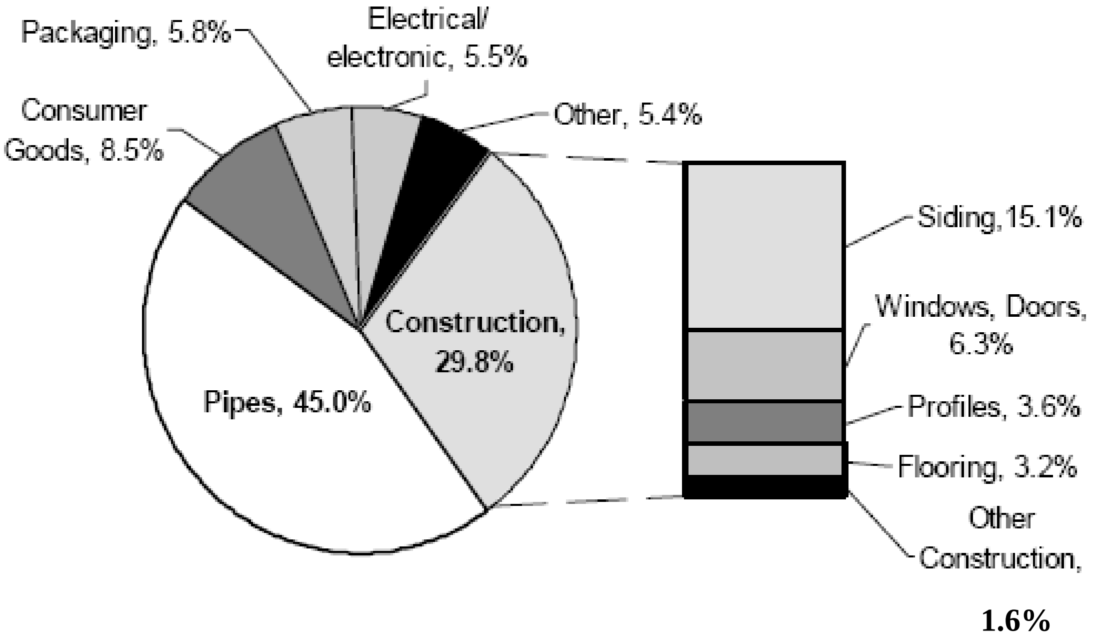


Fig. (2-4): Uses of PVC in US and Canada, 2002[41].

2-3-2 PVC Additives

Polymers are rarely used in their virgin form, that is, the form obtained from the manufacturing plants after isolation and purification. With some exceptions (such as PS, PE and PP), pure virgin polymers are not suitable for processing straightaway[36].

2-3-2-1 Fillers

Fillers are commonly employed in opaque PVC compounds to improve strength: to reduce cost and to improve dimensional stability, to improve electrical insulation properties, and to control the gloss. Various calcium carbonates are most commonly used fillers for PVC. Calcium carbonates ($CaCO_3$) are mineral fillers. They are supplied in five particulate forms: water-ground, dry-ground, ultra fine ground, precipitated, and surface treated [42]. The advantages of $CaCO_3$ over other mineral fillers for use in PVC include: lower cost, non-toxicity, transparency, low moisture content, easy coating ability and the acid-acceptance capability providing a degree of secondary stabilization for PVC during processing.

Approximately 80% of all the filler used in PVC is calcium carbonate. Titanium dioxide is second at around 12%, followed by calcined clay at about 5%. The remaining few percent is taken up by other materials, including glass and talc[43,44].

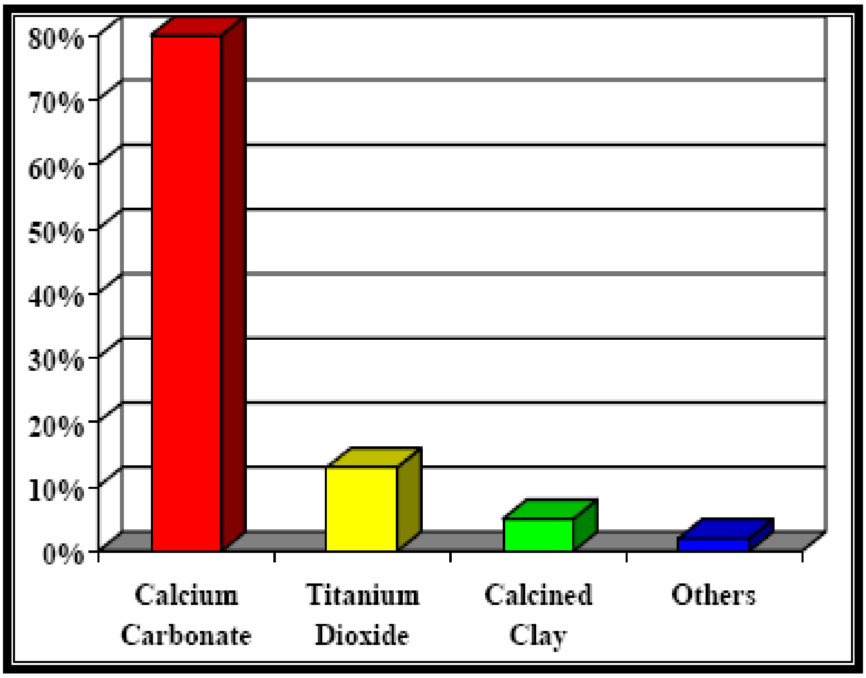


Fig. (2-5): Fillers are used with PVC [44].

2-3-2-2 Heat stabilizers

Heat stabilizers are used primarily to inhibit thermal degradation of PVC during processing. At elevated processing temperatures. PVC is subject to dehydrochlorination which will lead to an "unzipping" effect and results in degradation. To make the problem more complicated, the HCl given off during dehydrochlorinaton is a catalyst to further dehydrochlorinaton. Heat stabilizers for PVC must essentially perform two functions. First, they are added to prevent the dehydrochlorinaton from occurring initially. Secondly, the stabilizers are intended to react with the HCl given off, thus to slow the autocatalytic effect.

Some stabilizers perform both functions with a single product while some other stabilization systems require two or more additives to fillful the entire task.

The development of effective heat stabilizers is one of the major breakthroughs which allows PVC to be commercialized in such a wide variety of applications.

The types of heat stabilizers available for PVC include organotin compounds, mixed metal systems consisting of barium-cadmium (Ba-Cd), barium-zinc (Ba-Zn) or calcium-zinc (Ca-Zn), as well as lead-based systems. The type of heat stabilizer used depends on the applications. Organotin stabilizers are the common compounds used for PVC products. The tin content varies depending on the end-use[45].

Lead, despite all the discussions about its toxicity, is still the most used PVC stabilizer (Table 2-2) [38].

Table (2-2) consumption of PVC stabilizers on Europe in 1988 (in tons)[38].

Lead	120,000

Organotin	15,000
Mixed metal	15,000
Cadmium	0,05
Light stabilizers	6, 000

2-3-2-3 Plasticizer

Plasticizers may be defined as non-volatile solvents added to polymeric material to soften and render them plastic or flowable for easy processing.

They also reduce hardness, rigidity and brittleness of the polymers. The action of a plasticizer is considered to be the weakening of the intermolecular forces between macromolecules thereby enabling molecular chains to slide freely past one another. This results in greater flexibility and plasticity of the material but at the same time reduction in its tensile strength and chemical resistance. Because of the poor compatibility of plasticizers with highly crystalline polymers, their use is confined to amorphous polymers or polymers with low degree of crystallinity [36].

The addition of plasticizer to PVC changes its mechanical properties. It was demonstrated that the addition of small amounts of plasticizer could cause changes of all mechanical properties. For example, as depicted in Figure (2-6), after adding some certain amount of di-ethyl hexyl phthalate (DOP), it was observed that impact strength went down until 17% were added; then it started to go back up. Tensile strength increased until 8% were added and then decreased [46].

Phthalates prepared from alcohols with about eight carbon atoms are by far the most important class and constitute more than 70% of plasticizers used. For economic reasons, di-isooctyl phthalate (DIOP), DOP, and the phthalate esters, often known as di-alphanyl phthalate

(DAP) are used. Di-butyl phthalate and di- isobutyl phthalate are also efficient plasticizers [45].

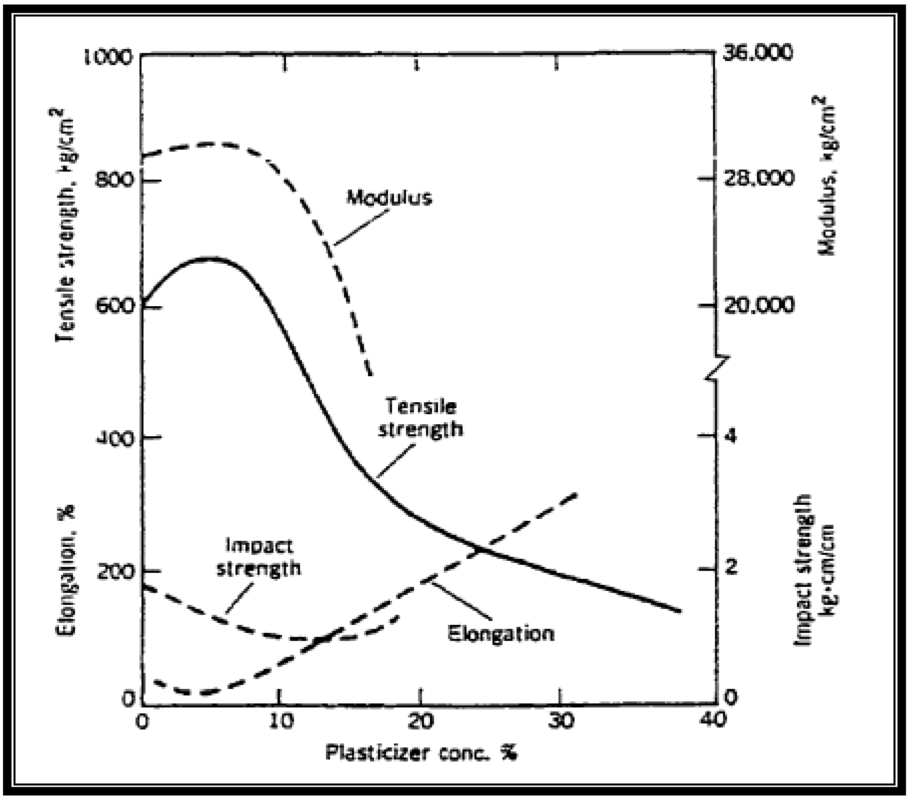


Fig. (2-6): Mechanical properties of PVC plasticized with various concentrations of DOP [45].

The stress–strain curves in tension of PVC/DOP blends prepared at 30 rpm are shown in Fig. (2-7). These results are typical for hard and brittle materials for blends with 10 phr of DOP, soft and tough for mixtures with 50 and 90 phr [47].

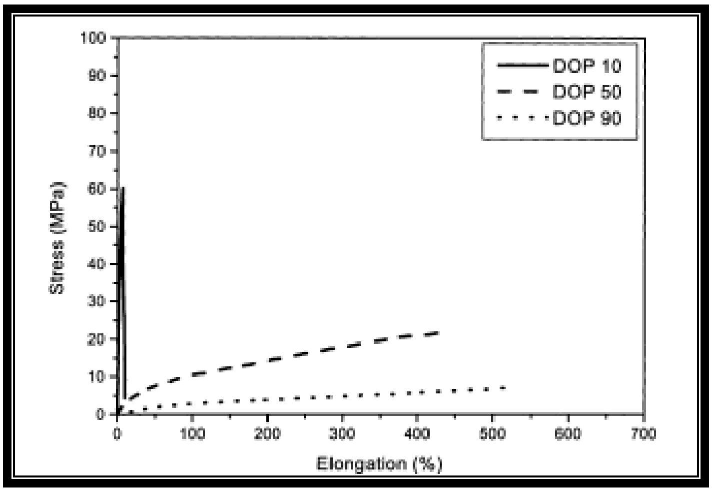


Fig. (2-7): Stress–strain curves of PVC/DOP extruded at 30 rpm[47].

2-3-2-4 UV Absorbers

UV (ultraviolet) radiation of wavelength 310nm is often considered the most damage to PVC. This range of wavelength excites the macromolecules of PVC in the sense of imparting excess energy sufficient to break bonds in the molecular chains. As a result, the free radicals formed initiate and participate in the degradation process which is accelerated by the presence of oxygen.

A variety of additives are available for the protection of plastics from degradation by ultraviolet (UV) light. The choice of UV stabilizer depends on such factors as the application, the polymer’s characteristics (particularly its absorption spectrum), the stabilizer’s effect on color, and the product’s expected life. Another factor that should be considered is toxicity, because most organic UV stabilizers tend to migrate to the surface.

The UV-protective additives which are frequently included in PVC for outdoor use afford additional and complementary protection. They absorb and dissipate die incident UV radiation, essentially before it can initiate degradation.

Carbon black and TiO_2 widely used as pigments for plastics, have a light stabilizing effect on many polymers including PVC. They are often referred to as "light screens". Each compound functions as a physical barrier to both UV and visible radiation[48].

2-3-2-5 Lubricants

While the addition of a lubricant in PVC-P is beneficial, for PVC-U it is essential.

The main function of the lubricants is to prevent sticking of the compound made of PVC and additives to processing equipment. Therefore, lubricant control the frictional and adhesive properties of plastics during processing and in service. Furthermore lubricants improve the dispersion of fillers and pigments in plastics and better dispersion could improve flow limits that which means better processing as well as material properties. Examples of these lubricants include stearic acid or other carboxylic acids, paraffin oils, and certain alcohols and ketones for PVC.

Lubricants are often classified as external or internal. The external lubricants have limited compatibility such that they will sweat out during processing to form a film between the bulk of the compound and the metal surfaces of die processing equipment.

They are considered to retard fusion or to promote metal release. Calcium stearate and lead stearate are often used as external lubricants.

Interna1 lubricants are mainly intended to improve the flow of the melt, or to reduce the melt viscosity. Unlike external lubricants they are reasonably soluble in PVC and have limited effect on fusion. Lubricants are more like plasticizers in their behavior at processing temperatures, whereas at room temperature, this effect is negligible. Wax derivatives, and long-chain esters are used as internal lubricants[48,49].

2-3-2-6 Pigments

Many pigments are available commercially for use with PVC. Pigment selection should be based on the pigments ability to withstand process conditions, its effect on stabilizer and lubricant, and its effect on end-use properties.

Most often used pigments are carbon black and titanium dioxide (TiO_2) [48].

2-3-2-7 Flame Retardants

The flammability is a major concern for polymeric materials, especially in the manufacturing of textile goods and children's toys. The inherent flame retardence in PVC means you can use less of an expensive flame retardency additive. Tritolyl phosphate and trixylyl phosphate are often used in PVC. Halogenated compounds such as chlorinated paraffins may also be used [32,50].

2-3-3 Processing of PVC

PVC raw materials are available as resins, lattices, organosols, plastisols, and molding compounds. Fabrication methods include injection, compression, blow or slush molding, extruding, calendering, coating, laminating, rotational and solution casting, and vacuum forming[37].

The word "extrusion" has its origin in the Greek root that means "push out". In the process of extrusion, the plastic material is continuously pushed or pumped through a die to produce a variety of continuous forms having constant cross-section.

The principle of extrusion is based on ability of thermoplastic to be formed into various shaped by the application of heat and pressure.

The machine is a mixing device cum pressure vessel and basically consists of two components: an extruder and a die. The extruder is mainly composed of a barrel with a screw rotating in it. The extruder barrel is further divided into three zones namely feed, compression and melting (metering) zones. The feed zone starts at the hopper end. Its function is to take the raw material (composed of granules and additives) from the hopper and transport (pump) them forward into the compression zone. In the compression zone, as the granules move along the screw, they are plasticized by contact with the heated wall of the cylinder barrel and by the generation of heat due to friction and shear between the layers of plastic. At the end of the melt zone, a breaker plate having perforations is often provided to perform various useful functions which include:

(1) increasing back pressure,

(2) converting rotational flow of the melt into flow parallel to the screw axis,

(3) holding back impurities, and

(4) holding back unplasticised material.

After coming out from the die, the extrudate is cooled immediately below its T_g to ensure dimensional stability.

This process can be used to produce any material that has a uniform cross-section, such as pipe, rods, and sheets [32,36].

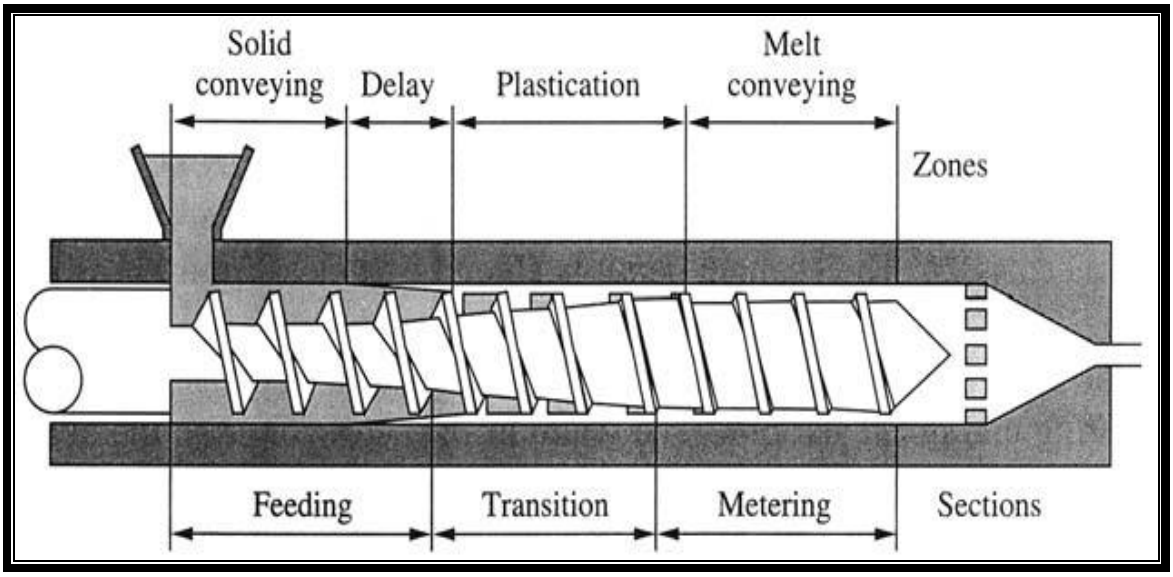


Fig. (2-8): Schematic representation of a single-screw extruder [51].

2-4 Polymer Degradation

Degradation of polymers may be considered as any type of undesired modification of a polymer chain backbone, side groups, or both. These modifications are usually chemical in nature; that is, they involve the breaking of primary bonds, leading to reduced molecular weight and altered physical properties. The causes of degradation may be environmental (such as heat, light, or atmospheric pollutants), induced, (as in rubber mastication), or a result of processing due to heat and/or air[52].

2-4-1 Radiative Degradation

Radiative degradation in polymers can give rise to both low-molecular-weight species, as in thermal degradation, or crosslinked structures, which are insoluble and infusible. Though crosslinking actually leads to an increase in the molecular weight of the sample, it is still considered a degradative process since the resulting product has unfavorably altered physical properties. There are generally two types of radiative degradation processes in polymers, grouped according to the amount of radiant energy involved and which result in different types of degradation.

Photolysis occurs when ultraviolet light (wavelength $\lambda = 10^2$–10^4 °A) imparts energy on the sample of the order 10^2–10^3 kJ/mol. Radiolysis occurs when higher radiant waves ($\lambda = 10^{-3}$–10^2 °A) impart energy of the order 10^5–10^{10} kJ/mol to the sample. Each of these types attacks the polymer chain in a different fashion.

Ultraviolet (UV) light is light that comprises only the shorter wavelengths of invisible radiation. It is a zone of invisible radiations beyond the violet end of the spectrum of visible radiations. Because the wavelengths are shorter than visible radiations, their photons have more energy. This energy is enough to initiate some chemical reactions and degrade many plastics. Thus UV light is more damaging than visible light to most plastics [37,52].

2-4-2 Thermal degradation

Thermal degradation is deterioration by heat. In plastics thermal degradation is usually oxidation or pyrolysis. Oxidation is the general reduction in properties by reactions taking place with oxygen and accelerated by the presence of high temperatures. Pyrolysis is reaction of the polymer purely with heat.

With pyrolysis, degradation occurs by breakage of the polymer chain called chain scission and resulting reduction in molecular weight [37].

2-4-3 Mechanochemical Degradation.

Mechanochemical degradation occurs in polymers as the result of an applied mechanical force. This type of degradation is quite common in machining processes such as grinding, ball milling, and mastication. In general, the degradation processes are similar to the other types of degradation, in that radicals are formed and cause subsequent reactions, such as oxidation and chain transfer, that can lead to either crosslinking or a reduction in molecular weight, though molecular weight reduction is the most common result. There are some unique aspects of mechanochemical degradation, however. In contrast to thermal degradation, radical formation is nonrandom, and the location of chain scission depends on the manner in which the forces are applied to the polymer. Also, the molecular weight decreases rapidly from an initial degree of polymerization for polymers under mechanical shear, then level off to a limiting degree of polymerization (Figure 2-9).

In addition to a reduction in molecular weight, mechanical forces generally lead to an increase in solubility, a narrowing of the molecular weight distribution, decreased tensile strength, decreased crystallinity, and increased plasticity. These effects are highly dependent upon the machining conditions [52].

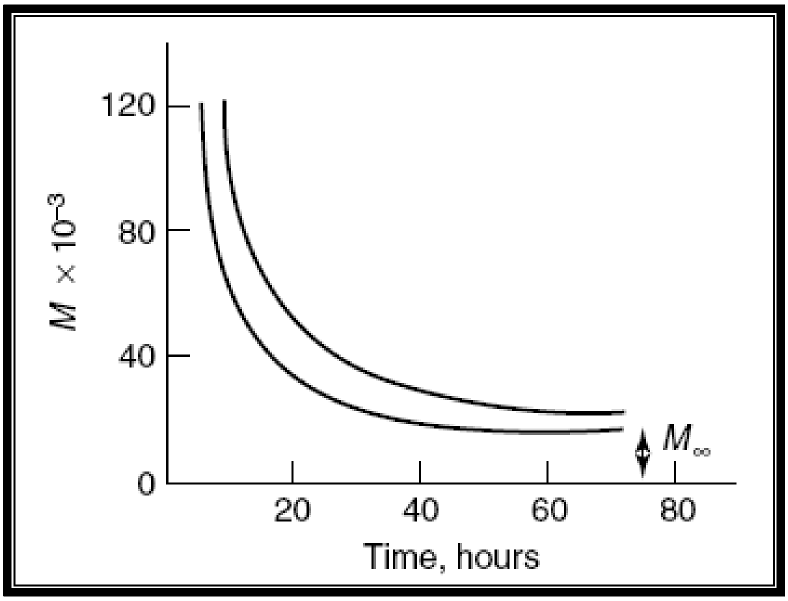


Fig.(2-9): Effect of machining time on molecular weight of polymer [52].

2-4-4 Chemical Degradation.

For most applications in the chemical process industry, chemical degradation is the most important type of polymer degradation. It is also the largest class overall, encompassing degradation due to both gaseous and liquid species on all polymer classes. Even within a polymer class, such as polyolefins, slight changes in the chain chemistry can lead to enormous changes in chemical compatibility.

In addition to oxygen, the most important gaseous agents that lead to polymer chemical degradation are nitrogen dioxide (NO_2) , sulfur dioxide (SO_2), and ozone (O_3) [52].

2-4-5 Biodegradation:

Biodegradation or biological degradation of polymers consists of those processes which are resulted from an attack on the material by living organisms, e.g., bacteria, fungi, insects, and rodents. Biodegradation is fundamentally a chemical process involving enzymes produced by microorganisms. High humidity, moderately increased temperature, and darkness are usually favorable for proper functioning of microorganisms [53,54].

2-5 Tensile properties of polymers

2-5-1 Stress–Strain Behavior of Polymers

Three important types of stress–strain curves are illustrated in Figure (2-10). The brittle plastic stress–strain curve is linear up to fracture at about 1% to 2% elongation. Typical stresses at break are of the order of 10,000 psi, or about $6x10^7$ Pa. Ordinary polystyrene behaves this way.

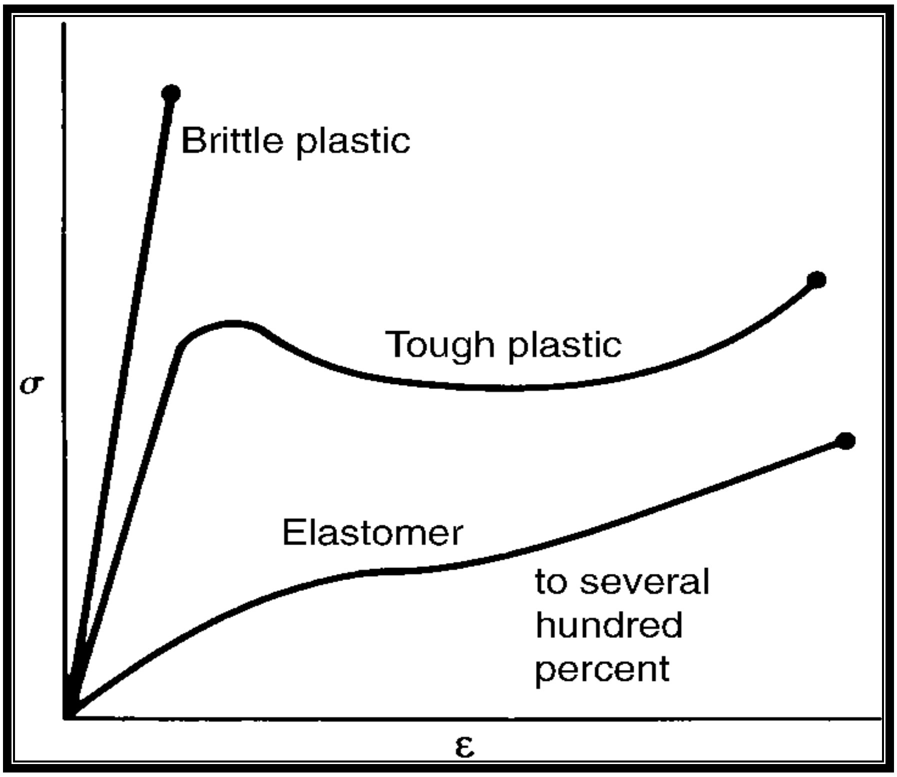


Fig. (2-10): Stress–strain behavior of three types of polymeric materials [33].

An example of a tough plastic is polyethylene, which is semicrystalline, with the amorphous portions above Tg. Its Young's modulus, given by the initial slope of the stress–strain curve, is somewhat lower than that of the brittle, glassy plastic. Typically this class of polymer exhibits a yield point, followed by extensive elongation at almost constant stress. This is called the plastic flow region and is clearly a region of nonlinear viscoelasticity. Stresses in the range of 2 to $5x10^7$ Pa are commonly exhibited in this range. Extension at constant stress in the plastic flow region is often referred to as cold drawing. Finally, the polymer strain hardens, then ruptures. Many tough plastics break at about 50% elongation.

The third type of stress–strain curve is that exhibited by elastomers. The equation of state for rubber elasticity governs here, with its peculiar nonlinear curve. Elongation to break for the elastomer may be of the order of several hundred percent and is indicated by the dot at the end of the curve. For crystallizing elastomers such as natural rubber, the curve swings upward rather sharply at the point of crystallization, and tensile strengths of 2 to $5x10^3$ psi ($2\text{-}3x10^7$ Pa) are common. Noncrystallizing elastomers such as SBR have much lower tensile strengths, often below 1000 psi. However, with the addition of reinforcing fillers such as finely divided carbon black, the tensile strength is much increased. Of course, this last material is widely used for automobile tires, one of the toughest materials known [33].

2-5-2 Effect of temperature on stress-strain curves of polymers

Polymers such as polystyrene and poly(methyl methacrylate), PMMA, with a high tensile modulus at ambient temperatures fall into the category of brittle materials, since they tend to fracture prior to yielding. “Tough” polymers, or those that undergo some deformation prior to failure, can be typified by cellulose acetate. These two categories of behavior are illustrated in Figure (2-11), along with their respective temperature dependences. It can be seen from Figure (2-11) that the effect of temperature on the characteristic shape of the curves is significant. As the temperature increases, both the rigidity and the yield strength decrease, while the elongation generally increases. For cellulose acetate, there is a ductile–brittle transition at around (273 K), above which the polymer is softer and tougher than the hard, brittle polymer below 273 K. For PMMA, the hard, brittle characteristics are retained to a much higher temperature, but it eventually reaches a soft, tough state at about 320 K. Thus, if the requirements of high rigidity and toughness are to be met, the temperature is important [34].

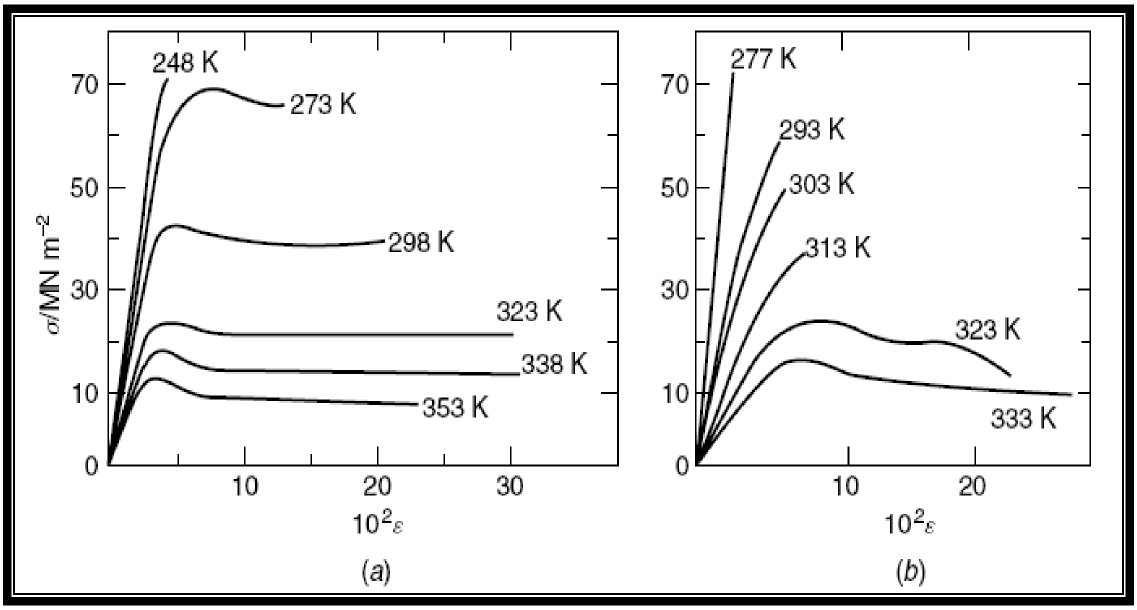


Fig. (2-11): Influence of temperature on the stress–strain response of (a) cellulose acetate and (b) poly(methyl methacrylate) [34].

2-5-3 Effect of strain rate on stress-strain curves of polymers

For many material, the stress-strain curves are sensitives to the strain rate $\acute{\varepsilon}$. The tensile tests are usually conducted in the range $10^{-4}\ s^{-1} < \acute{\varepsilon} < 10^{-2}\ s^{-1.}$ Materials can be tested over a wide range of strain rates; however, standardized tensile tests require well-characterized strain rates that do not exceed a critical value. High strain rate tests are often used to obtain information on the performance of materials under dynamic impact conditions[55].

Figure (2-12) shows the effect of different strain rate on the tensile response of PMMA [16].

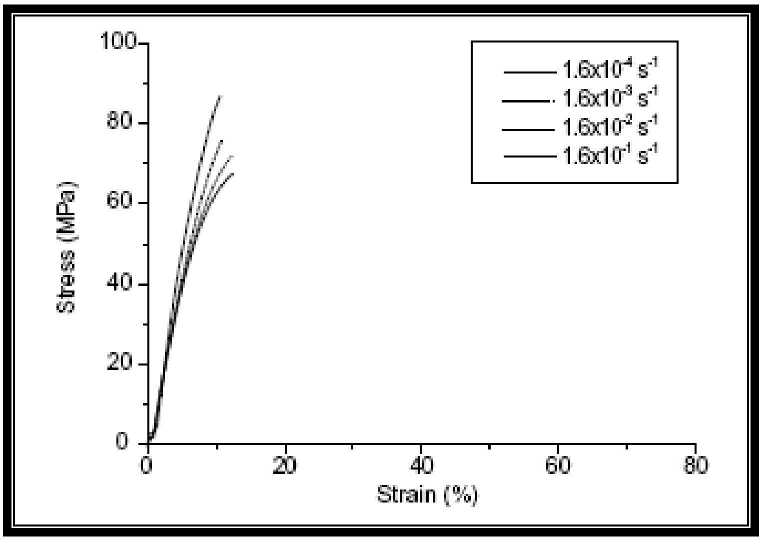


Fig. (2-12): Tensile tests made at different rates for PMMA [16].

2-6 Impact properties of polymer

2-6-1 Introduction

Plastics products are most likely to fail in a brittle manner under impact conditions, both due to strain rate effects and because large forces can be generated by low energy impacts on stiff structures [56].

Impact strength of many polymers is raised by introducing reinforcements in them. Toughness of many plastics is also improved by the addition of rubber material in them. These additions are called toughness modifiers [36].

2-6-2 Factors affecting the impact strength of polymeric materials

2-6-2-1 Nature of impact Tests

Impact tests can be broadly divided into two separate classes:

(a) Low velocity impact by a large mass, which is generally a swinging pendulum, where the breaking energy is determined from the loss in kinetic energy of the pendulum, or a falling weight in which the breakage energy is determined from the weight of the bal1 and the height from which it is dropped. The impact speeds normally attainable lie in the rang of 2 to 6 m/s.

(b) High velocity impact by a small mass using a gas gun or some other type of ballistic launcher. For such special test purposes, projectiles with impact speeds of 50 to 100 m/s are generally used [57].

2-6-2-2 Effect of Notches

The state of the surface of a solid has a profound influence on its impact strength. The notch in the Izod specimen serves to concentrate the stress, minimize plastic deformation, and direct the fracture to the part of the specimen behind the notch. Hence the impact strength of the notched specimens is less than that of the unnotched specimens [58].

2-6-2-3 Effect of Temperature

The impact strength of most polymers increases as the temperature is raised to the neighbourhood of their glass transition temperature, Tg**.** This is due to the fact that at temperatures in the neighbourhood of the glass transition temperature, the potential molecular motion is great enough to relieve any stress concentrators that may be present in the material [59].

2-6-3 Impact testing of polymers

The ability of a component to withstand a sudden impact is obviously of great importance for any practical application of the material. The impact testing of polymers is therefore equally important. By using standardized techniques it is fairly straightforward to obtain results that allow the comparison of one type of polymer with another, but it is less easy to obtain fundamental data.

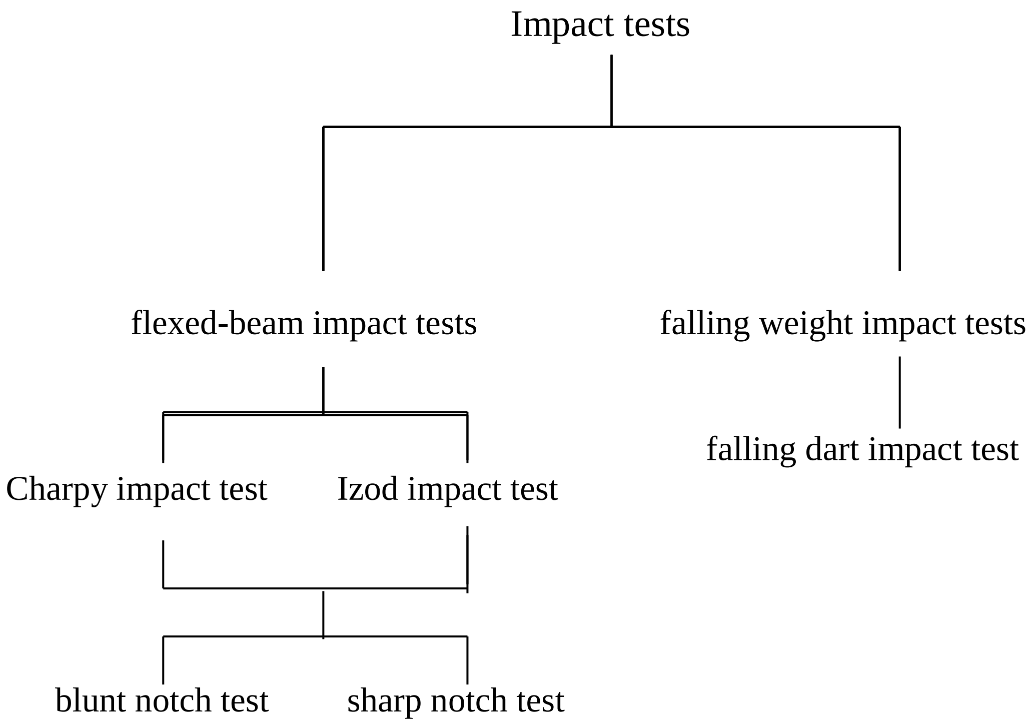


Fig. (2-13): The various kinds of impact tests [35].

Figure (2-13) shows the principal types of test. In the Charpy test a beam of the polymer is held at each end and is struck at its centre by a hammer with one or two knife edges, giving a three- or four-point impulsive bending stress, respectively. Figure (2-14) shows a diagram of a standard Charpy impact tester. Charpy testing is usually reported in units of J/m^2, or energy required to create a unit area of crack.

In the Izod test the specimen is held at one end and struck at the other. For either test a notch is cut in the sample at the point where it is to break and the sample is placed in the tester with the notch pointing away from the hammer, so that the blow tends to widen the notch. If the blow is strong enough the sample cracks at the foot of the notch and fractures. The standard type of specimen has a blunt notch, which is a V-shaped notch with a tip radius of 0.25 mm, but sometimes a sharper notch is made, into the foot of which a razor blade is driven to provide a starting place for a crack. Izod testing is usually reported in units of J/m (Joules per meter of crack), based on samples of 12.7 mm wide, 3.2 mm thickness, and 65 mm length.

In the falling-dart test a circular sample of polymer is supported horizontally and a pointed steel dart is allowed to fall so that it strikes the centre of the disc. The standard dimensions for this test are radius of test disc 6 cm, thickness of disc 2 mm and radius of dart tip 1 mm. The disc is supported horizontally by an annulus of 4 cm aperture to which it is clamped by a second annulus. The behavior of the sample can be studied under a variety of different degrees of severity of impact simply by varying the height from which the dart is allowed to fall [35].

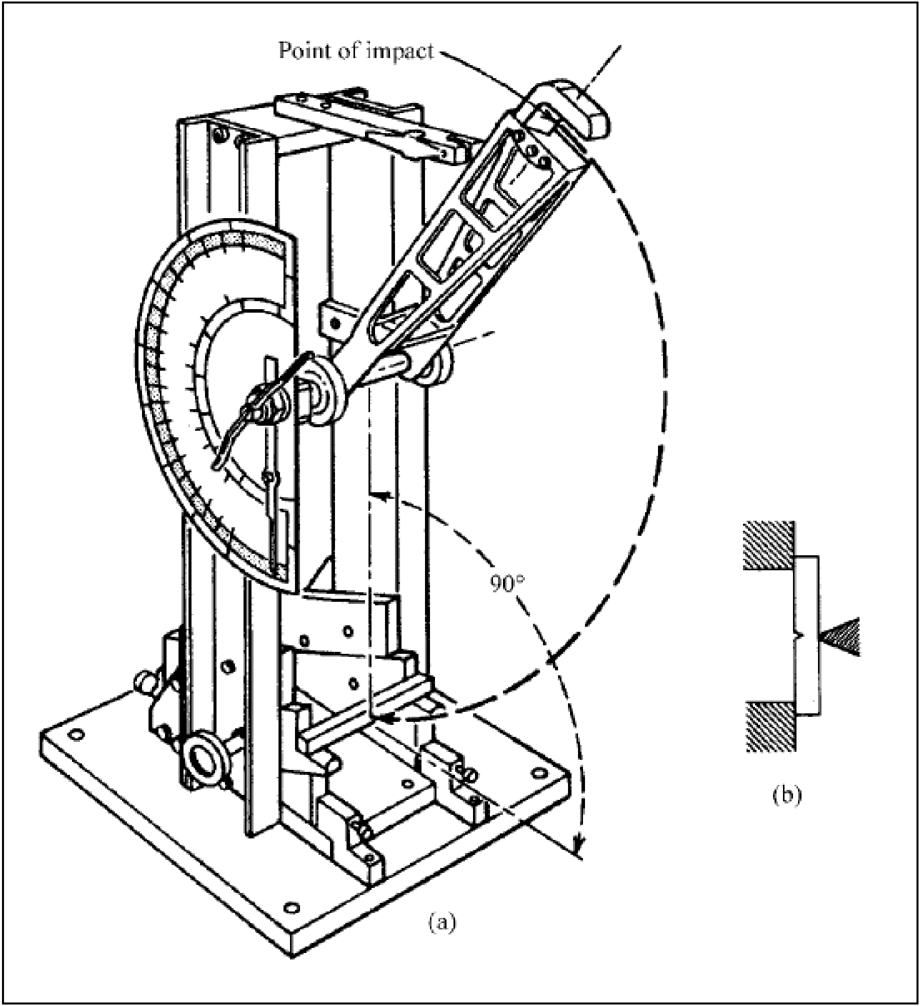


Fig.(2-14): The Charpy impact test: (a) the pendulum tester, ASTM 256; and (b) the sample and striking hammer tip [35].

2-6-4 Ductile-to-brittle transition

A Charpy test at one temperature is not sufficient, however, because the energy absorbed in fracture drops with decreasing test temperature. The temperature at which a change occurs from a high-energy fracture to a low-energy one is called the ductile-brittle transition temperature (DBTT). However, since, in practice, there occurs not a sharp change in energy, but instead, a transition zone, it becomes difficult to obtain this DBTT with precision.

The appearance of the fractured surfaces after an impact test also gives information about the type of fracture that has occurred [55].

2-7 Fatigue of polymers

2-7-1 Introduction

Fracture of components due to fatigue is the most common cause of service failure, particularly in shafts, axles, aircraft wings, etc., where cyclic stressing is taking place. With static loading of a ductile material, plastic flow precedes final fracture, the specimen necks and the fractured surface reveals a fibrous structure, but with fatigue, the crack is initiated from points of high stress concentration on the surface of the component such as sharp changes in cross-section, slag inclusions, tool marks, etc., and then spreads or propagates under the influence of the load cycles until it reaches a critical size when fast fracture of the remaining cross-section takes place. The surface of a typical fatigue-failed component shows three areas, the small point of initiation and then, spreading out from this point, a smaller glass-like area containing shell-like markings called “arrest lines” or “conchoidal markings” and, finally, the crystalline area of rupture.

Fatigue failures can and often do occur under loading conditions where the fluctuating stress is below the tensile strength and, in some materials, even below the elastic limit. Because of its importance, the subject has been extensively researched over the last one hundred years but even today one still occasionally hears of a disaster in which fatigue is a prime contributing factor [60].

Similar to metals, polymers can deform plastically and thus can fail in a similar way under cyclic loading. However, the microscopic mechanisms are not the same as in metals [52].

2-7-2 Thermal fatigue

Polymers deform viscoelastically. Under cyclic loads, the stress-strain curve upon unloading is not the same as upon loading. Therefore, there is a hysteresis between stress and strain, causing energy dissipation during the deformation, thus producing heat. The heat generated under cyclic loads cannot easily dissipate into the surroundings because the thermal conductivity of polymers is small. If heat generation exceeds heat dissipation, the temperature increases in each cycle until the temperature-dependent strength of the material is exceeded and the material fails. If the stress is reduced, the heat generation reduces as well, and the number of cycles to failure increases. For this reason, this phenomenon is called thermal fatigue. If the stress is reduced further, an equilibrium between heat generation and heat dissipation will be established without exceeding the strength.

Thermoplastic polymers fail by plastic yielding under thermal fatigue because the yield strength decreases with increasing temperature. Elastomers and duromers can also fail by thermal fatigue due to the reduction of Young's modulus with temperature which causes a continuously growing deformation.

If thermal fatigue occurs, the load frequency can strongly influence fatigue life. On the one hand, longer cycles provide more time to dissipate the heat, on the other hand, Young's modulus and the size of the hysteresis in the stress strain diagram are dependent on the frequency. If sufficiently long unloading occurs between the cycles, the generated heat can be dissipated, and there is no thermal fatigue. The geometry of the component is also important, for it determines the heat dissipation [52].

2-7-3 Mechanical fatigue

If the temperature increase during cyclic loading is sufficiently small so that no thermal fatigue occurs, the polymer fails by mechanical fatigue. Similar to metals, we can distinguish the stages of crack initiation and crack propagation.

Cracks can form in a polymer in different ways, depending on the dominating deformation mechanism. Fracture of single chain molecules or sliding of chain molecules can weaken the material locally and thus serve as initiating points for cracks. In many polymers (for example, polystyrene, polycarbonate, PMMA), crazing plays an important role, as it does in plastic deformation. Under cyclic loads, crazes may form and grow even if the loads are comparatively small, until they have grown sufficiently to act as microcracks. If a crack propagates, the stress concentration near the crack tip can initiate further crazes that coalesce with the crack. Because crazing depends on the hydrostatic stress state, the mean stress is especially important in this case. Alternatively, shear bands may form and be starting points for microcracks. If there are phase boundaries within the polymer, for example, between the amorphous and crystalline regions of a semi-crystalline polymer or between chemically different phases in a copolymer, these boundaries may initiate cracks due to the stress concentration they cause. Nevertheless, the fatigue strength of semi-crystalline polymers is in most cases superior to that of amorphous polymers.

Whether a polymer fails by mechanical or thermal fatigue is determined by many factors e. g., the load frequency, the stress level, the temperature, and the geometry of the component. In general, polymers with weak viscoelastic effects, which produce only a small amount of heat in each cycle, fail by mechanical fatigue. Among these are polystyrene and many duromers. Thermal fatigue is important in materials with a large hysteresis in the stress-strain diagram, for example polyethylene, polypropylene, and polyamide. Finally, both effects can interact because the increase in temperature changes not only the static, but also the dynamic material properties. In this case, the material heats up initially, and crack propagation sets in afterwards. This phenomenon can be observed in PMMA, PET and polycarbonate [52].

2-7-4 S-N curves of polymers

We first define some important parameters, these parameters are as follows:

cyclic stress range, $\sigma = \sigma_{max} - \sigma_{min}$, ………… (2-2)

cyclic stress amplitude, $\sigma_a = (\sigma_{max} - \sigma_{min})/2$, ……… (2-3)

mean stress, $\sigma_m = (\sigma_{max} + \sigma_{min})/2$, ……… (2-4)

stress ratio, $R = \sigma_{min} / \sigma_{max}$ ……… (2-5)

where σ_{max} and σ_{min} are the maximum and minimum stress levels, respectively.

Traditionally, the behavior of a material under fatigue is described by the S-N (or σ-N) curves, where S (or σ) is the stress and N is the number of cycles to failure. Such an S-N curve is frequently called a Wöhler curve, after the German engineer who first observed that kind of fatigue behavior [55].

There are four categories of cyclical stresses to consider. The first is called a reversed stress cycle, in which the stress alternates equally between compressive and tensile loads. A repeated stress cycle occurs when the maximum and minimum stress of a reversed stress cycle are asymmetric relative to the zero stress level. Other types of cyclical stresses include a fluctuating stress cycle, which has a maximum and minimum tensile or compressive load (but not both), and a random stress cycle, in which the stresses are neither periodic nor uniform in the magnitudes [34].

The fatigue behavior of polymers strongly depends on the load frequency because of their viscoelastic properties. If the frequency is sufficiently large, the polymer can fail by thermal fatigue due to the heat generated during deformation. This is shown for the example of a thermoplastic polymer in Figure (2-15). At low frequencies, the thermoplastic fails by crack formation and propagation, similar to a metal, at higher frequencies, thermal fatigue occurs, and the fatigue strength strongly decreases. The load frequency is for this reason usually limited to 10 Hz.

However, as Figure (2-15) shows, this may be due to thermal fatigue, and in this case the horizontal part of the curve meets the curve for true mechanical fatigue at higher numbers of cycles.

S-N curves of polymers have to be used with caution in designing components.

The fatigue strength depends much more strongly on the load frequency than in metals because the equilibrium between heat production and dissipation plays a crucial role. To design components, experiments should be as close to real service conditions as possible [52].

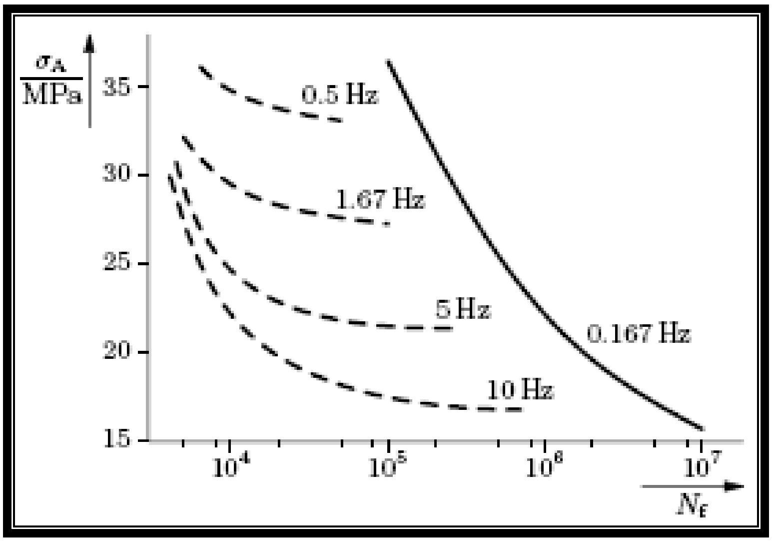


Fig. (2-15): S-N diagram of polyoxymethylene (polyacetal) at different loading frequencies [52].

Phenomenologically there are three regions in the stress versus number of cycles to failure (S–N curves); see Figure (2-16): For a sample undergoing cyclic stress–strain exercises, first there is a region where there may be no externally apparent damage. This is followed by a region of crack propagation, where the crack grows steadily with each cycle. The last region involves catastrophic failure, where one or two cycles more causes total material fracture. Fatigue response in this way is commonly observed: A material in service appears to be fine, and then breaks with little or no warning. Of course, the cracks may be propagating internally, not easily seen without instrumental examination.

The number of cycles to failure depends on the stress level, as illustrated in Figures (2-16) and (2-17). In some cases a so-called endurance limit is observed below which fatigue failure does not occur in realistic lifetimes of experiments.

The fatigue phenomenon is not an all-or-nothing situation. First, it is assumed by many investigators that all materials are flawed as made, even if the flaws are too small to be ordinarily noticed. On repeated stressing, these tiny flaws initiate cracks. In the next stage, these cracks propagate slowly, perhaps growing a bit with every cycle, or sometimes intermittently. Finally, the material fails, the crack growing through the sample in one stress cycle [33].

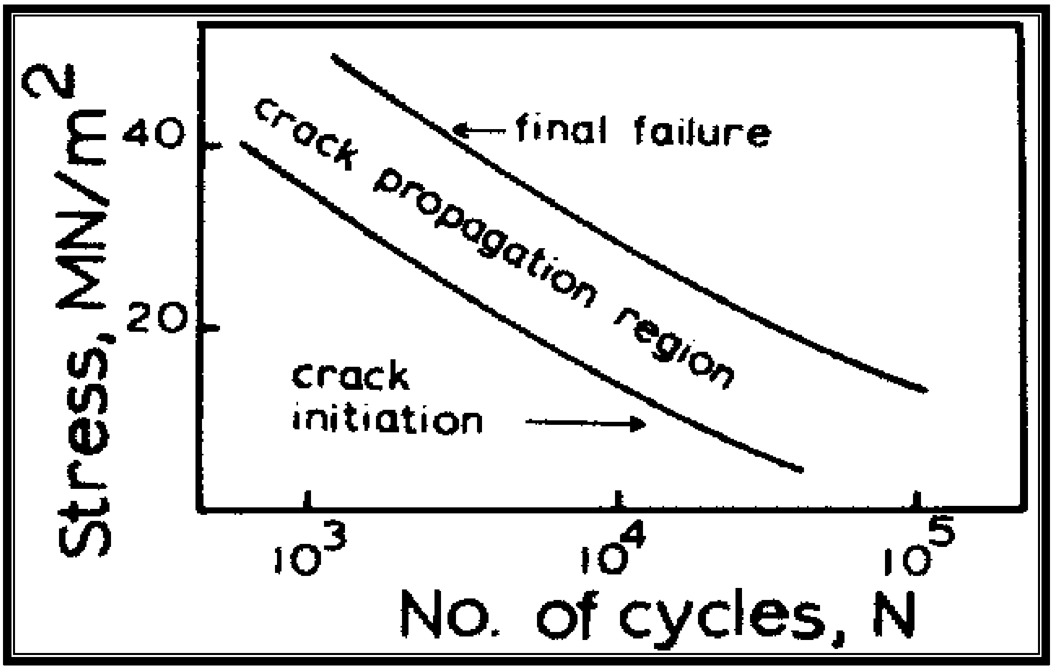


Fig. (2-16): The fatigue response of a polymer [33].

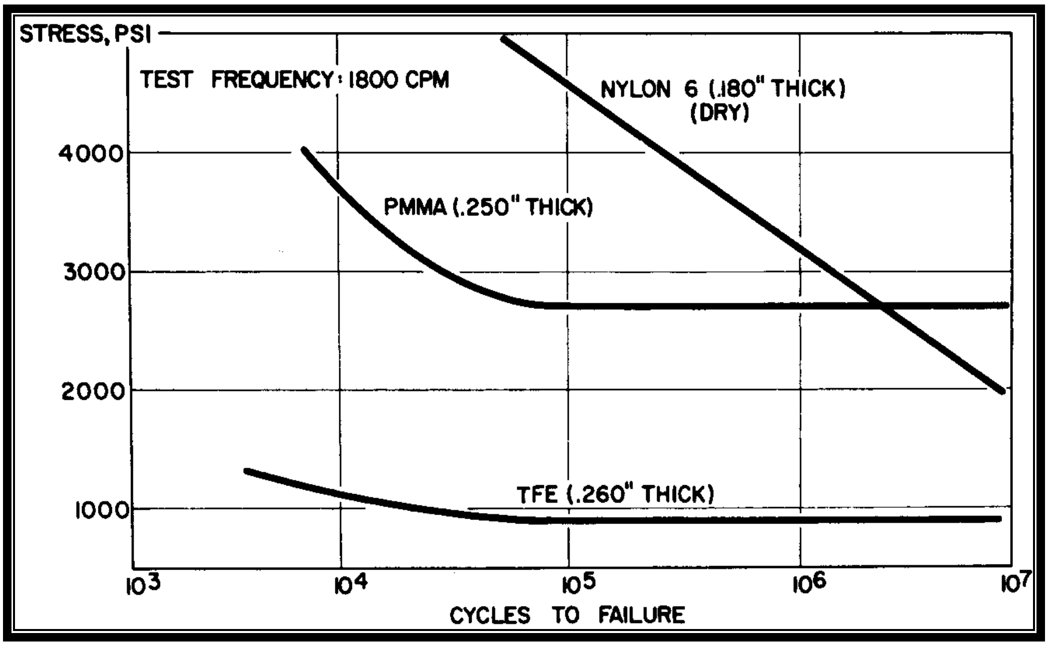


Fig. (2-17): Fatigue lifetimes versus stress level for nylon 6, poly(methyl methacrylate), and polytetrafluoroethylene [33].

2-7-5 Fatigue Crack Propagation

Fatigue crack propagation relates to the slow growth of cracks caused by cyclic stressing. In many fatigue crack propagation experiments, a notch is deliberately introduced in the specimen at a convenient location. The rate of growth of this crack and the morphology of the crack surface outline areas of current interest.

For a crack of length *a*, the fatigue crack growth rate is *da*/*dn*, where *n* represents the number of stress cycles. The stress intensity factor range is given by

$$\Delta K = K_{\max} - K_{\min} \qquad \text{……….(2-6)}$$

where $K_{\max}$ and $K_{\min}$ are the maximum and minimum values of the stress intensity factor during the cyclic loading. The crack growth rate is related to the stress intensity factor range by the equation (Paris' law)

$$da/dn = A_1\,\Delta K^{m} \qquad \text{………(2-7)}$$

where A_1 and *m* are parameters dependent on material variables, mean stress, environment, and frequency. While the rate of crack growth increases with crack length, equation (2-7) implies a straight line when log *da*/*dn* is plotted against Δ*K*, frequently observed over much of the range in Δ*K* (Figure 2-18). The actual rates of crack growth depend on several factors. First is the temperature of the experiment. Under fatigue propagation conditions, the crack tip may get quite hot even if the experiment is at room temperature.

This is important because viscoelastic motions depend strongly on the temperature and the frequency of the loading. Either the glass transition or secondary transitions such as the b transition may be involved, but the latter is usually the more important because most engineering plastics are well below their glass transition temperatures. The frequency sensitivity, defined as the multiple by which the fatigue crack propagation rate changes per decade of frequency, goes through a maximum at the temperature where the b transition segmental jump frequency is comparable to the test machine loading frequency.

Second, the rates of crack growth depend on the value of ΔK. If ΔK is low enough, the rate of crack growth may be essentially zero. If ΔK is high enough, one cycle may produce fracture. This results in a sigmoidal character to the fatigue crack growth curve.

Third, fatigue propagation depends inversely on the weight-average molecular weight. Below a critical value of Mw, the sample is brittle. At higher molecular weight ranges, the fatigue crack propagation rate decreases. Indeed, higher molecular weight samples are stronger in a variety of experiments [33].

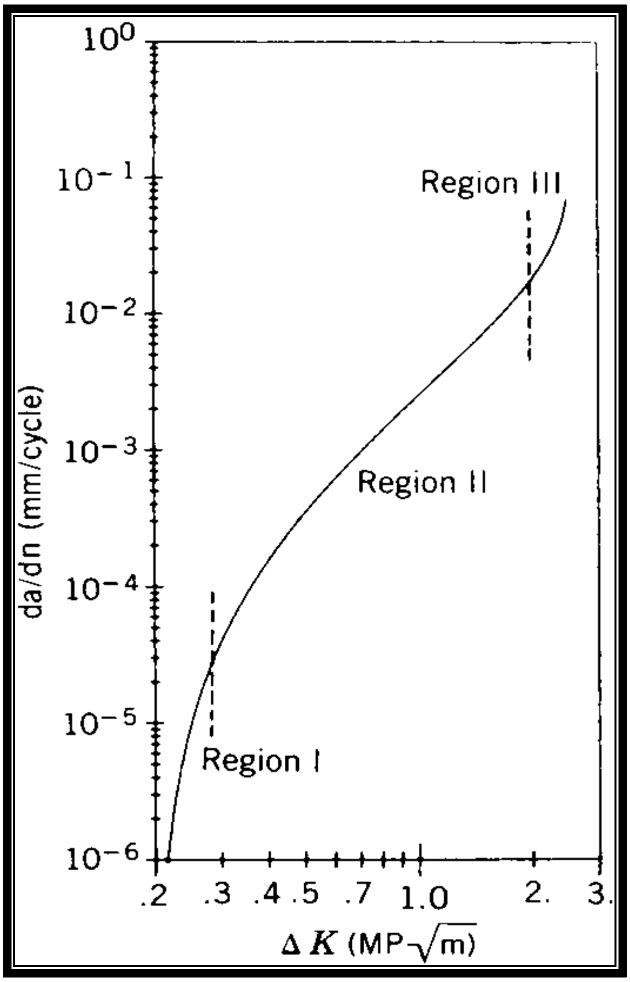


Fig. (2-18): Fatigue propagation in plastics [33].

2-7-6 Fatigue testing

Fatigue tests are usually carried out under conditions of rotating - bending and with a zero mean stress as obtained by means of a Wohler machine.

From Fig. (2-19), it can be seen that the top surface of the specimen, held “cantilever fashion” in the machine, is in tension, whilst the bottom surface is in compression. As the specimen rotates, the top surface moves to the bottom and hence each segment of the surface moves continuously from tension to compression producing a stress-cycle curve [60].

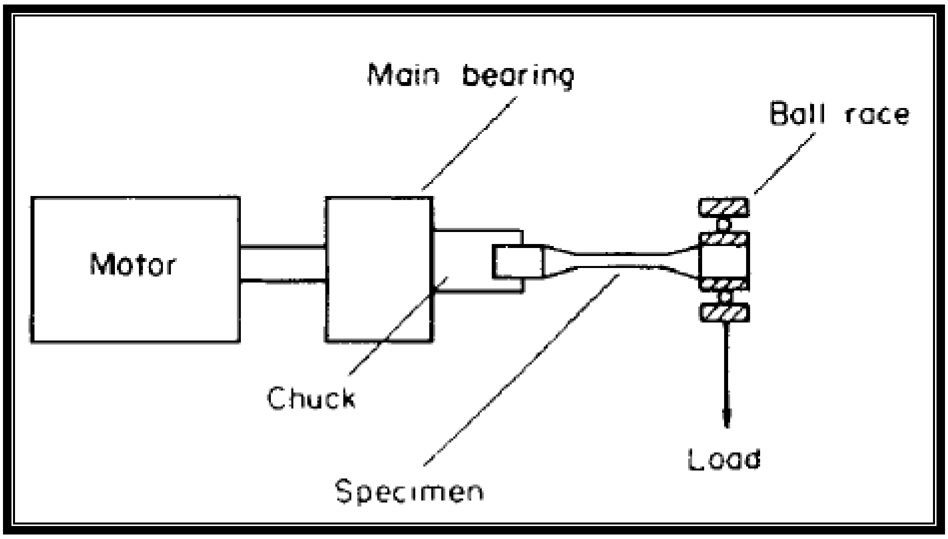


Fig. (2-19): Single point load arrangement in a Wohler machine for zero mean stress fatigue testing [60].

Chapter Three
Experimental Part

3-1Introduction

This study includes the investigation of the effects of temperature and UV radiation on tensile properties of two PVC pipes material at different strain rates as well as the studying of the impact strength and fatigue behavior with temperature and UV radiation.

This chapter explains the experimental procedure which was used in this study and includes the discussion of the specimens preparation for tensile, impact and fatigue tests of UPVC pipe material and the mechanical tests which were carried out on samples. Also description of the testing apparatus which used in this study.

3-2 Specimen Preparation

The specimens for tensile, impact and fatigue testing were prepared from commercially available four-inch extruded pipes which were manufactured by a local Iraqi company. Table (3-1) illustrates the two formulations which were used in the study.

Table (3-1): The two formulations were used in the study

Material	Weight	
	The gray	The white
PVC	100 kg	100 kg
Filler/$CaCO_3$	30 kg	50 kg
Stabilizer/lead	3,250 kg	3 kg
Plasticizer/DOP	250 g	250 g
Stearic acid	100 g	100 g
Titanium dioxide (TiO_2)	450 g	250 g
Carbon black	50 g	_____

The specimens were prepared from pipes, where rings were cut from the pipe (as illustrated in Figure 3-1) , slit and straightened between metal plates after heating for 30 min at 70°C in an electric oven.

Fig. (3-1): Ring was cut from PVC pipe.

3-2-1 Tensile Specimens Preparation

The specimens for tensile tests were then machined from the straightened plates according to the ASTM D638-03 standard method of test for tensile properties of plastics by using milling machine and the mould illustrated in Figure (3-2). The sample dimensions are given in Figure (3-3). Sample thickness for the gray was 5.6 mm, while for the white was 3.2 mm.

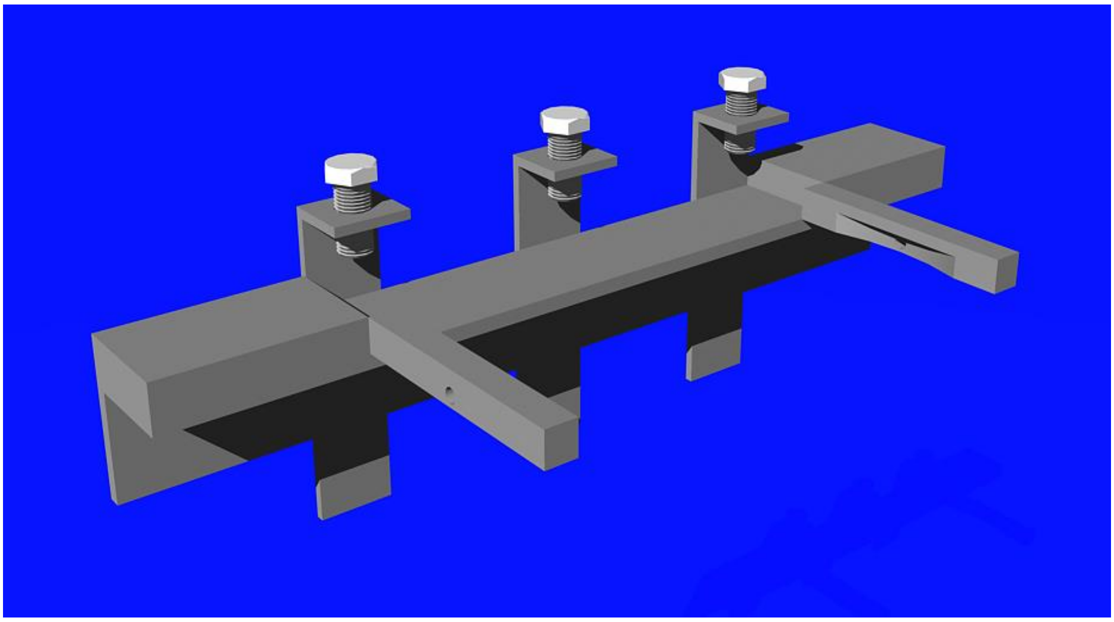


Fig. (3-2): The mold used to prepare the tensile sample.

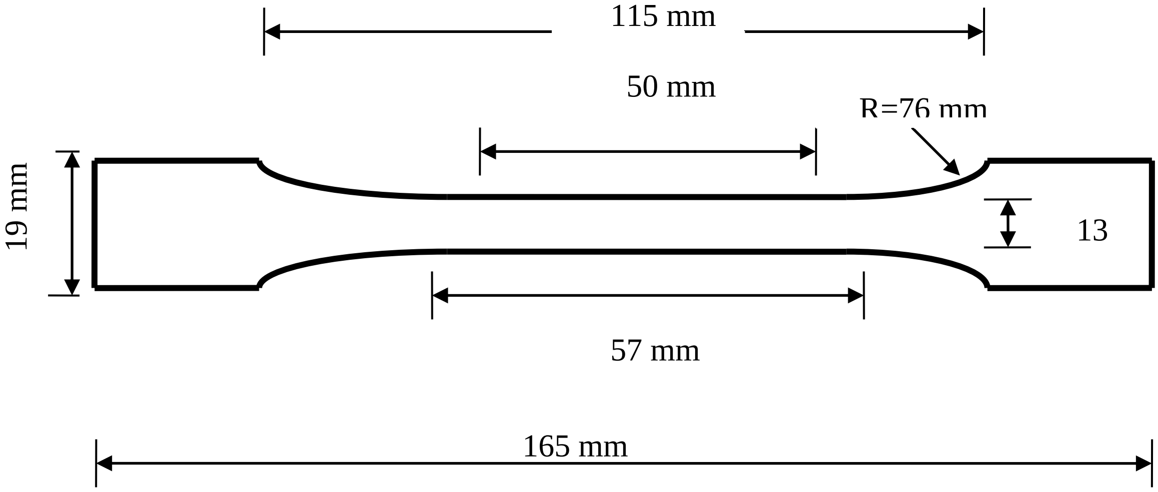


Fig. (3-3): Geometry and dimensions of the tensile specimen used in the study.

3-2-2 Impact Specimens Preparation

The specimens for impact tests were then machined from the straightened plates according to the ASTM. The sample dimensions are given in Figure (3-4).

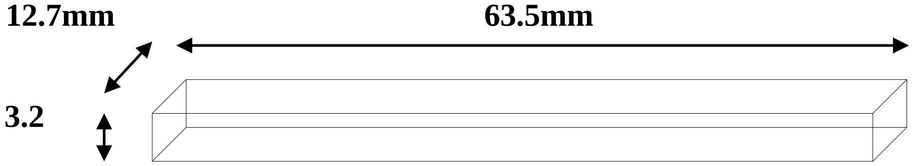


Fig. (3-4): Geometry and dimensions of the impact specimen used in the study.

3-2-3 Fatigue Specimens Preparation

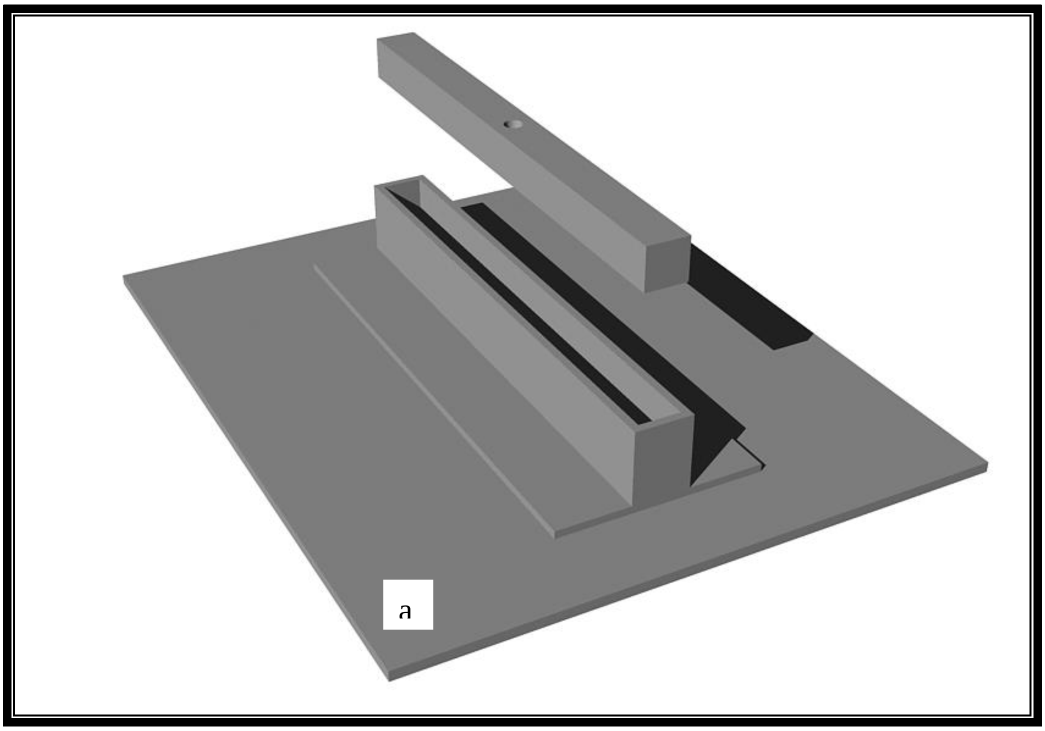
Because there was no production from the pipe that used in present study, it was suitable in thickness with the standard dimensions which was used in preparation of fatigue samples. So, the increasing of thickness of the grey pipe material to the thickness of fatigue sample was by two stages:

The first stage: Increase of thickness to 7.5 mm by softening of sample in an oven at 70°C for two hours, then it was put in the mould (Figure (3-5 a), then it was pressed by the press (Figure (3-6)).

The second stage: The specimen was resulted from first stage , put in an oven at 70°C for 90 min and put in the mould (Figure (3-5 b)) and then pressed by the same press, however we got the thickness which equalled 12 mm, hence, we got the rectangular sample which had these dimensions:

l =130 mm, w =12 mm, t =12mm.

Then, the sample was machined by using lathe to get on fatigue sample according to the British standards. Figure (3-7) illustrates geometry and dimensions of the fatigue specimen used in the study.



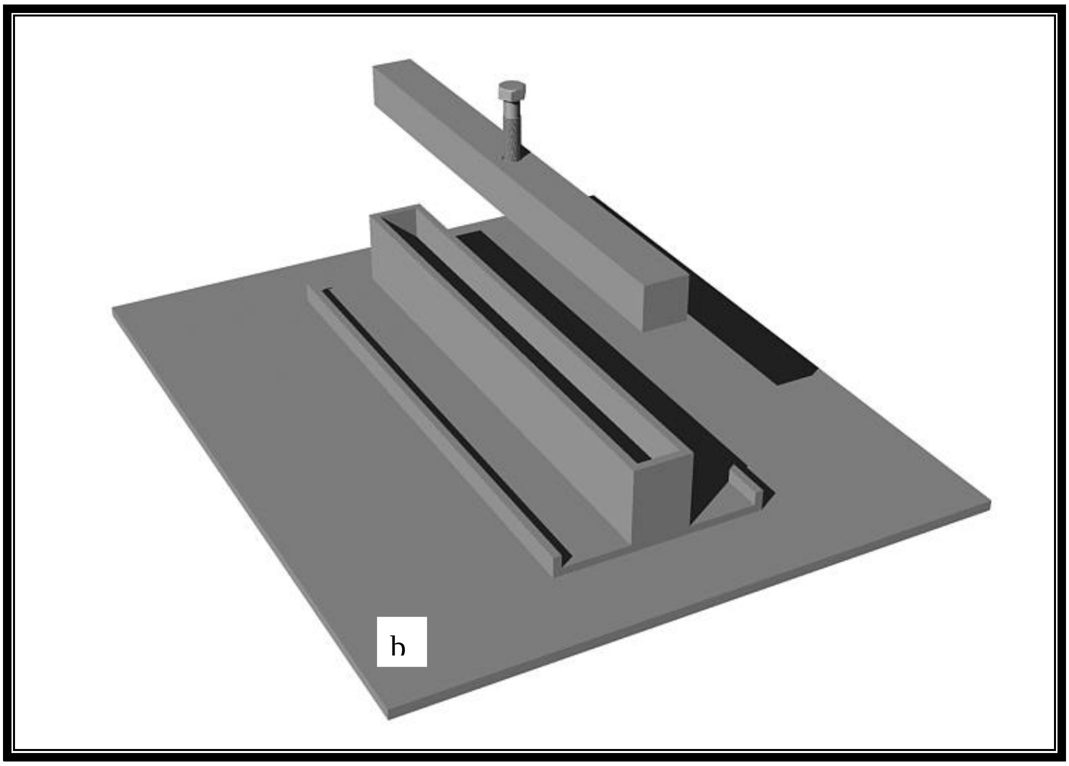


Fig.(3-5): The molds were used to increase the thickness:(a) 7.5, (b)12mm.

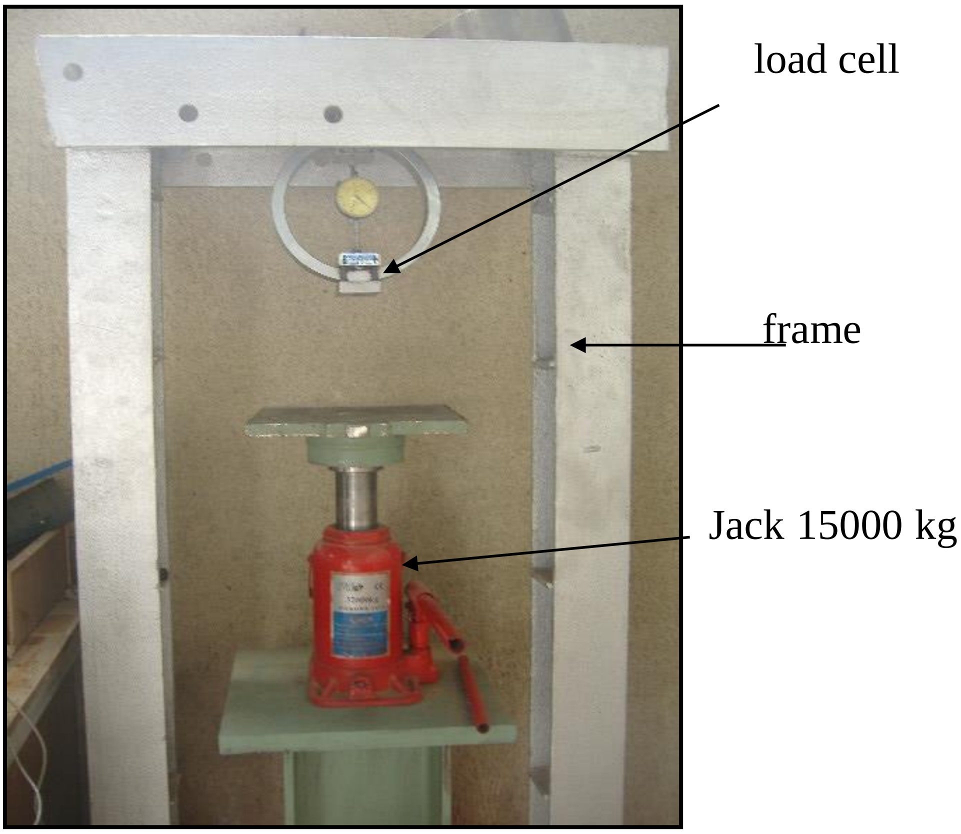


Fig.(3-6): The press was used in the study.

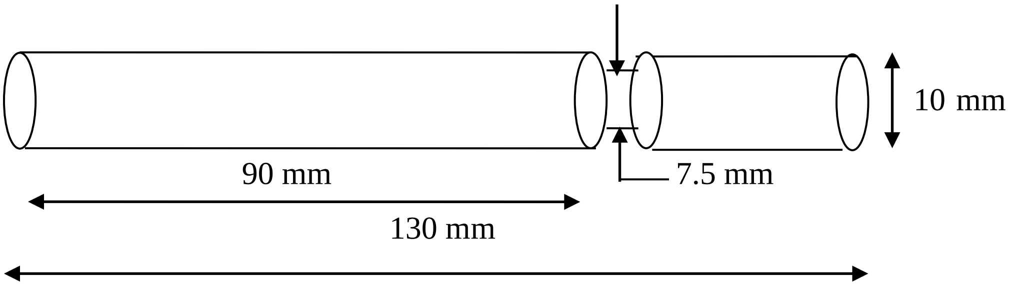


Fig.(3-7): Geometry and dimensions of the fatigue specimen used in the study.

3-3 Testing Apparatus

3-3-1 Electrical oven: It is used for softening, it is American manufacturing, temperatures range is (311- 561) K.

3-3-2 Instron 1195

The Instron1195 machine is used to perform tensile tests. The Instron 1195 (illustrated in Figure 3-8) has the following specifications:

- Load Cells: 5 N - 100 KN.
- Crosshead Speed Range: 0.5 - 500 mm/min.
- Return Speed: 500 mm/min.
- Crosshead Speed Accuracy: 0.1% of Set Speed.
- Testing Type: Tension and Compression.

Fig.(3-8):Instron universal testing machine.

3-3-3 Environmental Chamber

The environmental chamber which was fabricated contains two spring ovens that is the one inside another ,extends the upper one with the sample, and they are surrounded with the insulator. The two ovens are linked with controller, the temperature is determined and regulated by it. A thermocouple puts near of sample to measure a temperature of sample during the test. A glass wool put on upper and lower ovens to ensure fully insulation. Figure (3-9) illustrates the environmental chamber.

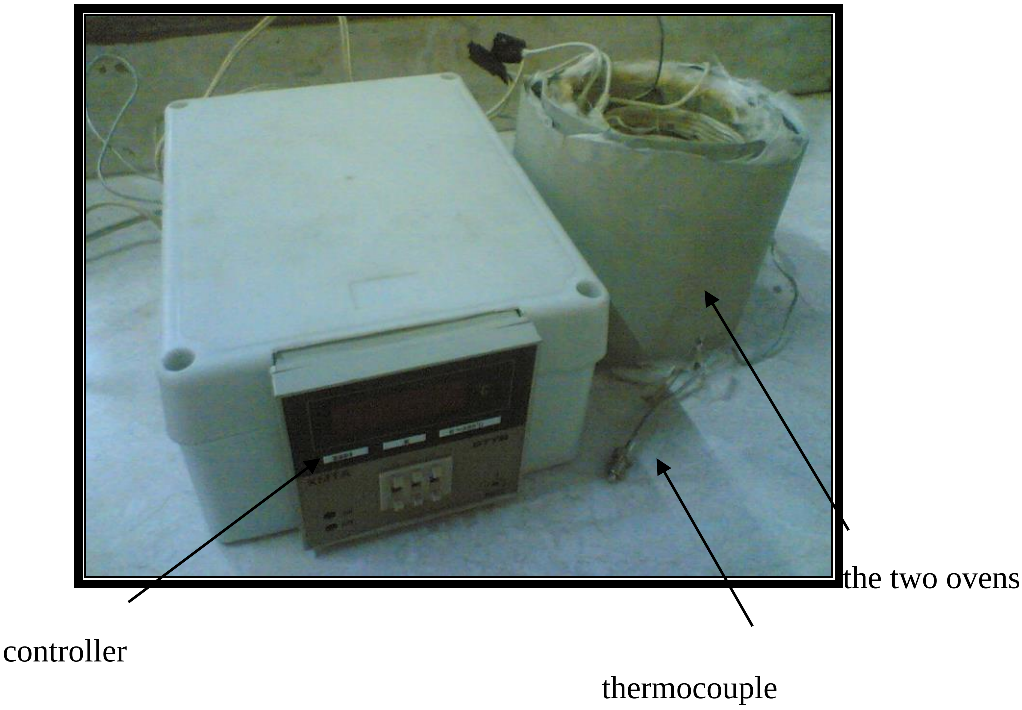


Fig.(3-9): The environmental chamber.

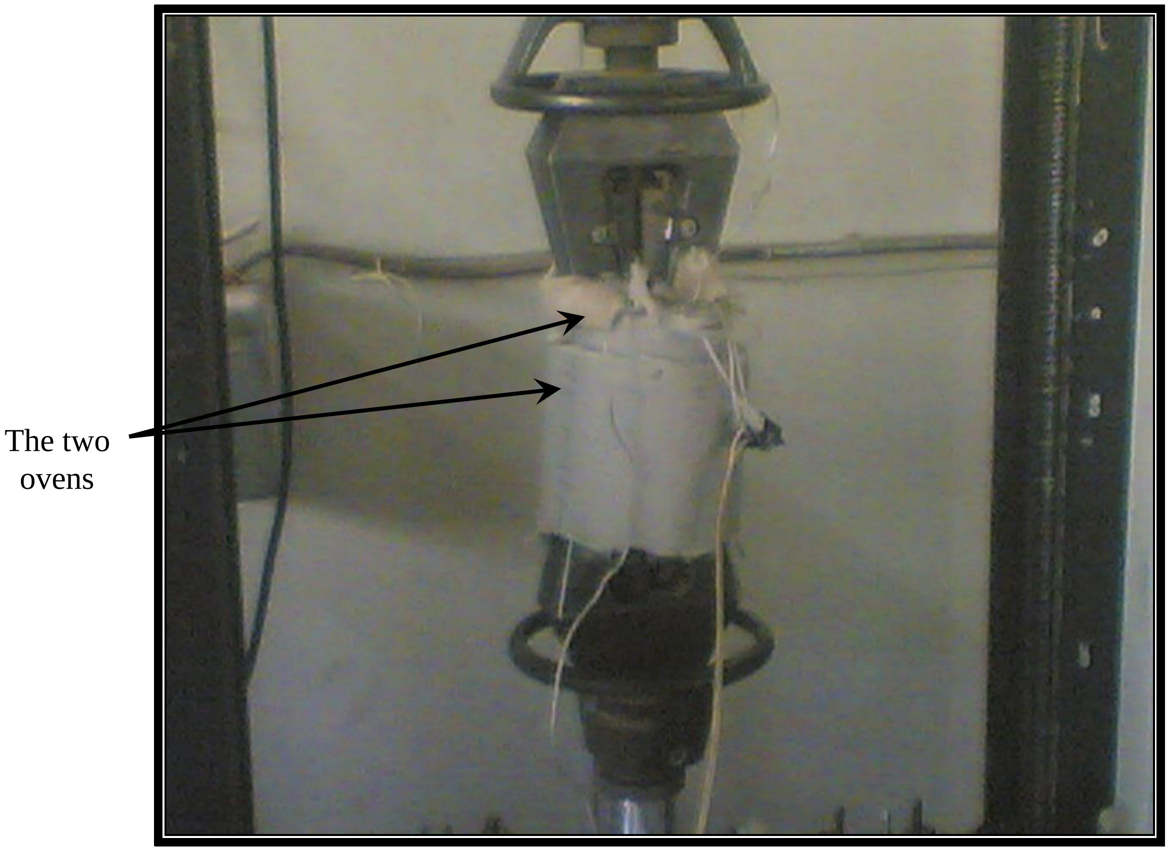


Fig.(3-10): Instron universal testing machine with the environmental chamber.

3-3-4 UV *apparatus*

Accelerated UV exposure tests are used to predict the performance of outdoor exposed polymers, as natural weathering takes several years.

Samples for tensile, impact and fatigue tests were exposed to UV-radiation from UV source works on 16 watt (380 KJ mol $^{-1}$) and wave length 375-380 nm, which is shown in Fig (3-11). Surface examination, color change , tensile, impact and fatigue were determined as a function of exposing time, where the specimens were exposed to UV for different times.

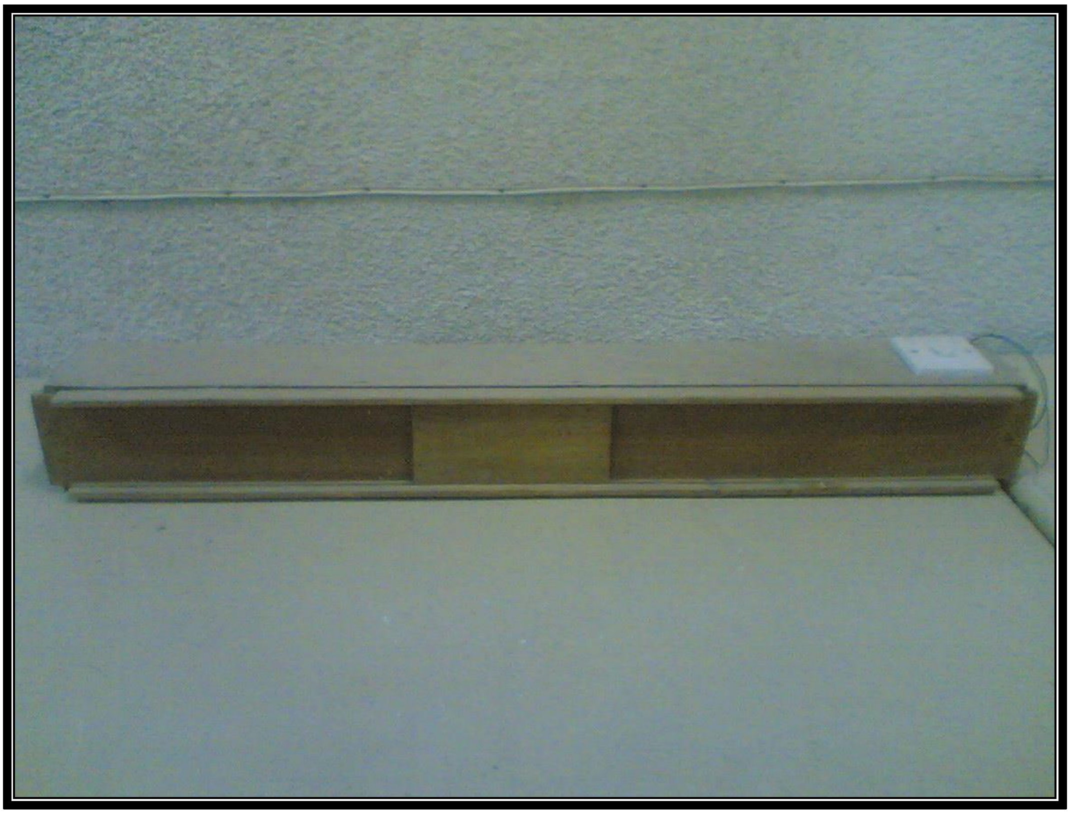


Fig.(3-11): UV-Lamp.

3-3-5 Impact test instrument

Charpy impact test consists of standard test piece that will be broken with one blow of a swinging hammer. The test piece is supported at both its ends in a way that the hammer strikes it at the middle. The testing method of this instrument includes lifting of the pendulum to its maximum height and fixing it firmly as shown in Figure (3-12). The specimen is fixed in its pertaining place, and then the energy gauge is initialized (on zero position) after that, the pendulum is freed where its potential energy would be changed to kinetic energy. Some of this kinetic energy is utilized to fracture the specimen, while the energy gauge reads the value of fracture energy (UC) for the sample under test. Impact strength (I.S.) is calculated by applying the relationship:

I.S. =US/A …………. (3-1)

Where:

US: is the fracture energy (Joule) which is determined from Charpy impact test instrument.

A: is the cross-sectional area of the specimen.

Fig.(3-12): Charpy impact testing machine.

3-3-6 Fatigue testing machine

Fatigue test was conducted for samples by using HSM 19 mk3 type of rotating bending manufactured by HI-TECH that illustrated in Figure (3-13). The cycles number of machine is 5600 rpm, because of these cycles, the bending stress is formed and its aspect is the sine wave with constant amplitude and mean stress is equalled zero, the stress ratio is equalled (-1).

The machine is provided with calculator records the number of cycles of sample during its rotating, and when the sample is failed, the machine is stopped automatically due to switch off the electricity which cause it micro-switch.

The sample in fatigue test is exposure to the load vertically on the sample axis to be generating the bending moment, therefore the sample surface will be exposure to tensile stress and compressive stress at rotation of sample.

The left jaw in fatigue testing machine replaced with other has short length to suitable the sample (Figure 3-14).

The bending stress is calculated as following:

$\sigma_b = M * Y/I$............ (3-2)

$M = (p * L)$; $Y = r = d/2$; $I = \pi d^4/64$

$\sigma_b = (115.7 * 32 * P)/\pi * d^3$ ………… (3-3)

where :

σ_b: is the bending stress (MPa).

P : is the applied load (N).

d : is the diameter of sample (mm).

L: is the length of applied load about the notch of sample (mm).

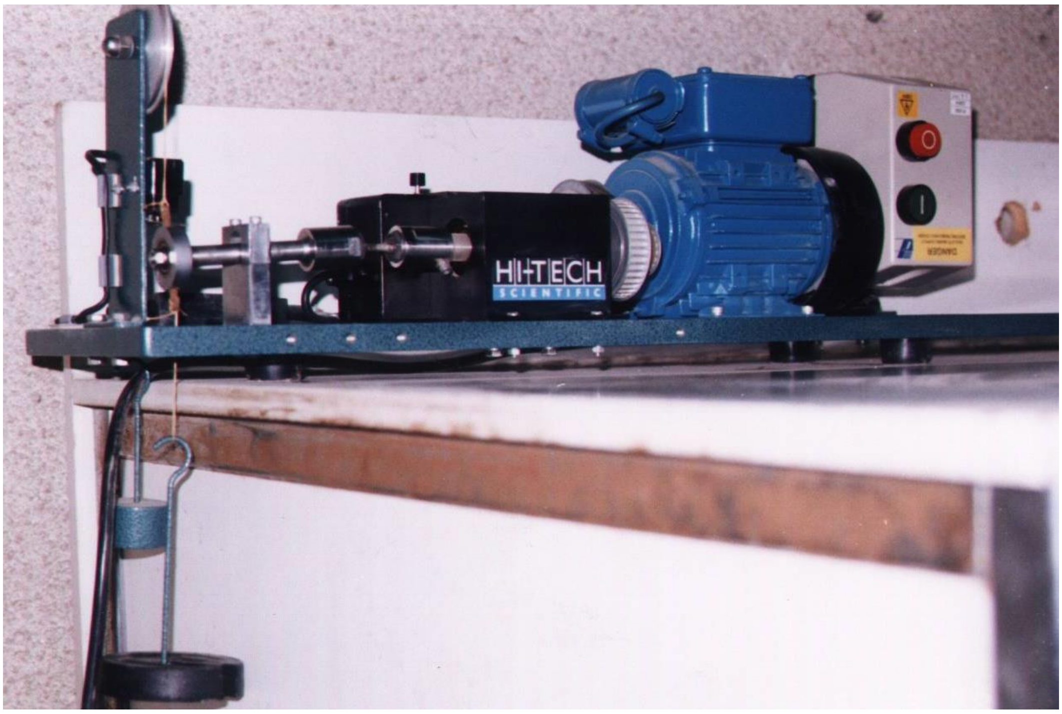
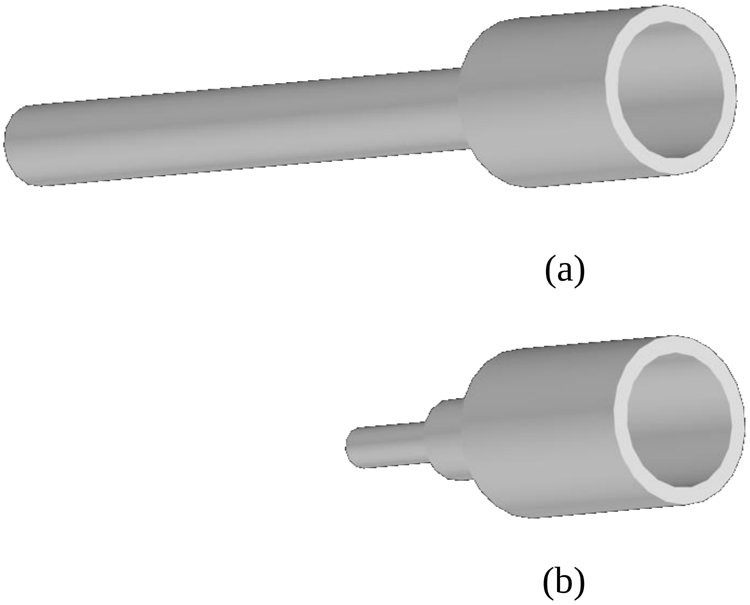


Fig.(3-13): Fatigue testing machine.


(a)

(b)

Fig.(3-14): The left jaw in fatigue testing machine: (a) before modifying (b) after modifying.

3-3-7 The optical microscope

(Nikon , Eclipse , ME 600 L , made in Japan) which linked with digital camera (Nikon Digital Camera DXM 1200 F) was used to examine the fracture surfaces of tensile, impact and fatigue samples to observe effects of: temperature and strain rate in tensile test, temperature in impact test and temperature and fatigue loads in fatigue test. Also observation of the effect of UV radiation on surface of PVC pipes material. The examination was conducted in Ministry of Science and Technology / Office of Materials Science. Figure (3-15) illustrates the optical microscope.

Fig.(3-15): The optical microscope.

3-4 Mechanical Tests:

3-4-1 Tensile Tests:

Tests were carried out on samples at each of these temperatures: 25, 50 and 70°C and at crosshead speeds of 5, 50 and 100 mm/min. The tests were carried out on exposed samples to UV for different times (7,17,30 and 45 days) at crosshead speed of 5 mm/min as well.

The raw data from a tensile test are the load versus elongation measurements made by the load cell and the extensometer, respectively. To eliminate sample geometry effects, the extension is divided by the initial length to obtain the dimensionless strain (which is occasionally multiplied by 100 and reported as % elongation for samples that undergo large deformations), and the load is divided by the cross-sectional to obtain the stress. Stress is plotted versus strain, and the result is a stress–strain diagram. The data obtained from tensile tests provide information on the yield stress, elastic modulus and fracture strain. Figure (3-16) illustrates samples of tensile test.

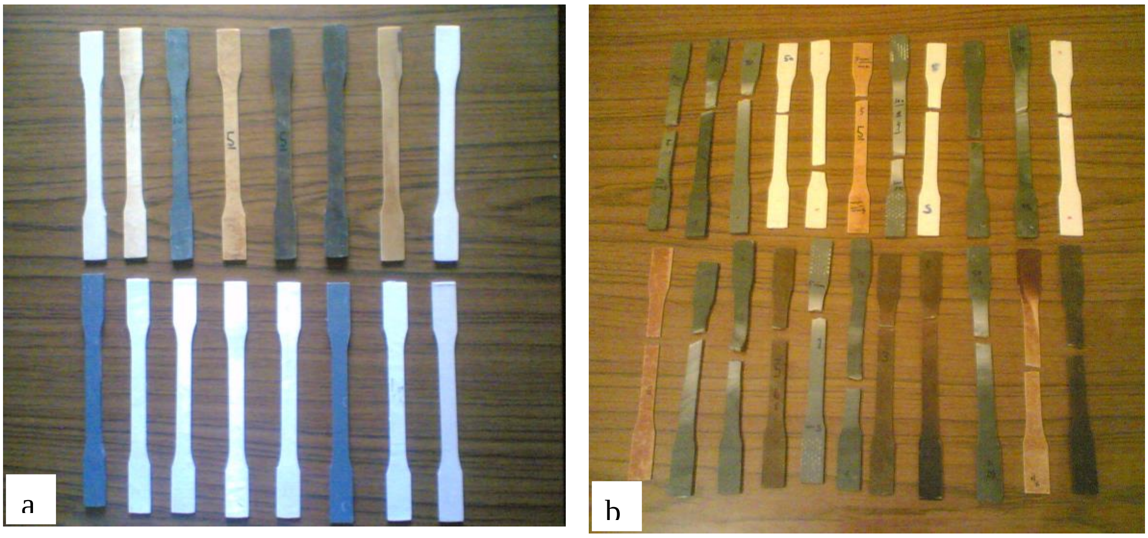


Fig.(3-16): Samples of tensile test:(a) before test (b) after test.

3-4-2 Impact tests

Tests were carried out on samples at each of these temperatures: 7,15,26,35,40,45,48 and 51°C, as well as the tests were carried out on samples which exposed to UV for different times (7,17,30 and 45 days).

To study effect of surface cracks on impact strength for two types of PVC pipes material. The samples in this study were yielding again to impact test at room temperature after they had notched in surface with different depth of range from (0.25-1.25) mm. Notches were obtained by using cutter which had angle (45) and it was putting in milling machine. Figure (3-17) illustrates samples of impact test.

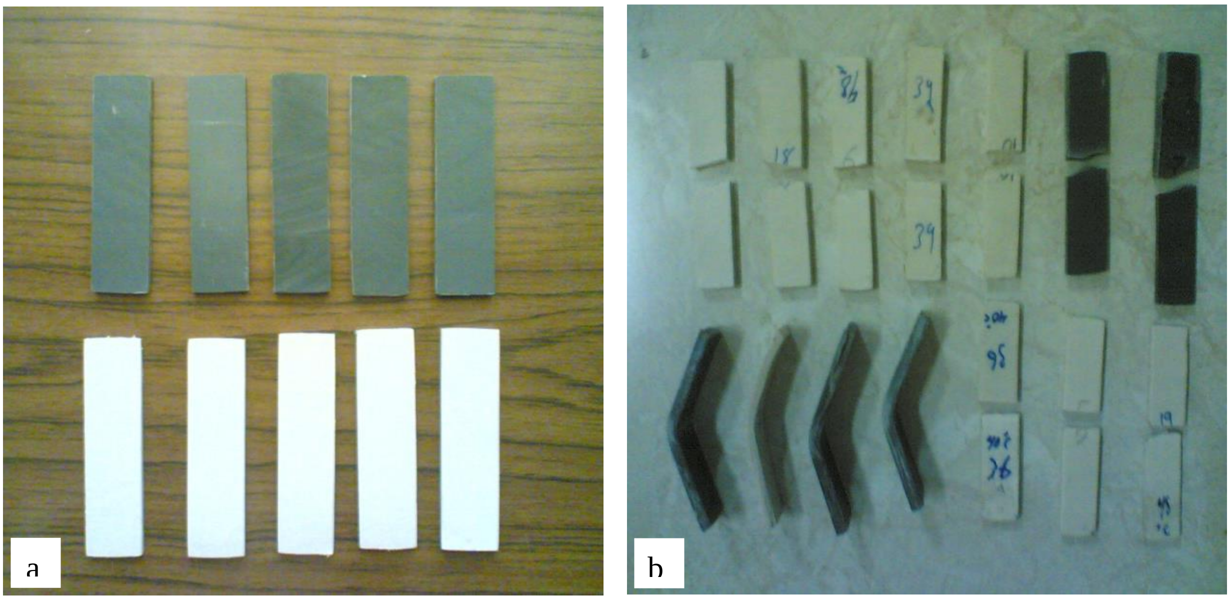


Fig.(3-17): Samples of impact test: (a) before test (b) after test.

3-4-3 Fatigue tests

To indicate the fatigue behavior, fatigue test was conducted on samples at different stresses. The fatigue test was also conducted on samples at different temperatures to show effect of temperature on fatigue behavior. In temperatures above room's temperature, the samples were exposed to hot air from a blower and the temperature was measured by a smart sensor infrared thermometer showing in Figure (3-18), where it applies ray to the sample and the temperature records on the screen which finds in the sensor. The temperatures that sensor is measured range from (-18°C) to (1050°C). In case, temperatures which were lower than the room temperature, the sample was surrounding with ice and temperature of sample was measured by the sensor.

To known effect of UV radiation on fatigue properties of PVC pipe material, the fatigue samples were tested after their exposed to UV radiation for different times (7,17,30 and 45 days). Figure (3-19) illustrates samples of fatigue test.

Fig.(3-18): Infrared thermometer.

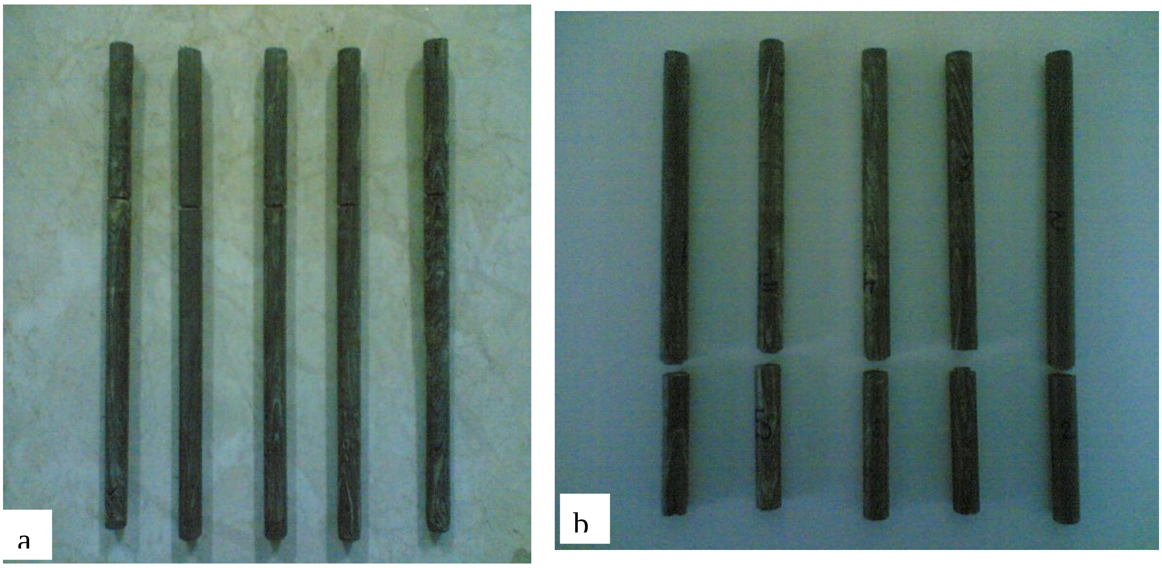


Fig.(3-19): Samples of fatigue test : (a) before test (b) after test.

Chapter Four

RESULTS AND DISCUSSION

4-1 Introduction

In this chapter, the results obtained from the experimental tests are discussed. It includes the description of the results of tensile tests obtained at different crosshead speeds and temperatures as well as exposure time to UV radiation. Also it discusses the impact behavior at change of temperature and exposure time to UV radiation. Finally, it discusses the fatigue behavior of PVC pipe material at different stresses, temperatures and exposure times to UV.

4-2 Tensile properties

4-2-1 Effect of strain rate and temperature on tensile properties of PVC pipes material:

Figures (4-1), (4-2) and (4-3) show stress-strain curves for the gray pipe for different temperatures at (5), (50) and (100) mm/min respectively. Figures (4-4), (4-5) and (4-6) show stress-strain curves for the white pipe for different temperatures at (5), (50) and (100) mm/min respectively.

Effects of temperature (28, 50 and 70°C) and crosshead speeds (5,50 and 100 mm/min) on yield stress, elastic modulus and fracture strain have been shown in the following sections.

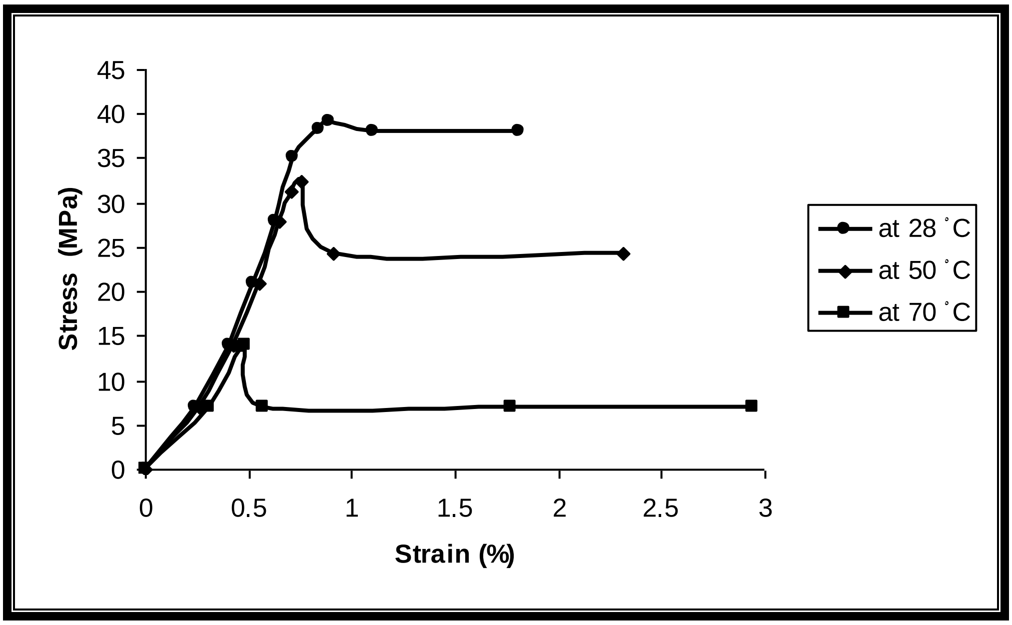


Fig.(4-1): Stress-strain curves for the gray pipe at 5 mm/min for different temperatures.

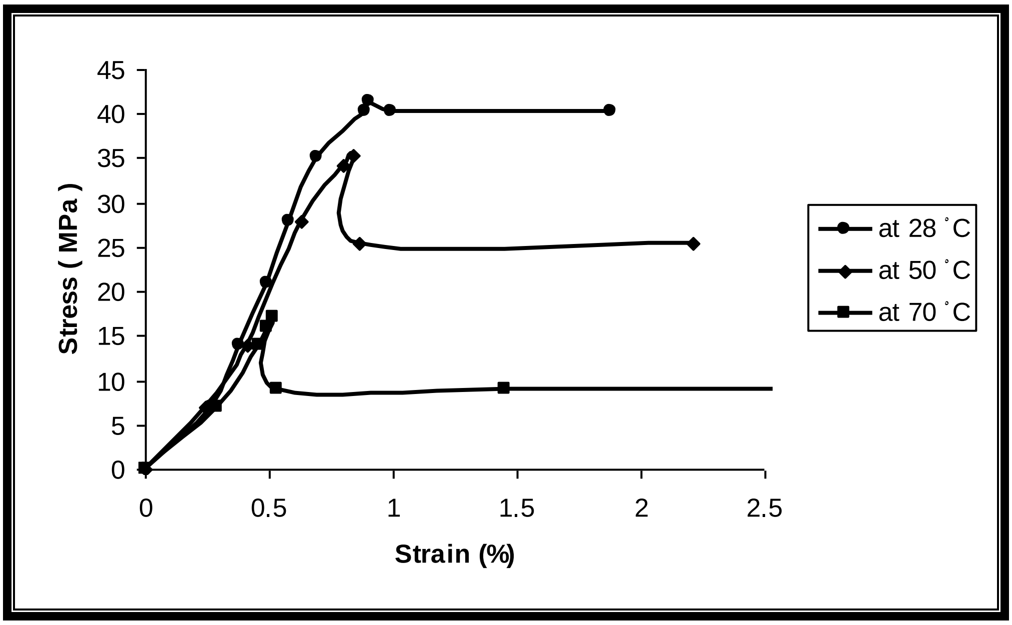


Fig.(4-2): Stress-strain curves for the gray at 50 mm/min for different temperatures.

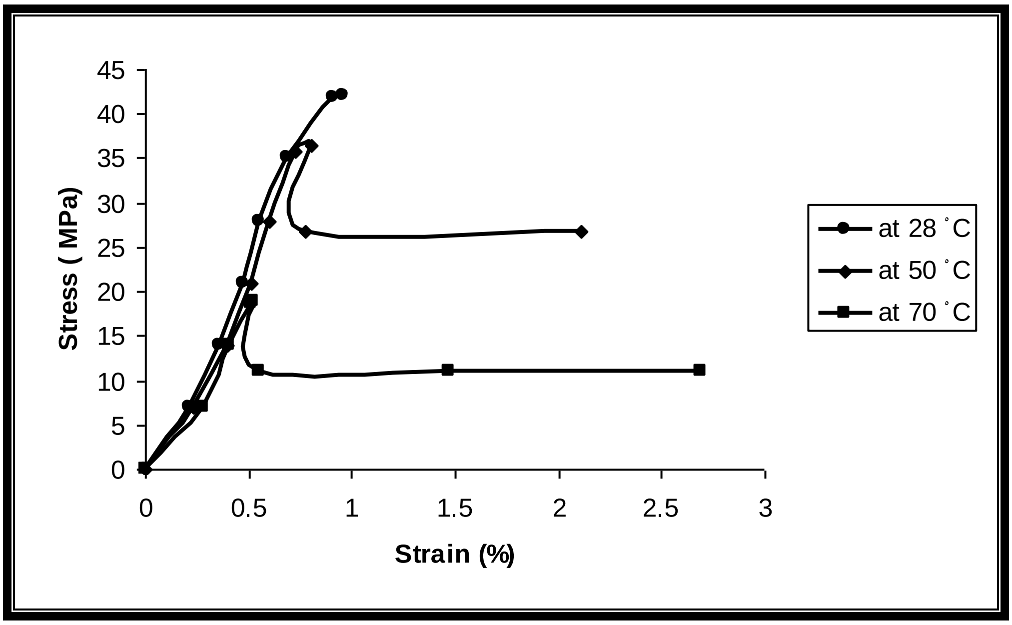


Fig.(4-3): Stress-strain curves for the gray at 100 mm/min for different temperatures.

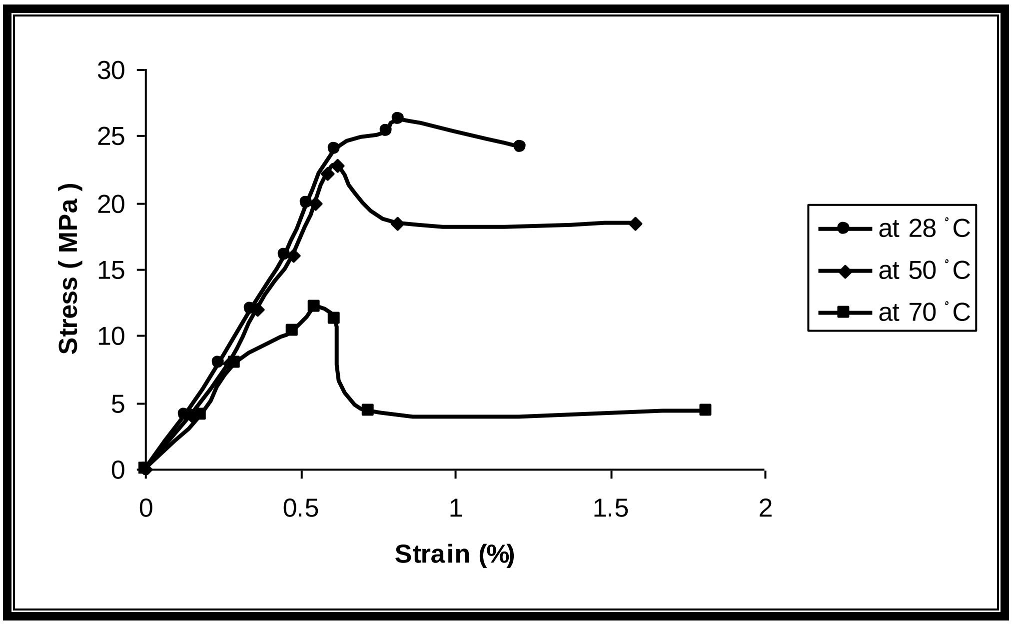


Fig.(4-4): Stress-strain curves for the white pipe at 5 mm/min for different temperatures.

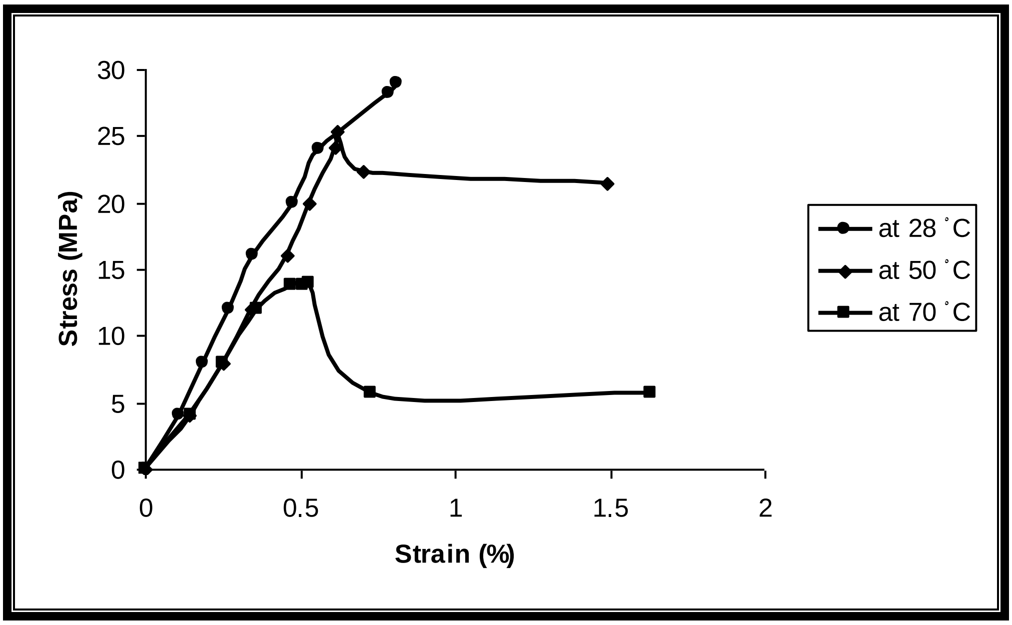


Fig.(4-5): Stress-strain curves for the white pipe at 50 mm/min for different temperatures.

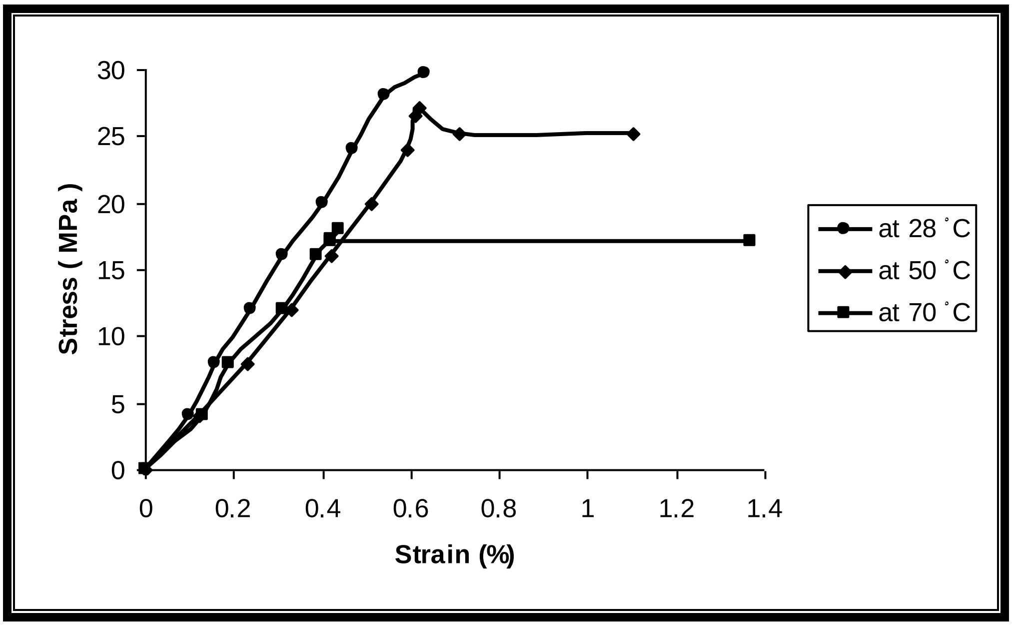


Fig.(4-6): Stress-strain curves for the white pipe at 100 mm/min for different temperatures.

4-2-1-1 Yield Stress

In all Figures (4-1, 4-2, 4-3, 4-5, 4-6), it can be seen that the tensile yield stress increases with crosshead speed at all temperatures. This behavior belongs to insufficient time to plastic deformation.

However, it decreases with increasing temperature at all crosshead speeds. The reason of this behavior is that the bond between material molecules becomes weak therefore the easy of molecular mobility and plastic deformation.

The maximum value of yield stress occurs at 28°C and 100 mm/min whereas the minimum value occurs at 70°C and 5 mm/min.

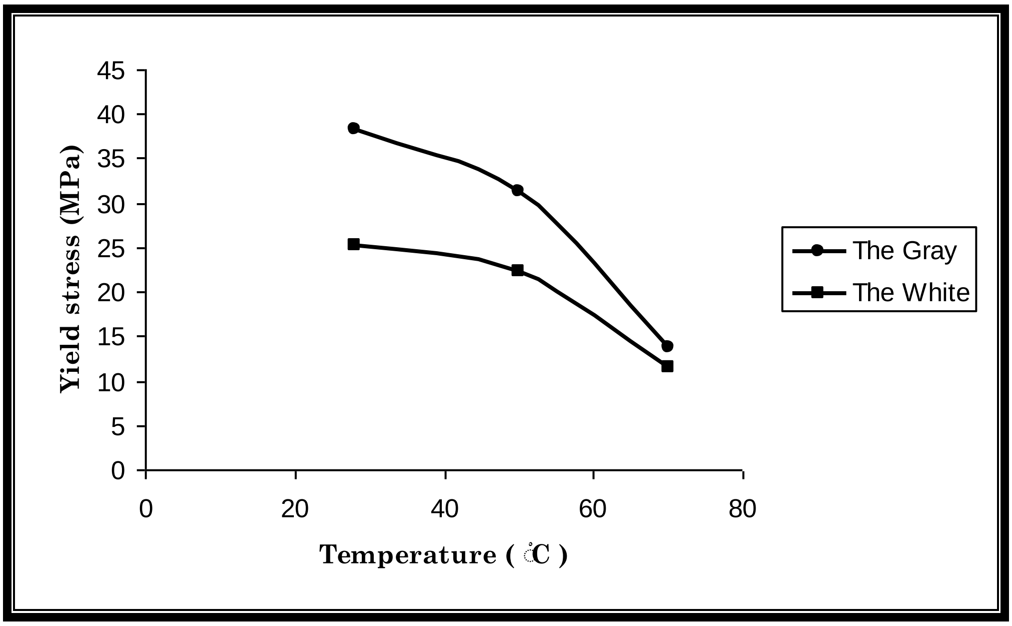


Fig.(4-7):Variation of yield stress with temperature for two PVC pipes material at 5mm/min.

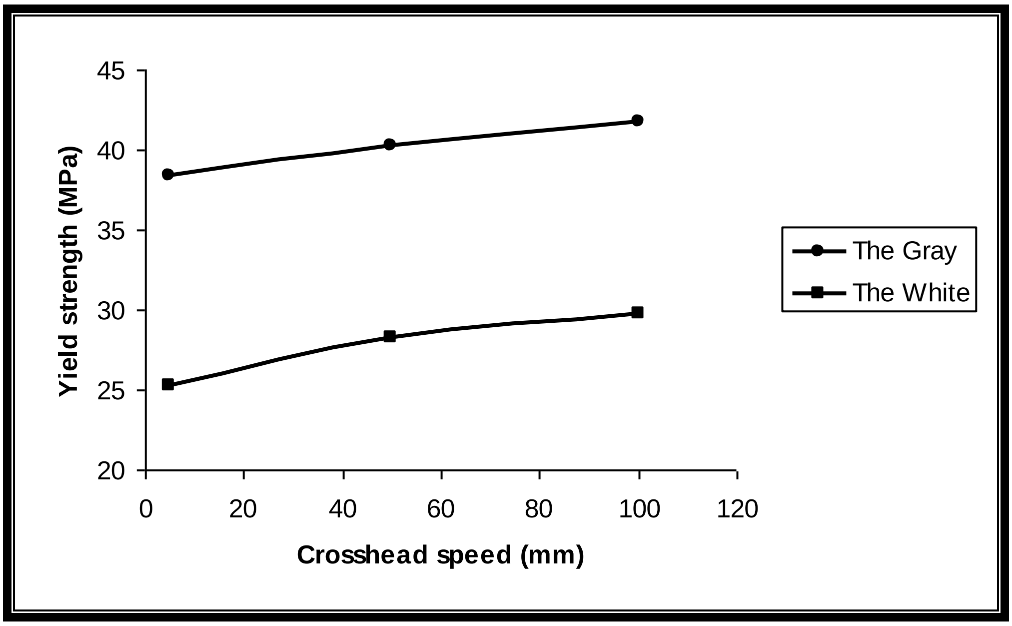


Fig.(4-8):Variation of yield stress with crosshead speeds for two PVC pipes material at 28°C.

4-2-1-2 Elastic Modulus

Fig. (4-9) shows variation of elastic modulus with temperature for two PVC pipes material at 5 mm/min. It can be seen that the elastic modulus decrease with increasing temperature. When the temperature increases, PVC pipe material transition from the glassy state to plastic state, that meaning increasing in length of polymer chain and decreasing in the elastic modulus.

Fig.(4-10) shows variation of elastic modulus with crosshead speeds for two PVC pipe materials at 28°C. When the crosshead speed increases, the sample breaks quickly due to insufficient time to remove the bond between molecular chains. This results increasing of elastic modulus.

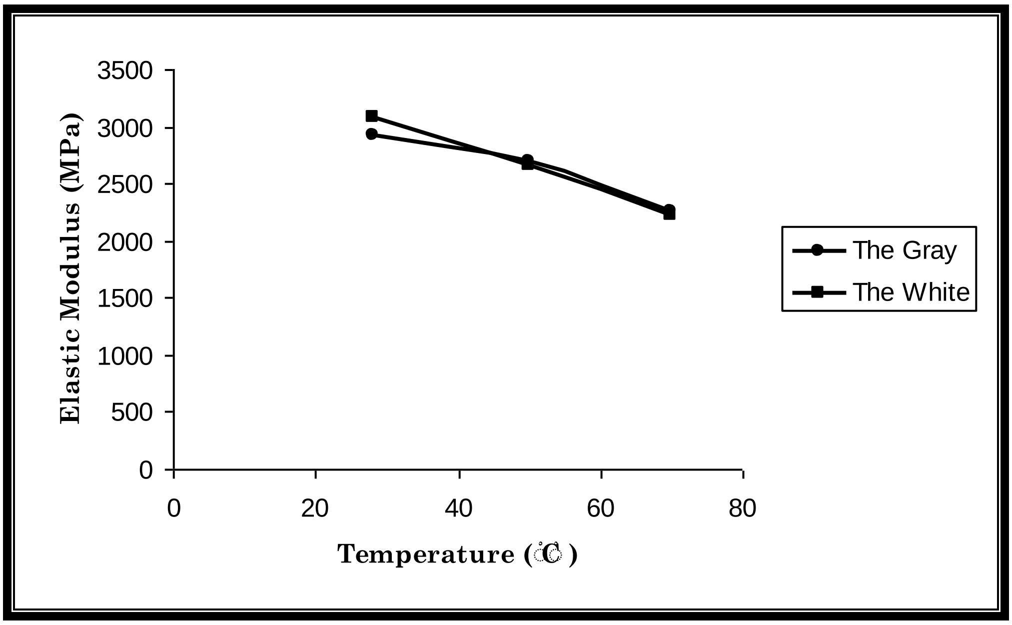


Fig.(4-9):Variation of elastic modulus with temperature for two PVC pipes material at 5 mm/min.

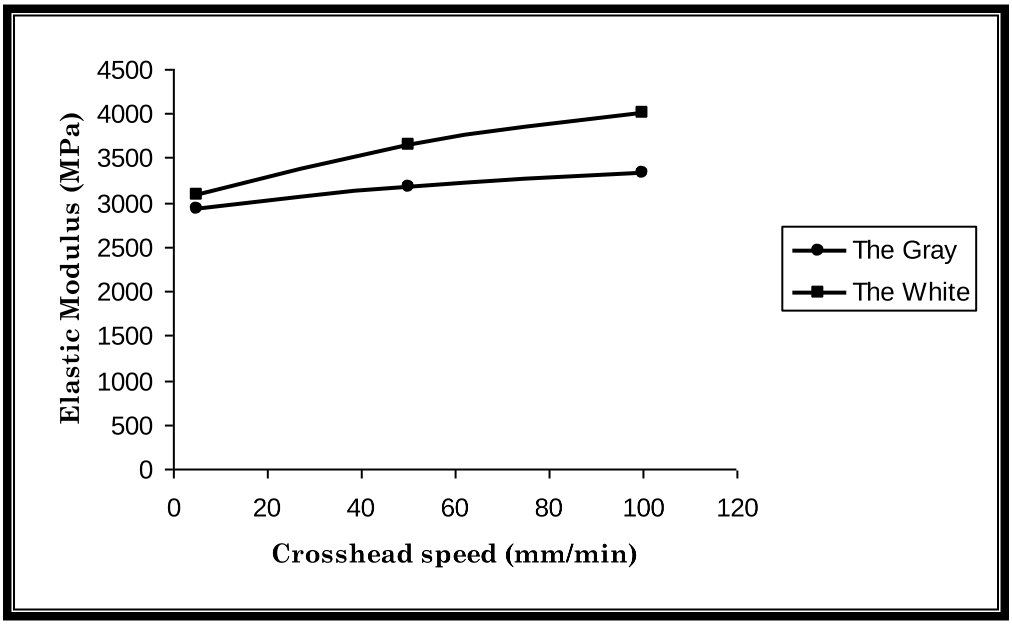


Fig.(4-10):Variation of elastic modulus with crosshead speeds for two PVC pipes material at 28 °C.

4-2-1-3 Fracture Strain

Fig.(4-11) illustrates the relationship between fracture strain and temperature, when temperature increases the fracture strain increases and the increasing is large at 70°C.

This is because the molecular chains are frozen from moving at low temperatures. Whilst at 70°C increases rapidly because of enhancement of molecular mobility.

Fig.(4-12) illustrates variation of fracture strain with crosshead speed for two PVC pipes material at 28°C. It can be seen that the fracture strain decreases with increasing crosshead speed. That back to decrease the elongation of material due to strong of the bond between the molecules and insufficient time to remove this bond.

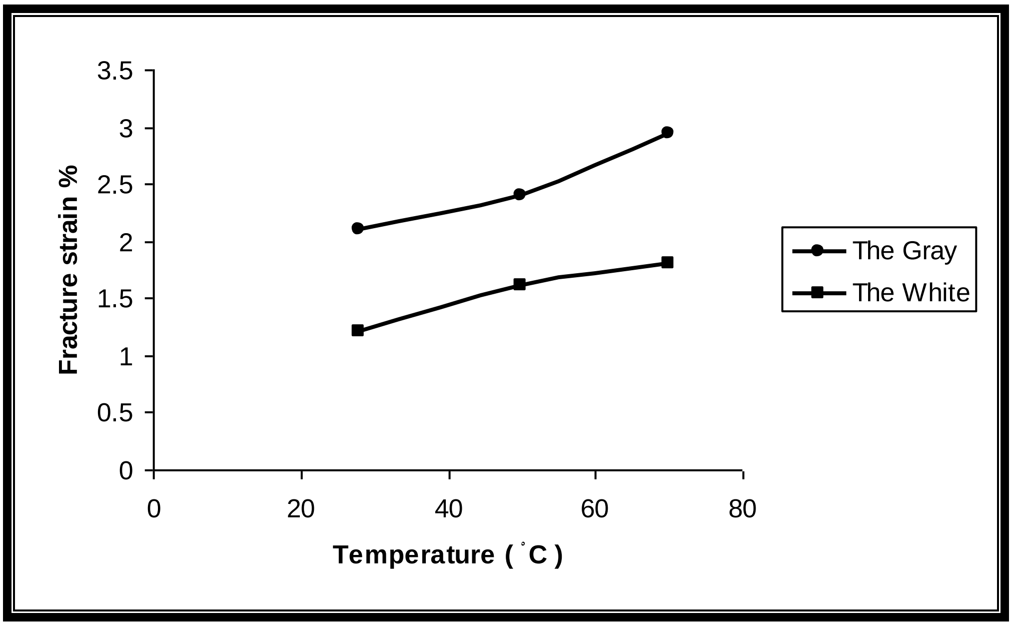


Fig.(4-11):Variation of fracture strain with temperature for two PVC pipes material at 28°C.

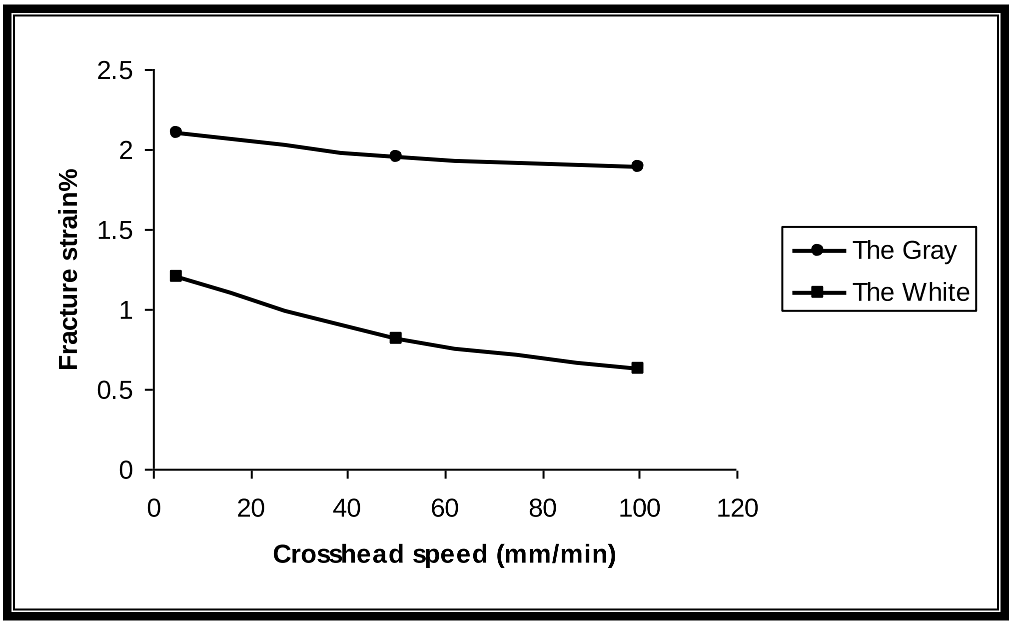


Fig.(4-12):Variation of fracture strain with crosshead speed for two PVC pipes material at 28°C.

4-2-2 Effect of UV radiation on tensile properties of PVC pipe material

Effect of exposure of the tensile samples to UV radiation for different times (7,17,30 and 45 days) on tensile properties such as yield stress, elastic modulus and fracture strain are discussed in the following sections. Figures (4-13) and (4-14) illustrate stress-strain curves for the gray and white pipe materials respectively at different times from exposure to UV.

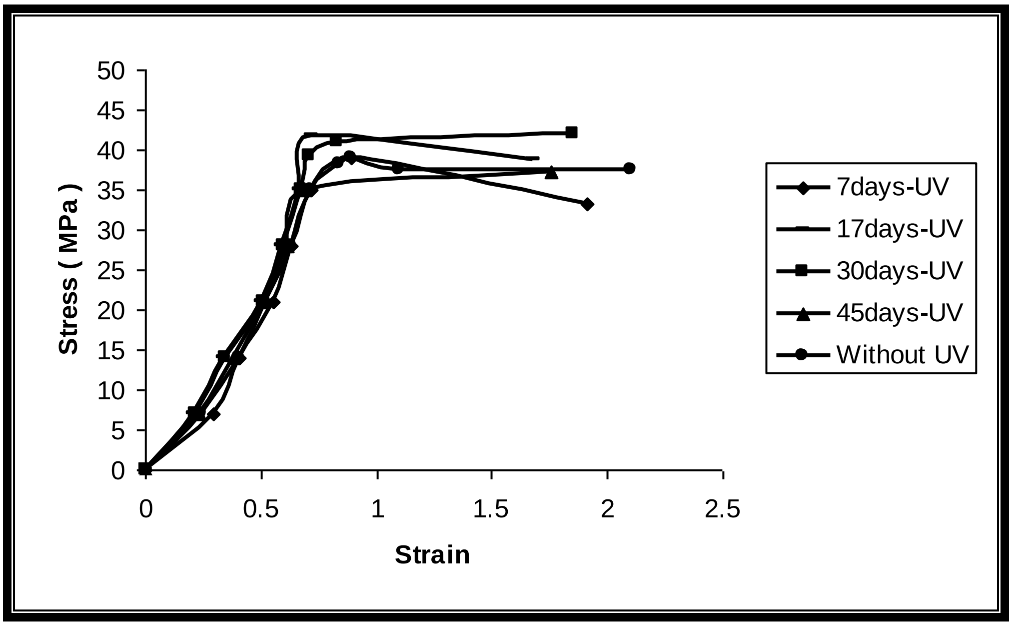


Fig.(4-13): Stress-strain curves for the gray pipe at different times from exposure to UV at 28°C.

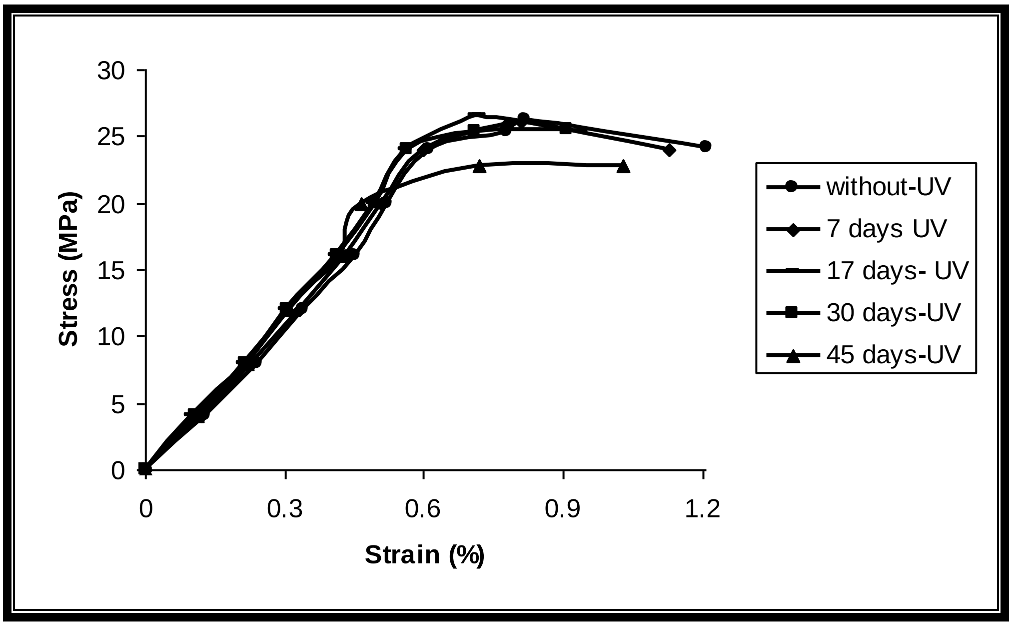


Fig.(4-14): Stress-strain curves for the white pipe at different times from exposure to UV at 28°C.

4-2-2-1 Yield Stress

Fig.(4-15) shows variation of yield stress with UV radiation for the two pipe materials. It can be seen that the yield stress increase with the first periods of exposure to UV but it decreases with increasing exposure time to UV. Because happening cross-linking caused by UV radiation , the material is unable the plastic deformation so, the yield stress is increased. Many cracks are happened in the exposed sample to UV for a large time that caused weak in the bound therefore, the material need a low stress in order to yield.

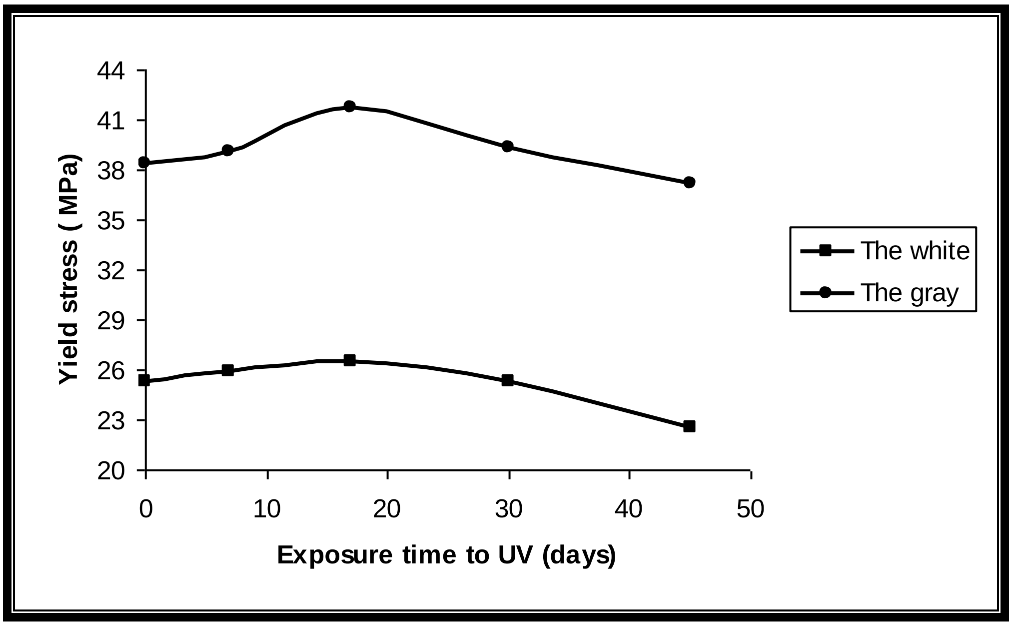


Fig.(4-15):Variation of yield stress with UV radiation for two PVC pipe materials.

4-2-2-2 Elastic Modulus

Fig.(4-16) shows variation of elastic modulus with UV radiation for two pipe materials. It can be seen that the result of elastic modulus is corresponding with the yield stress where it increases with the first periods then it decreases with the large periods of exposure to UV. In elementary times of the exposure, the elasticity of material decreased due to the strong bond between the polymer chains. When the cracks are occurred densely, the linkage reduced that serves to enhancement of elasticity.

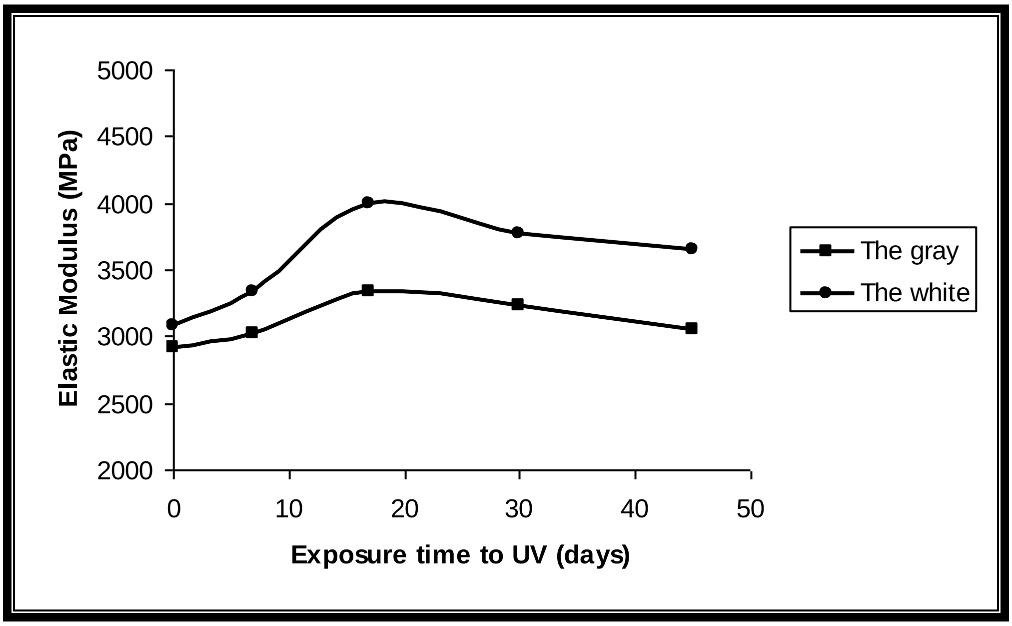


Fig.(4-16):Variation of elastic modulus with UV radiation for two PVC pipe materials.

4-2-2-3 Fracture Strain

Figure (4-17) shows variation of fracture strain with UV radiation for two pipe materials. It can be seen that the fracture strain decreases with increasing the time of UV radiation, where due to happening cross-linking and cracks, the material becomes brittle and it breaks directly after its yield, so the elongation is reduced.

From previous Figures (4-15, 4-16 and 4-17), it can be seen that the white kind is effected by UV larger than the gray one. This is due to absence of carbon black and the lower content from TiO_2.

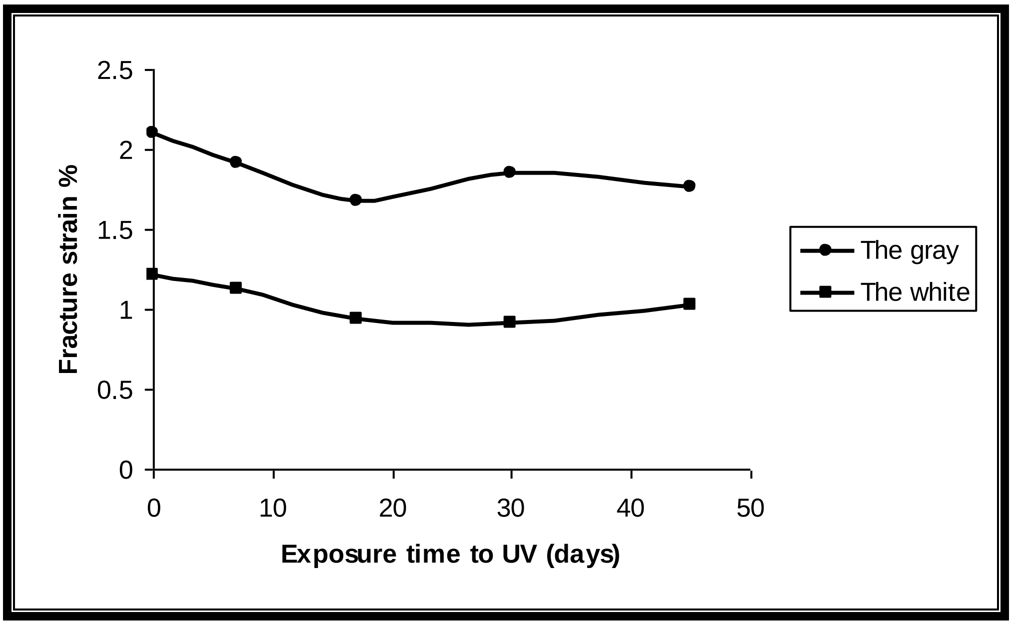


Fig.(4-17):Variation of fracture strain with UV radiation for two PVC pipes materials.

4-3 Impact strength

Impact strength is calculated of samples by Charpy method where it usually expressed about the impact strength by the energy to break divided by the cross sectional area of the sample to avoid the difference in the dimensions of samples.

Figure (4-18) shows that the impact strength changes with increasing of temperatures for two types of PVC pipe materials, where the impact strength for the gray at room temperature is (34.21 kJ/m^2) and increases gradually until reaching to(69.13kJ/m^2) at 51°C. After this temperature, the samples do not break as in the figure (3-16 b).

The reason of this behavior is that the material becomes ductile and the bonds are among molecules of material become weak therefore they will be move slidingly. So, the material needs to very large energy to break. Contrarily to above, the impact strength decreases at temperatures under room temperature. This behavior is occurred due to a material that becomes brittle, so it is unable to dissipate the energy but the energy is absorbed absolutely. At last, the catastrophic failure is occurred.

Figure (4-19) illustrates that the impact strength decreases with increasing time of exposure to UV. This behavior is due to cross-linking induced by UV radiation therefore, the material becomes so hard and bound, when it exposed to a sudden blow becomes unable to dissipated the energy.

While the above behavior is correspondent with the white pipe, but the different results of the gray pipe are found. The impact strength is lower than the gray kind, this is belong to that the white kind contains calcium carbonate with high magnitude where the non fibrous fillers result the lowering in the impact strength [61].

In UV radiation case, the impact strength is decreased so much, the reason of this behavior is absence of carbon black and Tio_2 is lower than the gray.

Figure (4-20) shows variation of impact strength with crack depth of the two pipes material at room temperature. It can be seen that the impact strength decreases with increasing the crack depth. That attributes to the notch sensitivity where the notch that is fond in the sample is result formation and concentration a localized stresses, that causes break the sample at the exposure to impact loading [62].

From Table (11 in appendix), it can be seen that the notched Charpy energies are much lower than the unnotched Charpy energy. This would be expected since an Charpy test carried out with a notched specimen gives an indication of the energy required to propagate a crack that has already been initiated whereas a test using an unnotched specimen gives an indication of the energy required to initiate and propagate a crack through a material.

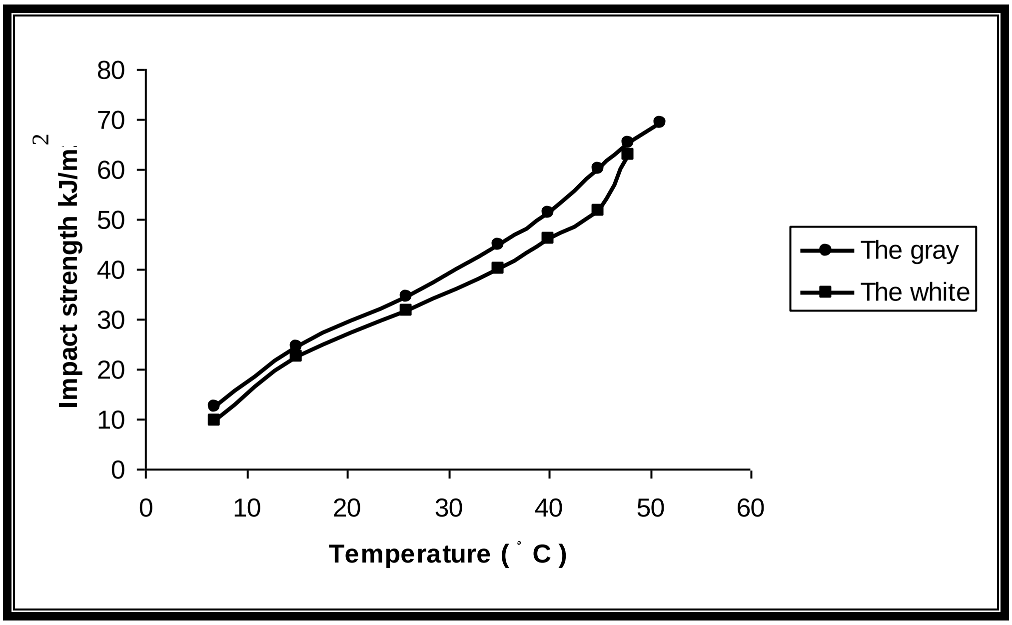


Fig.(4-18):Variation of impact strength with temperature of the two pipe materials.

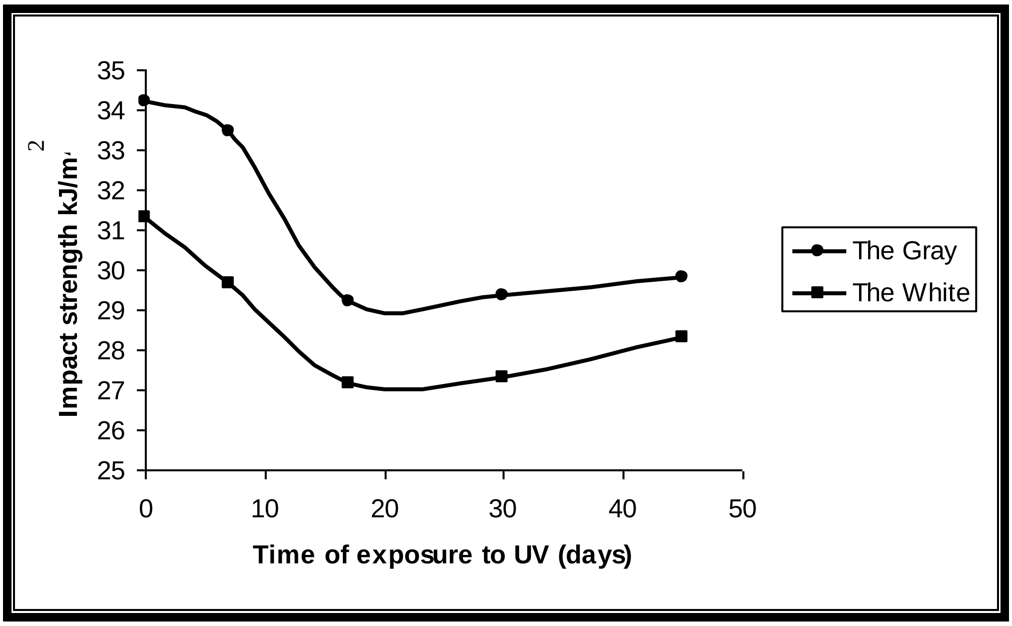


Fig.(4-19):Variation of impact strength with the time of exposure to UV(days) of the two pipe materials.

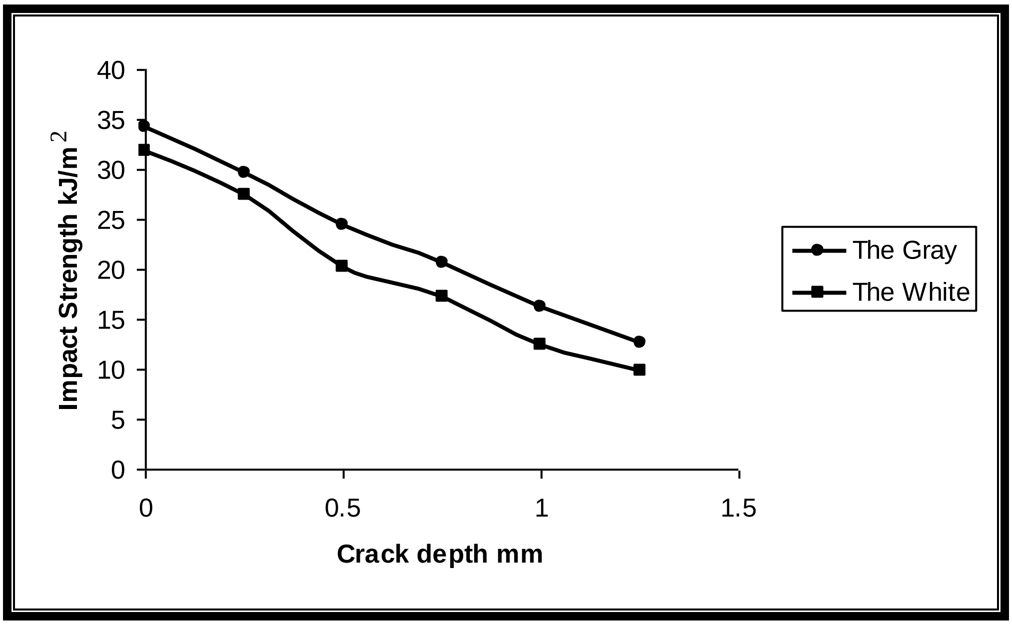


Fig.(4-20):Variation of impact strength with crack depth of the two pipe materials at room temperature.

4-4 Fatigue behavior

PVC pipes used for water distribution, are subjected to an internal pressure, which can vary according to the water demand. The resulting fluctuating, stresses the pipe wall causing fatigue loading.

The relationship between stress amplitude (MPa) and cycles to failure (N_f) is graphed by reverse bending at stress ratio R=-1, where Y-axis represents stress amplitude while X-axis represents cycles to failure.

From Figure (4-21) it is observed when stress amplitude is high, the cycles to failure are low due to elastic-plastic deformation which occurred on the surface, followed by the growth of crack and then failure. This mechanism of failure is called Elastic-Plastic Fracture Mechanics. When the stress is low, the cycles to failure are high due to the elastic failure which is called Linear Elastic Fracture Mechanics .

Fig.(4-22) shows the relationship between temperature and cycles to failure. It is observing from that, the cycles to failure will be decreasing so much with increasing the temperatures when the cycles to failure are (334218),(4671) at (6°C),(50°C) respectively. That back to the molecular chains (at low temperatures) are consistent with each other inside the material. The molecules are unable to move and the strong bonding among the molecules will obstruct propagation of crack so, final failure will occur when there is too many cycles.

On the contrary, with high temperatures the bonds among the molecular chains are weak, that is easy to grow and propagate the crack quickly. Finally, the final failure will happen with a few cycles.

Fig.(4-23) shows variation cycles to failure with the exposure time to UV. It can be seen that the cycles to failure increase with increasing time of exposure to UV.

From this Figure, it can be seen that it is not noticeable change in the cycles to failure after (7) days from the exposure to UV but after this time (17 days), increasing in the cycles to failure is occurred.

This behavior attributes to obtain the cross-linking between the molecular chains. However, the material becomes very hard due to the strong bond between the molecules of material. This serves to delay of the formation and propagation of the crack. Therefore , the final failure occurred after a large number of the cycles.

It can be seen from the same figure, the cycles to failure decrease too much after exposure to UV for (45) days . this is due to form cracks that meaning happing of the first stage from fatigue stages therefore and due to found these cracks , a few cycles are enough to propagate the crack and happening the failure.

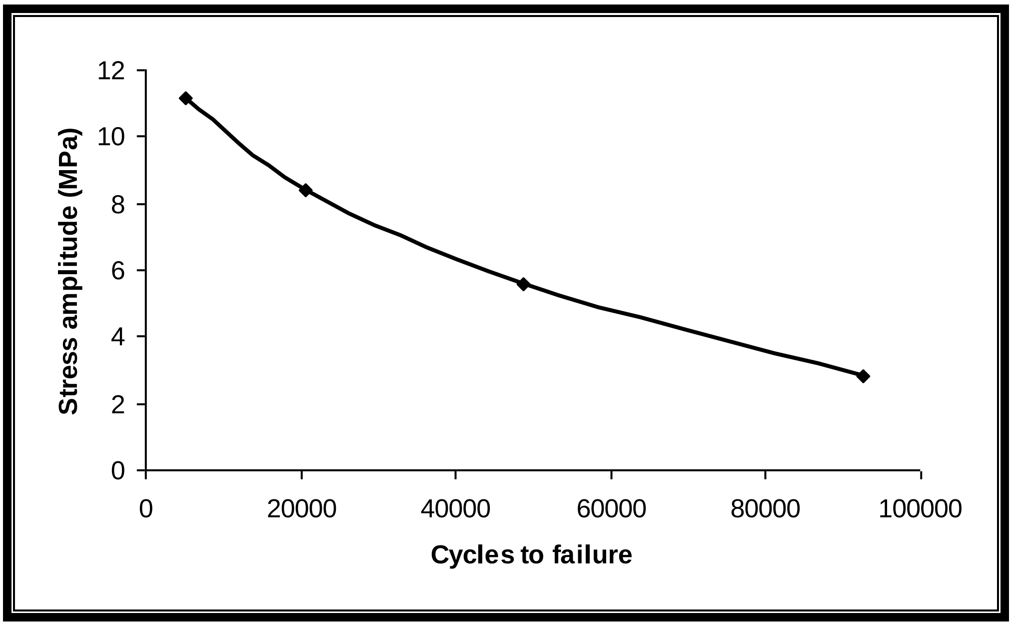


Fig.(4-21): The relationship between stress amplitude and cycles to failure for PVC pipe material.

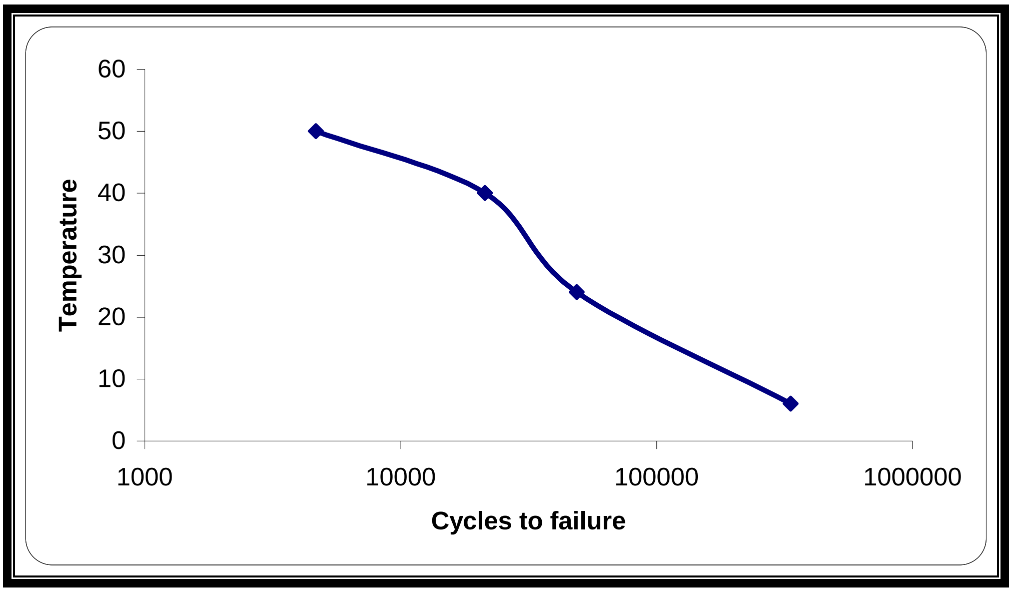


Fig.(4-22): Variation of cycles to failure with temperatures at constant stress (5.58 MPa).

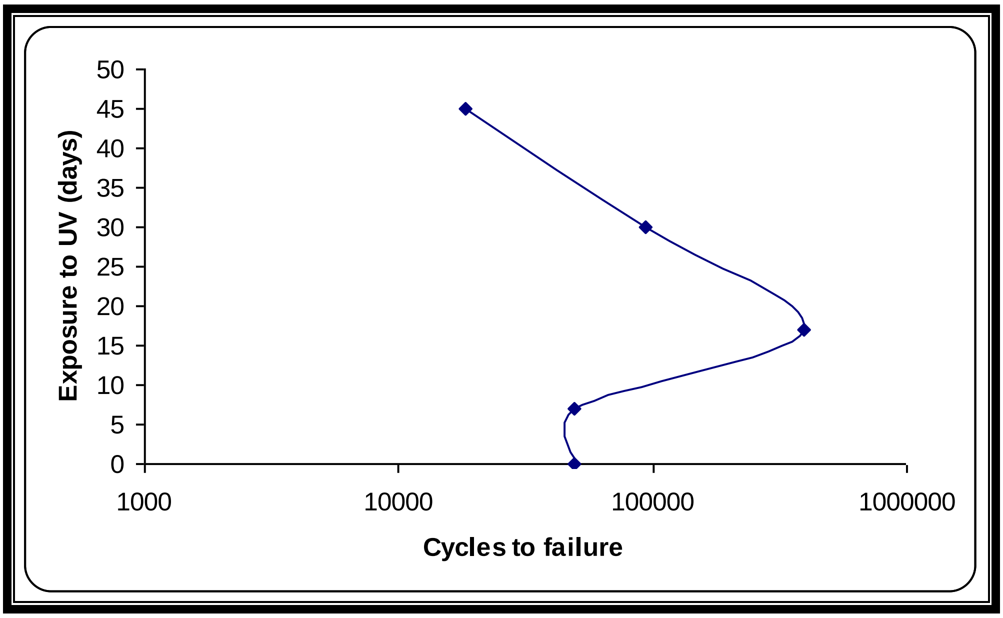


Fig.(4-23): Variation of cycles to failure with exposure time to UV at constant stress (5.58 MPa).

4-5 Results of optical Microscope

According to the Figures (4-24, 4-25), it can be observed that there is a change in color of sample, where PVC deteriorates by releasing hydrogen chloride HCl, forming conjugated double bonds which give a yellow-brownish color and a burned surface appearance.

Figures (4-26 a, b, c) show that when it is at room temperature and high strain rate and until at low strain rate, the brittle fracture is observed, while the ductile fracture occurred at high temperatures and low strain rate.

From figures (4-26 a, b) , it can be seen happening of crazing in samples at high temperatures where this phenomena involves a localization of the plastic deformation in the material.

In impact test, Figures (4-27 a, b, c) show also that the ductile failure is observed in high temperatures, while the brittle failure is recognized in low temperatures.

Figures (4-28 a, b, c) show the fracture surfaces of fatigue test samples are tested at different conditions.

It is observed from Figures (4-26),(4-27) and (4-28) that with plastics a brittle failure gives fracture surfaces which are smooth and glassy or somewhat splintered, with a ductile failure the surfaces often have a whitened appearance.

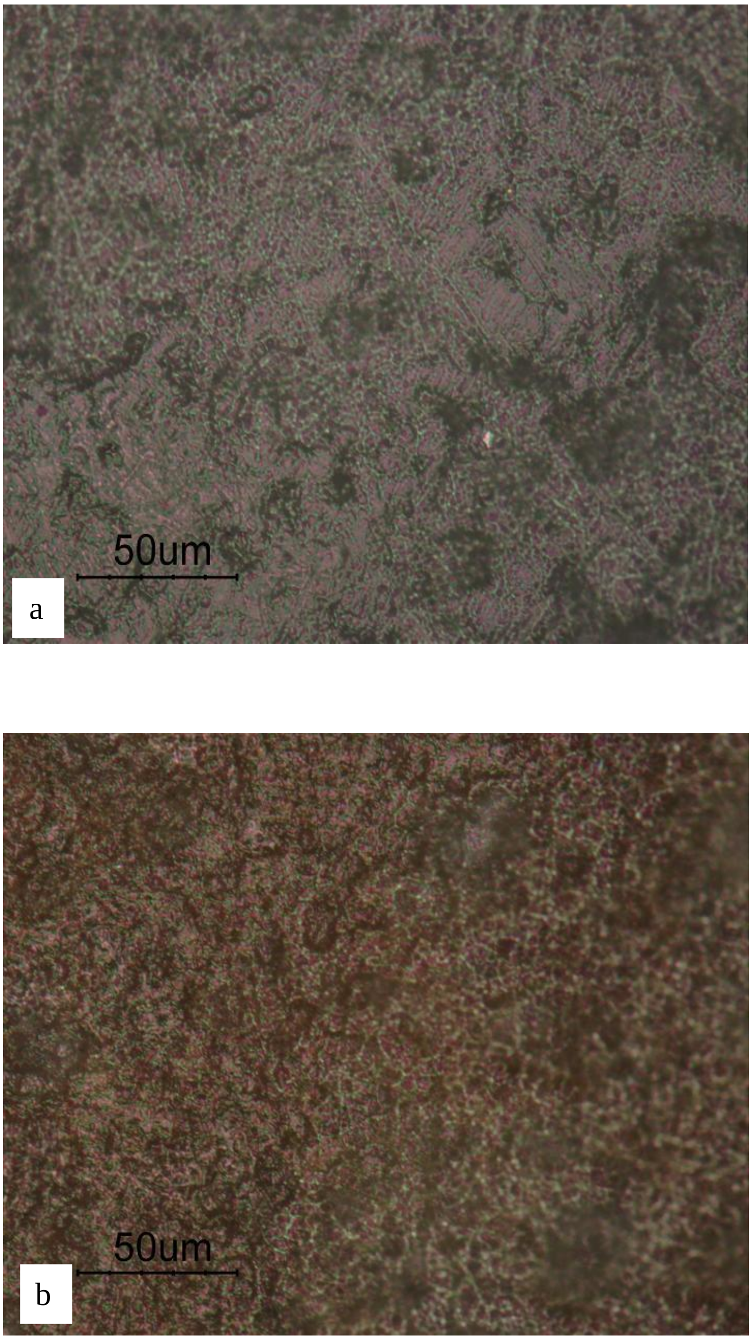


Fig.(4-24): Effect of UV on surface of the gray pipe (a) after 7 days (b) after 45 days (magnification 500x).

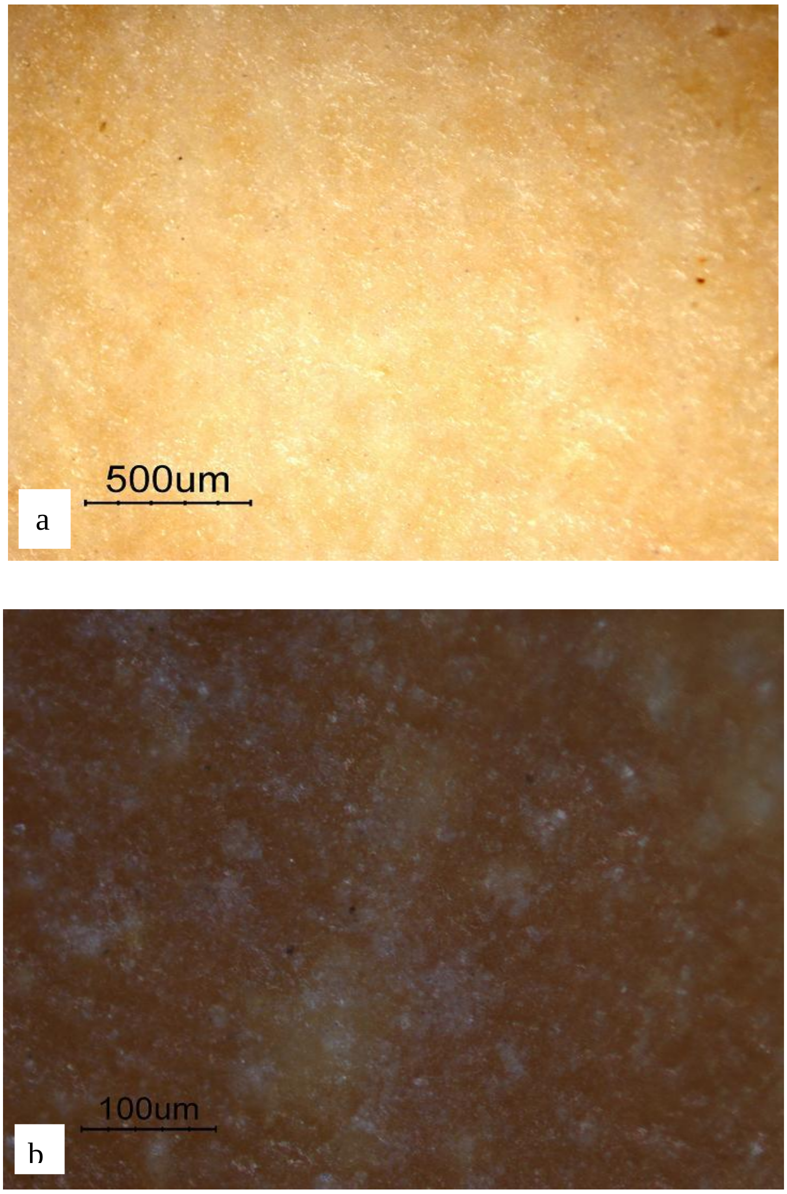
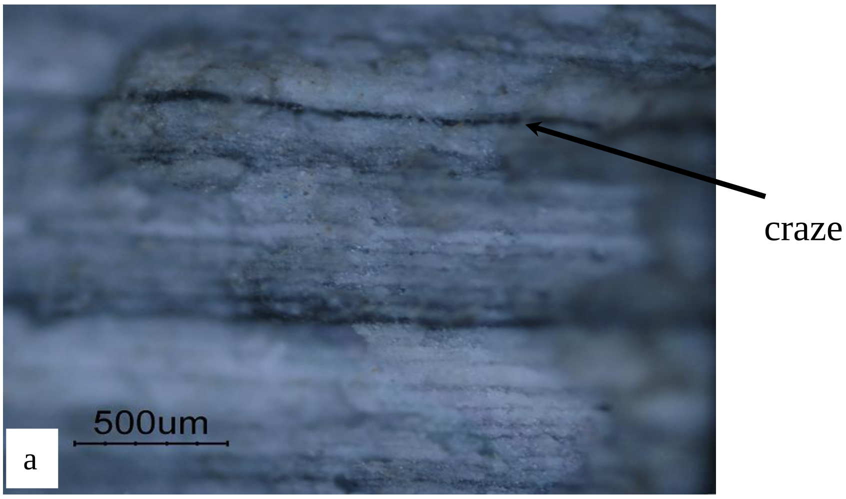
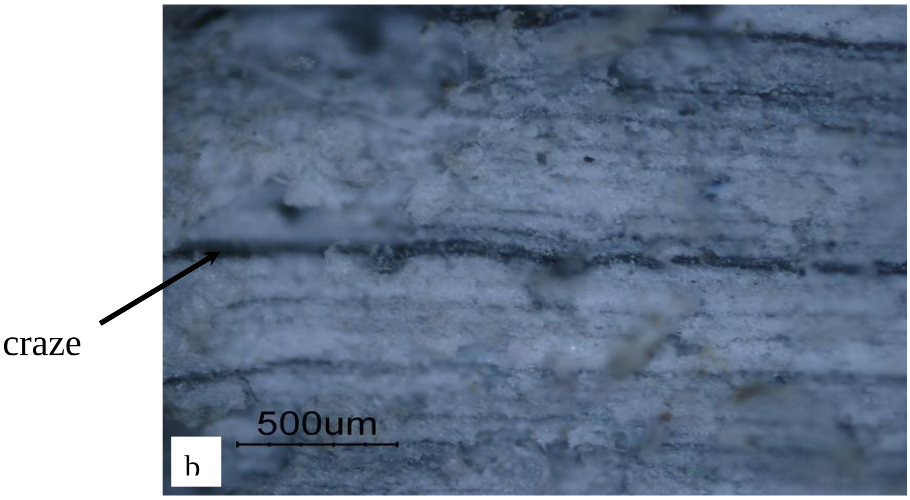


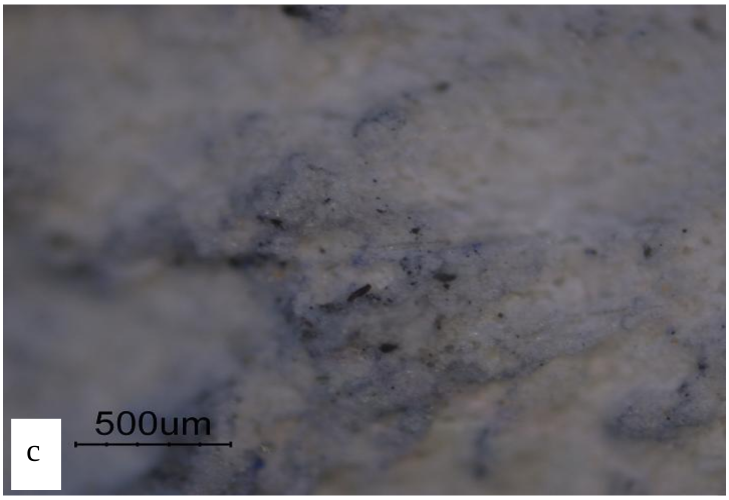
Fig.(4-25): Effect of UV on surface of the white pipe (a) after 7 days (b) after 45 days (magnification 500x).



Tensile test sample tested at 70°C and 5mm/min .

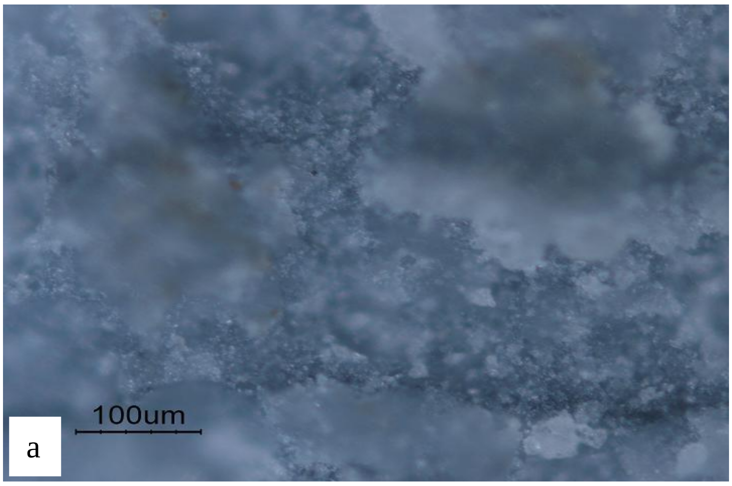


Tensile test sample tested at 70°C and 100 mm/min .

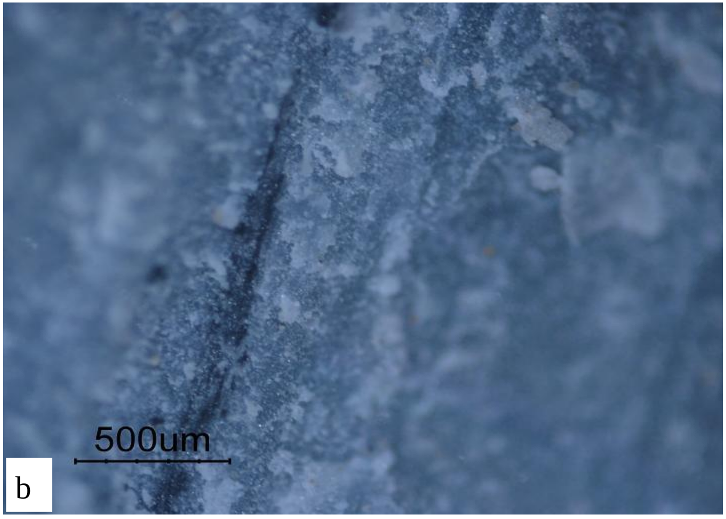


Tensile test sample tested at 28°C and 100 mm/min

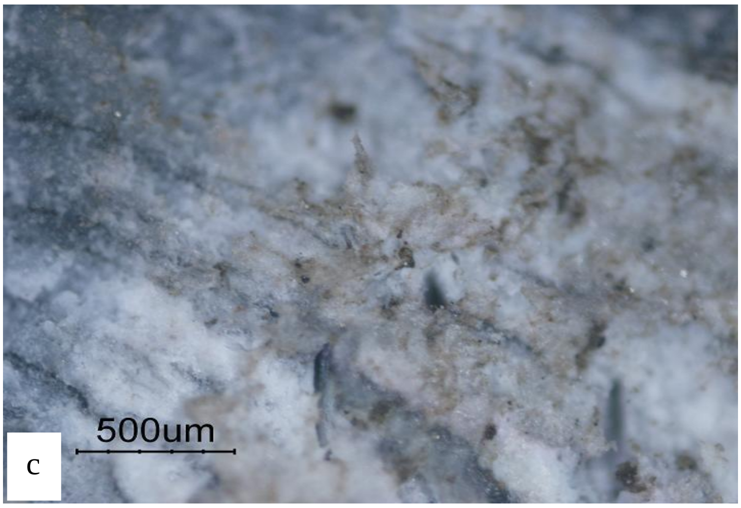
Fig.(4-26): Fracture surfaces observations for the tensile test samples (magnification 50x) .



Impact test sample tested at 26°C

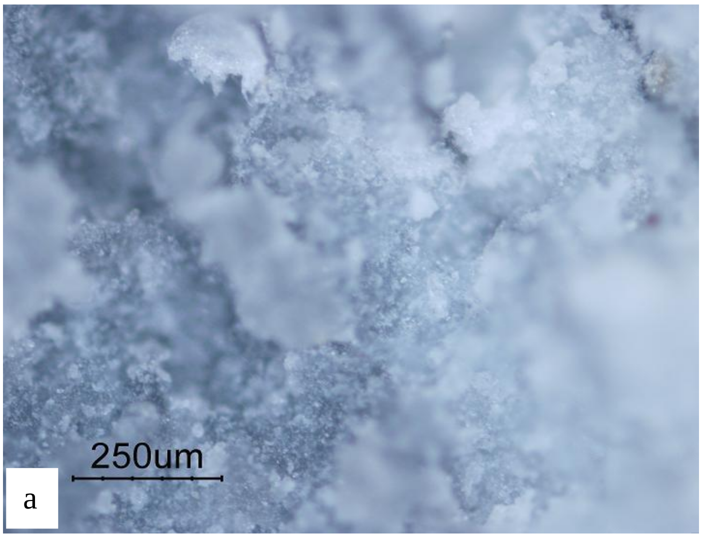


Impact test sample tested at 50 °C

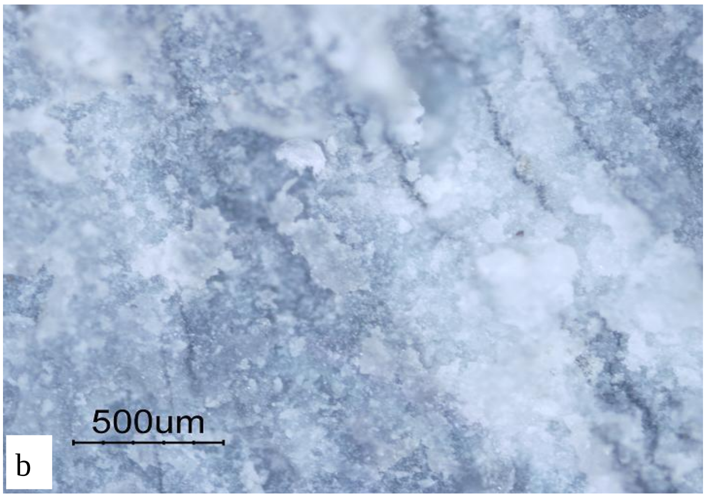


Impact test sample tested at 7 °C

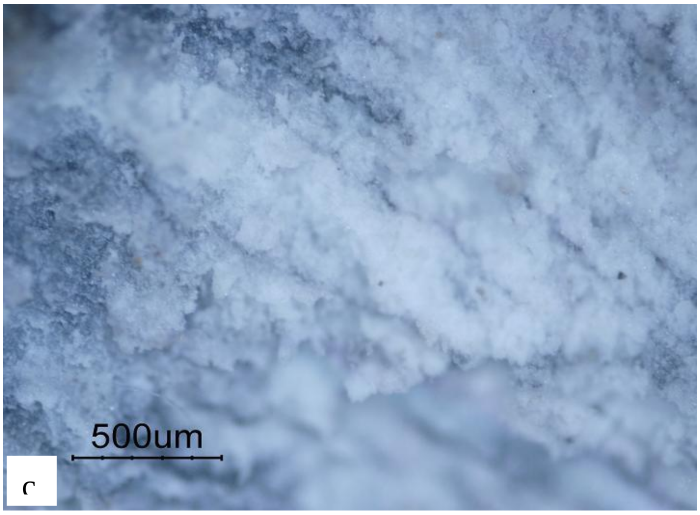
Fig.(4-27): Fracture surfaces observations for the impact test samples (magnification 50x) .



Fatigue test sample tested at 40 °C



Fatigue test sample tested at 24°C



Fatigue test sample tested at 6°C

Fig.(4-28): Fracture surfaces observations for the fatigue test samples (magnification 50x).

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

5-1 Conclusions

According to the results of the present study, the following conclusions were obtained:-

1- The yield stress decreased from (38.34 MPa) to (13.62 MPa) with increasing temperature from (28 °C) to (70°C) at (5 mm/min) , while it increased from (38.34 MPa) to (41.78MPa) when the crosshead speed increased from (5 mm/min) to (100 mm/min) at (28 °C) .

1- The elastic modulus decreased from (2916.66MPa) to (2258.06MPa) with increasing temperature from (28 °C) to (70°C) at (5 mm/min) , while it increased from (2916.66 MPa) to (3233.31 MPa) when the crosshead speed increased from (5 mm/min) to (100 mm/min) at (28 °C) .

3- The yield stress and elastic modulus increased then decreased with increasing the time of UV radiation.

4- The fracture strain increased with increasing temperature at all crosshead speeds (5 mm/min, 50 mm/min, 100 mm/min). The increase was the largest at 70°C due to increase the ductility of material. Whilst the fracture strain decreased with increasing time of UV radiation.

5- The impact strength increased from (34.21kJ/m^2) to (65.38 kJ/m^2) with increasing temperature from (26°C) to (48°C) respectively, while at low temperatures the impact strength of PVC pipes material drastically changes for the worse.

6- The impact strength decreased with increasing the time of exposure to UV and the increasing in the crack depth.

7- The cycles to failure decreased with increasing stress and temperature while they increased then decreased with increase the time of exposure to UV. The cycles to failure were (48818) and (392022) for unexposed sample and for exposed sample to UV for 17 days respectively.

8- The impact strength of the white pipe material was lower than the gray pipe due to the high content of calcium carbonate. At room temperature, the impact strength for gray pipe was (34.21 kJ/m^2) while for white pipe was (31.78 kJ/m^2).

9- The white pipe was affected by UV larger than the gray pipe due to absence of carbon black and the low content of TiO_2.

5-2 Recommendations for future work

The following recommendations can be helpful for further study:-

1- Effect of strain rate and temperature on fracture toughness of PVC pipe material.

2- Use of temperatures higher and lower than that used in the present study.

3- Effect of temperature and UV radiation on bending, compressive and creep properties of PVC pipe material.

4- Effects of strain rate and temperature on tensile properties of the other types of pipe materials.

5- Effect of natural weathering on the mechanical properties of the two type of PVC pipe materials.

Examination Committee Certification

We certify that we have read this thesis, titled **"Effect of Temperature and UV on Some Mechanical Properties of PVC Pipes"**, and as examining committee examined the student **"Mohammed Razzaq Mohammed "** in its contents and in what is connected with it, and that in our opinion it meets the standard of a thesis for the degree of Master of Science in Materials Engineering.

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NOMENCLATURE

Symbol	Description	Unit
A	cross-sectional area of the specimen.	m^2
E	Elastic modulus	MPa
I.S.	Impact strength	kJ/m^2
K_{max}	The maximum value of the stress intensity factor	$MPa.m^{0.5}$
K_{min}	The minimum value of the stress intensity factor	$MPa.m^{0.5}$
l	Sample length	mm
N_f	Cycles to failure	-
R	stress ratio	-
T	Temperature	℃ or K
t	Sample thickness	mm
UC	Fracture energy	kJ
w	Sample width	mm
ΔK	Stress intensity factor	$MPa.m^{0.5}$
v	Crosshead speed	mm/min
ε□	Strain rate	s^{-1}
ε_f	Fracture strain	-
ε	Engineering strain	-
σ_{ys}	Yield stress	MPa
σ_a	cyclic stress amplitude	MPa
σ_m	mean stress	MPa
σ	cyclic stress range	MPa
σ_{max}	Maximum stress level	MPa
σ_{min}	Minimum stress level	MPa
λ	wavelength	°A

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الخلاصة

إن أنابيب البولي فنيل كلورايد(PVC) المستخدمة في نقل المياه وكذلك المستخدمة في الصرف الصحي أصبحت تنافس الأنابيب المصنعة من المواد الأخرى نظراً لخواصها الجيدة.

تم في هذا البحث دراسة بعض الخواص الميكانيكية لنوعين من أنابيب PVC تحت ظروف مختلفة.

تم تحضير العينات بتقطيع الأنبوب إلى حلقات تسخن في الفرن لغرض الحصول على قطع مستوية ثم حضرت عينات الشد، الصدمة و الكلال من هذه القطع طبقاً للمواصفات القياسية.

تم في هذه الدراسة بحث تأثير معدل الانفعال (سرعة رأس الجهاز) ودرجة الحرارة ومن جانب أخر تأثير الأشعة فوق البنفسجية على خواص الشد لأنابيب PVC . كذلك تم دراسة تأثير درجة الحرارة والأشعة فوق البنفسجية على مقاومة الصدمة وسلوك الكلال لمواد أنابيب البولي فنيل كلورايد.

أظهرت نتائج اختبار الشد بان إجهاد الخضوع ومعامل المرونة يزداد بزيادة معدل الانفعال ونقصان درجة الحرارة. إن قيم إجهاد الخضوع ومعامل المرونة هي (38.34MPa) ، (2916.66 MPa) عند (28 Ċ) بينما كانت (13.62 MPa) ، (2258.06 MPa)عند (70 Ċ) على التوالي. إن كل من إجهاد الخضوع ومعامل المرونة يزداد ثم يقل بزيادة فترة التعرض إلى إشعاع UV في حين أن انفعال الكسر يزداد بزيادة درجة الحرارة ونقصان معدل الانفعال ويقل بزيادة فترة التعرض إلى إشعاع UV.

أوضحت نتائج اختبار الصدم بان مقاومة الصدمة تزداد بزيادة درجة الحرارة وتقل مع زيادة كل من فترة التعرض إلى الأشعة فوق البنفسجية وعمق الشق. بلغت

قيمة مقاومة الصدمة ($34.21kJ/m^2$) عند (26 Ċ)في حين بلغت (65.38 kJ/m^2) عند (48 Ċ). إن مقدار مقاومة الصدمة هي ($34.21kJ/m^2$) للعينة غير المعرضة إلى الأشعة بينما كانت (29.18 kJ/m^2) للعينة المعرضة إلى الأشعة فوق البنفسجية لمدة 17 يوم.

أظهرت نتائج اختبار الكلال بان عدد الدورات لغاية الفشل يقل مع ازدياد الإجهاد المسلط. كذلك لوحظ بان عمر الكلال يقل مع ازدياد درجة الحرارة حيث بلغ عدد الدورات (334218) عند(6 Ċ) بينما كان (4671) عند (50 Ċ) . كما بينت النتائج بان عدد الدورات يزداد بشكل كبير بعد تعريض عينة إلى UV لمدة(17) يوم ولكن بعد هذه الفترة فان العدد يقل كثيراً. بلغ عدد الدورات لغاية الفشل (392022)، (18224) و (48818) لعينات معرضة إلى UV لمدة 17 يوم ، 45 يوم و لعينة غير معرضة للأشعة عند الإجهاد نفسه (5.58 MPa) على التوالي.