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Working-life effects on the properties of plastic thermopipes

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Mechanical properties and morphological studies of polypropylene thermopipes manufactured in Jordan and usually used in heating system networks, have been investigated. Samples were chosen to represent new and different working periods (1, 3.5 and 6 y). The flow resistance of water inside the pipes showed a slight decrease in the first year followed by an increase after the second year of use. A decrease in resistance was observed with increasing working temperature and Reynold's number. The stress–strain tests exhibit property changes towards brittleness and glassy behaviour, observed after 6 y working service. Evidence of deformation was seen by scanning electron microscopy (SEM). Deterioration and cracks on the internal surfaces of aged thermopipes were also noticed.

1. Introduction

Jordan has witnessed large expansions in the plastic industry over the past ten years, and this constitutes an important asset to Jordan's economy. In particular, polypropylene pipes (or thermopipes) are used extensively in heating systems at large [1]. In fact, thermopipes are considered as the primary substitute for the commonly used iron pipes. The observed increase in market share reflects its importance as a promising material for industry, technology and engineering applications [2–4]. Polypropylene is, however, a crystalline thermoplastic produced by polymerizing propylene monomer in the presence of a stereo-specific catalyst. The latter helps in building up long chains in such a way that a systematic arrangement of the methyl groups is achieved [2]. Thermal properties, such as the low conduction and high specific heats, places the pipes ahead of metallic pipes. On the other hand, the mechanical properties, including fluid resistance, are higher while strength is lower than in metallic pipes [5]. The mechanical properties are, however, influenced by several factors, such as ageing, thermal degradation, erosion and ultraviolet irradiation. Air and water, oxygen and nitrogen may penetrate and dwell within the plastic, affecting all polymer properties by deforming the chain flexibility and affecting the material, causing it to become more brittle with a tendency towards a glassy behaviour [6]. In particular, the role played by oxygen and its transport within polymeric films has been extensively studied, and several methods have been devised to coat polymers with anti-oxygen protective films [7].

The potential applications of polymeric materials have recently received much attention and wider interest in studies of ageing of plastic used for heating systems. Data on the mechanical properties and their modifications with ageing have been reported [8–10]. These include studies of the brittle fracture behaviour of the creep rupture of polystyrene [8] which indicated a decrease in the life times for rupture with ageing and consequently caused the material toughness to be reduced. On the other hand, the change in the mechanical properties of polyethylene terephthalate [9] has resulted in an increase of yield stress followed by a decrease in the percentage of elongation to break, such that a value equal to zero has been reached after 110 d working life at 40 °C. In another investigation of the ageing time superposition effect of polycarbonate on the torsion of cylindrical solid samples, an increase in stress needed for 4.5% strain at 70 °C was observed [10].

The present study was conducted upon request from the manufacturing company, Plastic World, Jordan, to investigate the effects of working life on some of the thermopipes properties, including flow resistance measurements, stress–strain tests and morphology.

2. Experimental procedure

Thermoplastic pipes (DIN 8078T2) used in heating systems were supplied by Plastic World Company, Amman, Jordan. Four samples were extracted from differently aged networks representing new, 1, 3.5 and 6 y service periods. Samples 2.5 m long, (enough to produce a readable pressure gradient and fully developed flow with 25 cm entrance length) and 12.5 mm diameter (enough to produce fully developed flow), were taken from each aged pipe. The developed flow was observed to be fully turbulent. Inner and outer

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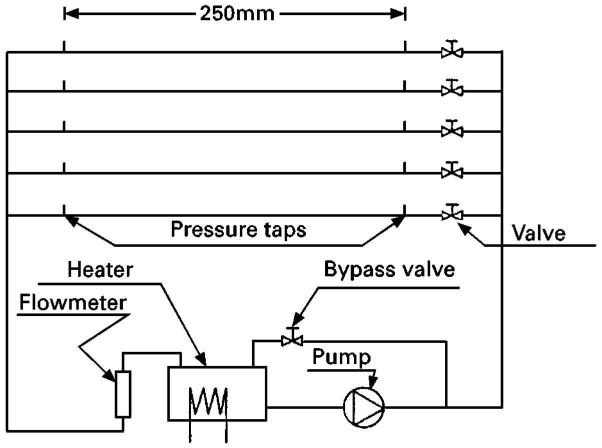

Figure 1 Schematic diagram of the pressure gradient apparatus.

diameters were all measured before installation. The flow resistance, being the main specification used for pump design and selection employed in heating circuitry, can markedly influence the power consumption. Pressure difference tests were performed at various working temperatures ranging from 50–90 °C. Such measurements were made using a locally constructed apparatus, see Fig. 1. A U-shape water tube manometer with a positive displacement rotameter flow meter were used. A set of thermocouples was used to monitor the temperature. An insulated tank with a temperature controller was used as a reservoir for supplying water. Stress–strain tests were performed using shorter samples of working lengths 30 cm each, fitted to a tensile testing machine. The surface topography of all samples was also studied using Leitz scanning electron microscopy (SEM). Such morphological investigations were conducted after surface cleaning in distilled water and then a thin gold layer was vacuum deposited to avoid surface charging during SEM measurements.

3. Results and discussion

3.1. Pressure gradient measurements

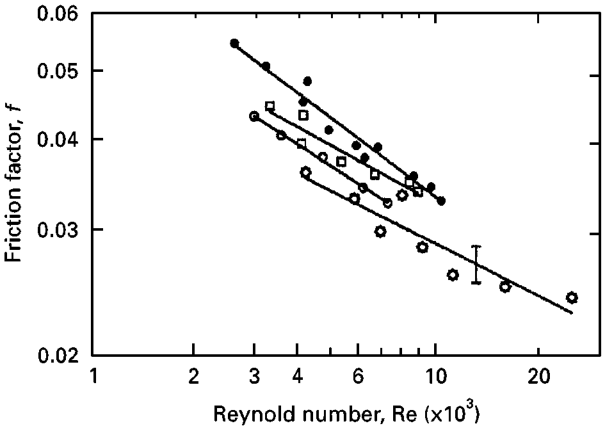

Figure 3 Friction factor, *f*, plotted against the Reynold's number, *Re*, for a new pipe at different working temperatures: (●) room temperature, (□) 50 °C, (◇) 70 °C, (✪) 90 °C.

Fig. 2 presents the water pressure gradient versus the working service time at a working temperature of 70 °C. It clearly shows a pressure gradient at a working period of 1 y. This is due to the initial thermal conditioning of extra elasticity and the first fall of contaminants on the inside surface of the tube pipes. Longer working times, however, result in a significant increase in the pressure gradient, attributed to internal surface roughness created by degradation in which the properties also exhibit some degree of brittleness. It should be mentioned that the same behaviour was observed at all temperatures examined. In Fig. 3 the friction factor, *f*, is plotted against the Reynold's number, *Re*. The data clearly show a rapid decrease of *f* with *Re*, i.e. the flows shown are turbulent. The decrease with temperature, on the other hand, indicates the effect of surface roughness which is primarily smoothed out by the increasing diameter of the pipes, rather than by the change in water density, as the temperature variations in the range studied are insignificant.

Fig. 4 shows the water pressure gradient plotted against the working temperature. Generally, the pressure gradient was observed to decrease with increasing temperature under a constant flow rate of 5×10^{-3} m^3 min^{-1}, for all samples. However, the variation of the pressure gradient per degree, is about − 15 Pa

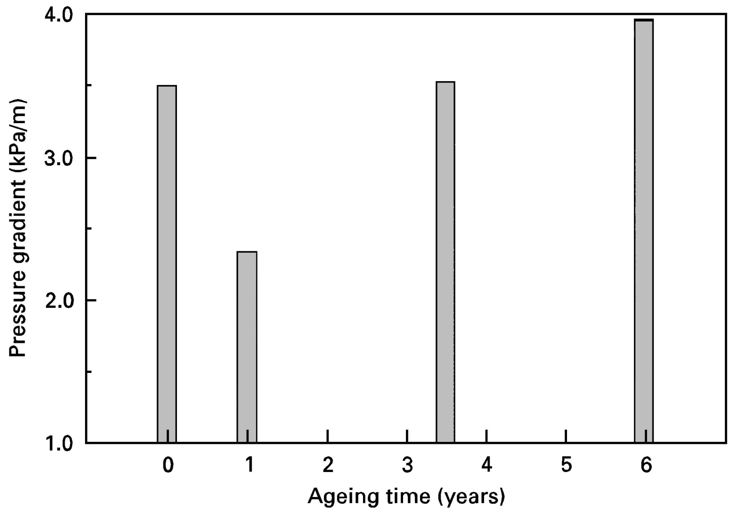

Figure 2 Water pressure gradient plotted against working service time for a flow rate of 5×10^{-3} m^3 h^{-1} at 70 °C.

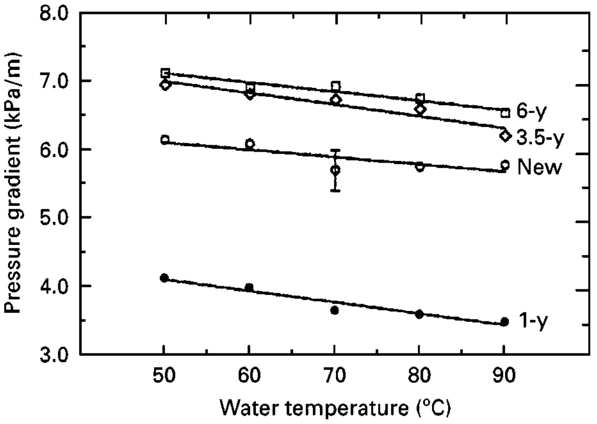

Figure 4 Water pressure gradient as a function of water temperature for various working periods.

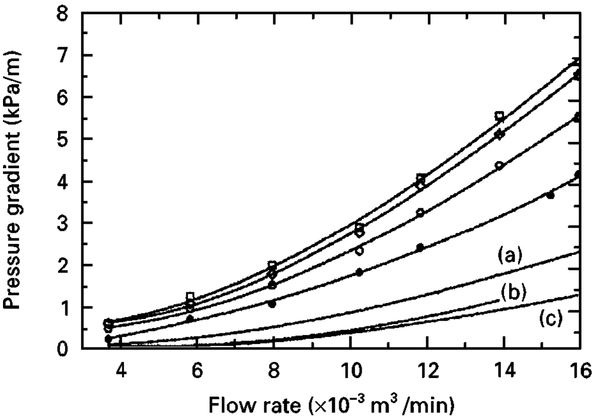

Figure 5 Water pressure gradient versus rate of water flow at room temperature: (○) new, (●) 1.5 y, (◇) 3.5 y, (□) 6 y. Also shown are data for (a) copper polyurethene and (c) steel [4]. Data for polyurethane (b) represent measurements conducted under the same conditions as this work.

$m^{-1}\,°C^{-1}$. Such a value enforces our suggestion that the change in water density is very limited to produce such pressure gradient. Therefore, the degree of surface roughness is responsible for the pressure gradient.

Fig. 5, shows the usual design curves used for pressure gradient as a function of water flow rate at room temperature. The results for copper and steel are extracted from Jennings [4] for comparison. The results for polyurethane represent measurements made under the same testing conditions. All samples reveal pressure gradients higher than either copper or iron metal pipes. This is attributed to a high degree of surface smoothness obtained in metal pipes. It should be mentioned that the design of the pump head is not affected by this difference, due to the fact that design layout in thermopipe circuitry is always shorter. In addition, all measurements were conducted at pressures low enough for pressure variations to be neglected.

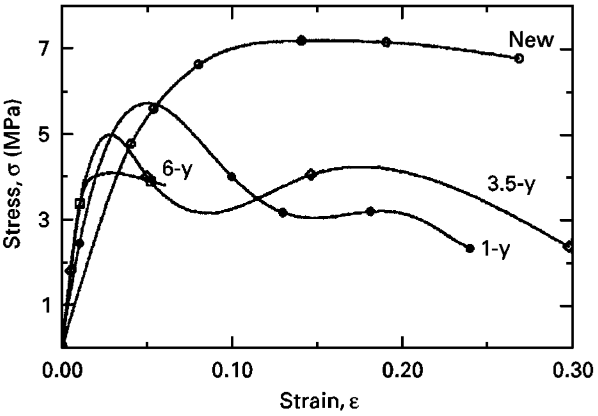

Figure 7 Stress–strain diagram representing each sample.

3.2. Strength measurements

Fig. 6 shows a photograph of the samples after deformation under the same applied load, of 4 MPa. A decrease in the strain value is observed with ageing. Failure, however, occurred almost instantly in the 6 y sample. This deformation behaviour reflects the tendency of the pipes to exhibit brittleness and glassy properties. In Figs 7 and 8, stress–strain curves and changes in both the stiffness and tensile strength are illustrated. The stiffness increases over two-fold (from 0.14 GPa to 0.32 GPa) after attaining a working life of about 3 y where it is then almost constant. In contrast, the tensile strength falls rapidly from 7.3 MPa to

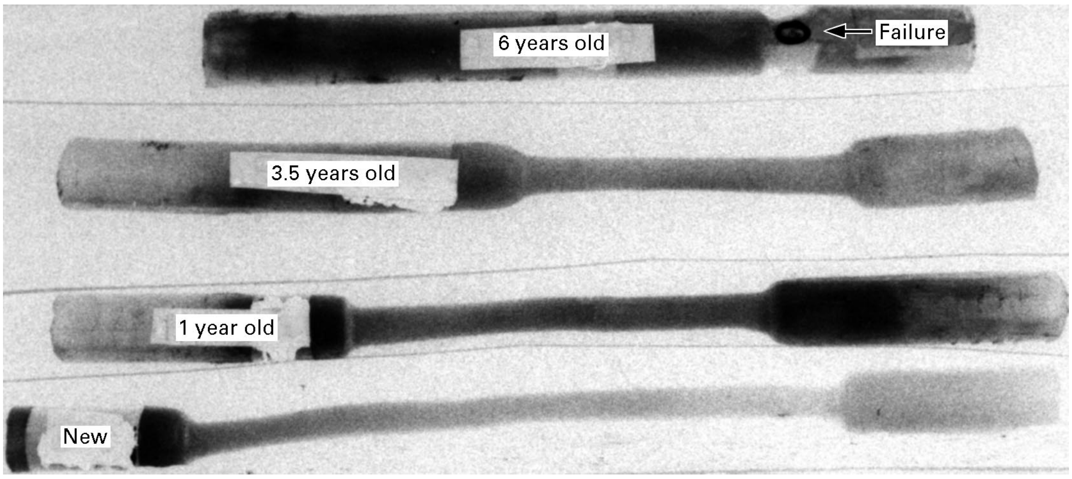

Figure 6 Samples illustrating the resulting deformations.

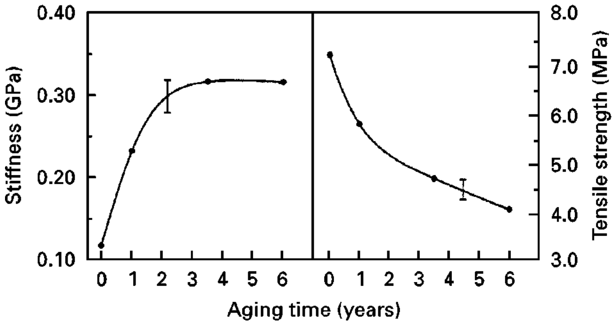

Figure 8 Stiffness and tensile strength curves plotted against working time.

TABLE I Recommended pipe length and diameter

Length (m)	Diameter (mm)
9.0	10
7.5	15
6.3	20
5.1	30
4.5	40
4.0	50
3.6	60
3.3	70
3.1	80
2.9	90
2.8	100

4.0 MPa (46%) where then it also becomes constant. A similar behaviour was reported in the literature for other kinds of plastics [11, 12].

The observed changes in the mechanical properties are attributed to three effects. First, cyclic deformation or thermal degradation causes the material to become more brittle. Second, surface developments are caused by thermal and matter (erosion) effects. This can be best described by referring to scanning electron micrographs, see later. Finally, the adsorption of air oxygen and nitrogen into the polymer bulk can alter its mechanical properties. Based on a previous investigation conducted by our group using nuclear reaction analysis of the same samples [6], an increase in the concentration of both oxygen and nitrogen within the polymer at the inner and outer surfaces was observed. This effect markedly influences the bonding forces inside the material, which decreases its strength. The above reaction is further enhanced by the high temperature of water flowing inside the pipe with ageing. It is worth mentioning that all specimens were taken from under-floor conduits, which implies that there is no effect due to ultraviolet irradiation.

Consequent to this degradation behaviour, the used pipe length affects the plastic deformation and the pipe life. For a pipe in service of more than 3 y, the results conclude that the recommended pipe length, determined by simple stress analysis, should not exceed that listed in Table I, unless some kind of intermediate support is used.

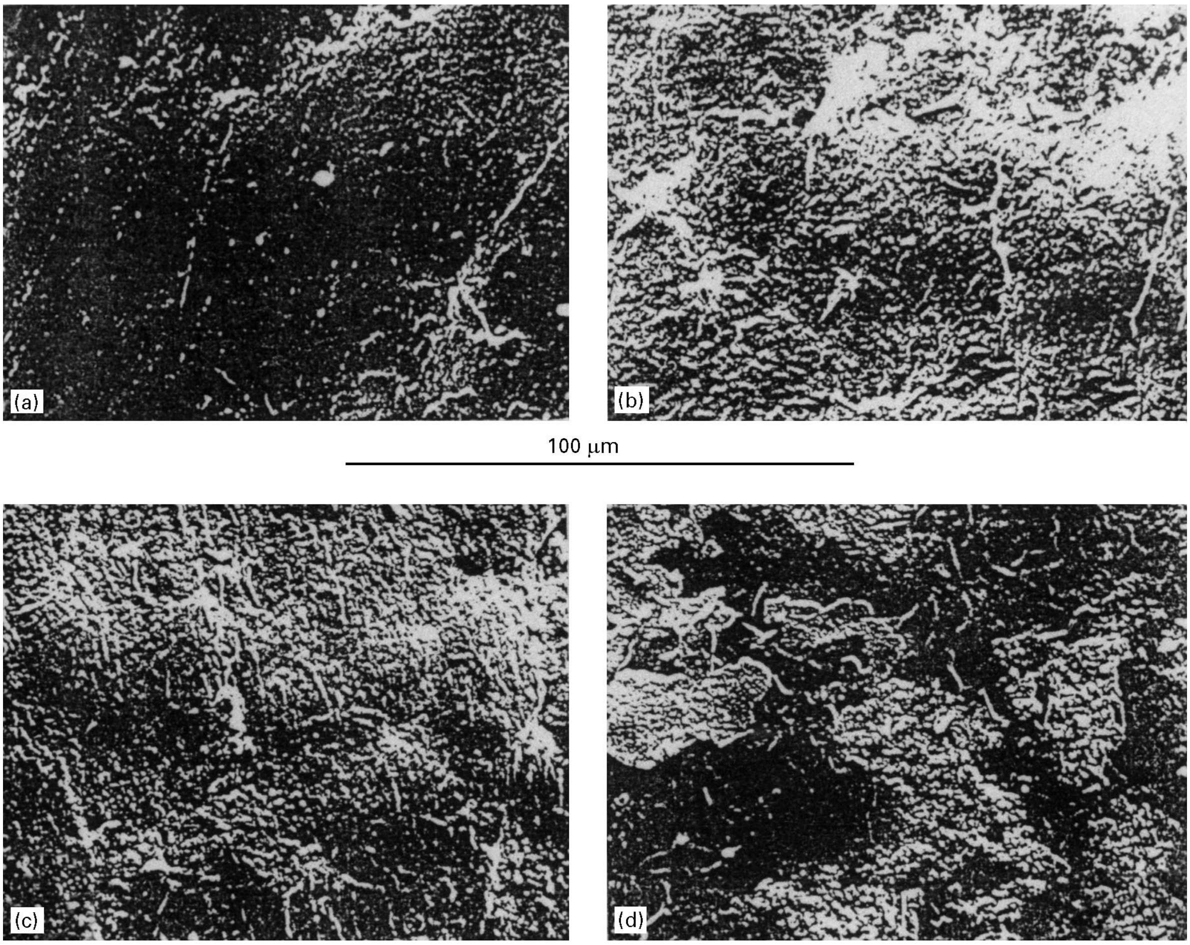

Figure 9 Scanning electron micrographs illustrating the surface topographic changes which took place: (a) new, (b) 1 y (c) 3.5 y, and (d) 6 y working periods.

3.3. Scanning electron microscopy

Fig. 9 shows micrographs of the different samples investigated. Fig. 9a shows a manufacturing surface roughness for the new samples, as expected, with no clear observation of holes or scratches. In Fig. 9b, some surface topographic changes have occurred, indicating the beginning of the influence of service on the inner surface of the pipes. Rough surfaces with mild scratches but no cracks are observed. The influence of hot water on surface topography (Fig. 9c) was observed to be greater by noting the development of some holes and small cracks. More serious effects are observed in Fig. 9d which shows the presence of further deep cracks and the formation of a relatively very rough surface by displacement of some pieces indicating that thermal degradation took place. Such surface developments will surely influence the physical and mechanical properties, such as ductility, hardness, brittleness and yield behaviour.

4. Conclusion

The effects of working life on the properties of polypropylene thermopipes using flow resistance measurements, stress–strain tests and scanning electron microscopy studies have been assessed. The water flow resistance data indicated that the working time initially decreased the flow resistance, followed by an increase with ageing. The stress–strain tests, supported by scanning electron micrographs, showed deformations and exhibit property changes towards brittleness and glassy behaviour. Deterioration was noted through the development of surface cracks, islands and holes. However, it is felt that more product refinements are needed to this type of plastic pipe which is extensively used in construction projects and which, supposedly, must serve many working years with unnoticeable deterioration.

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