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The Migration of Plasticisers from PVC Cable Sheathing into Expanded Polystyrene Insulation.

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THE MIGRATION OF PLASTICISERS FROM PVC CABLE SHEATHING INTO EXPANDED POLYSTYRENE INSULATION.

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SUMMARY

The rate of plasticiser migration from a PVC sheathed twin plus earth cable in expanded polystyrene beads (EPS) was measured at temperatures of 60, 70, 78.5 and 83°C. From the results the temperature dependence of the migration process has been determined. The temperature of the cable sheathing in an EPS filled wall cavity was measured with the cable carrying its rated current. The results are used to extrapolate a rate of plasticiser migration at service temperatures. Sheath flexibility is used to determine the acceptable limit of plasticiser loss. The likely service life of the PVC cable sheathing in EPS insulant is discussed.

INTRODUCTION

Plasticiser loss from externally plasticised polymers is a well known phenomenon. Loss can occur through migration into surrounding materials or liquids, or through volatile loss into the surrounding atmosphere. Plasticiser migration from plasticised polyvinyl chloride (PVC) into materials such as polyethylene, polystyrene and unplasticised PVC has been reported [1,2]. Generally, the correct selection of plasticiser minimises this problem. Reports have appeared in the literature of accelerated plasticiser migration from PVC cable sheathing in contact with expanded polystyrene insulant (EPS) [3,4,5]. Some reports have suggested the enhanced migration is unlikely to cause problems [3,4], while in other cases electrical authorities have required the use of ducting to prevent contact [6].

PVC plasticised with phthalate esters is used as electrical cable sheathing for most electrical cable used for lighting and heating manufactured in New Zealand. These plasticisers are competitively priced and have proved suitable for most applications.

The use of EPS as an insulation material in New Zealand is increasing. It is mainly used in sandwich panel construction where coated metal panels are adhered to EPS block. Recently interest has been shown in the use of EPS beads and block for retrofit cavity insulation. The beads can be blown into cavities loose or adhesive coated, dependent on the system used. A number of these systems have been appraised by the British Board of Agreement [eg 7,8,9]. The certificates warn that there may be some acceleration of plasticiser loss from the PVC cable sheathing, with a resulting stiffening

of the cable, but the risk of fire is likely to be low. There appears, however, to be little experimental data available to assess whether the durability of PVC sheathed cables will be unduly lessened by exposure to EPS.

PLASTICISER MIGRATION INTO EPS

Experimental Procedure

Commercially available tough plastic sheathed (TPS) 1.5mm twin-plus-earth electrical cable was conditioned at $20 \pm 2^\circ\text{C}$ and 65+5% relative humidity for seven days. The cable consisted of three cables individually sheathed with PVC (approximately 1 mm thick) and an external sheath approximately 1.4mm thick. The sheathing was plasticised with dioctyl phthalate (DOP) at 58 parts per hundred parts of resin (phr) and a chlorinated paraffin extender (27 phr).

The total plasticiser loading was determined by extraction in di-ethyl ether for 16 hours with a Soxhlet apparatus.

To determine the effect of temperature on the rate of plasticiser migration into EPS, cable embedded in loose EPS beads was subjected to temperatures of 60, 70, 78.5 and 83°C . Lengths of cable 750mm long were placed, either in rigid PVC or aluminium tubes of 50mm diameter and surrounded by EPS beads (diameter 3-5mm), or in a 900 x 430 x 410mm container filled with EPS beads. The tubes and container were placed in a hot air oven and pairs of cables removed at successive time intervals. Plasticiser loss was determined by measuring the weight loss of the cable after removing the plasticised polystyrene film which formed on the sheath. The film was peeled off with negligible loss of PVC sheathing. The volatile loss of plasticiser from cables in air at 85°C was also measured. The cables were suspended in aluminium tubes which were closed at each end to limit the rate of air movement over the sheath surface as would occur in practice in a closed cavity. An attempt was made to determine the percentage plasticiser loss which would constitute cable failure. Samples of the insulated cable were refluxed in di-ethyl ether and the weight loss used to determine plasticiser loss. The flexibility of the insulation was assessed by bending the cable (2.9mm diameter) around a 13 mm mandrel, as suggested in Australian Standard AS 1660 [10], at room temperature and at 4°C .

Results

Cables immersed in EPS beads at 60°C in a matter of days developed a coating of adherent EPS beads. On visual and microscopic examination it was observed that the beads were dissolving in plasticiser at the surface. Samples of cable placed through EPS block at this temperature caused the polystyrene to shrink away from the cable. After several months in the beads the sheath was entirely covered in a tough flexible layer of plasticised polystyrene. At the three higher temperatures using the aluminium tubes to hold the cable and EPS beads, the results obtained were very erratic. This was attributed to the uneven packing of the EPS beads around the cable as the beads at the cable surface were consumed by the plasticiser migration process. Totally immersing the cables in EPS beads in a container resulted in better agreement between replicates.

The loss of plasticiser as a percentage of the initial sheath weight at four temperatures is shown in Fig. 1. The points are the average of two replicates. The curved line which results indicates that the migration of plasticiser is not likely to be a surface evaporation controlled process, because this would result in linear plasticiser loss versus time plots [2].

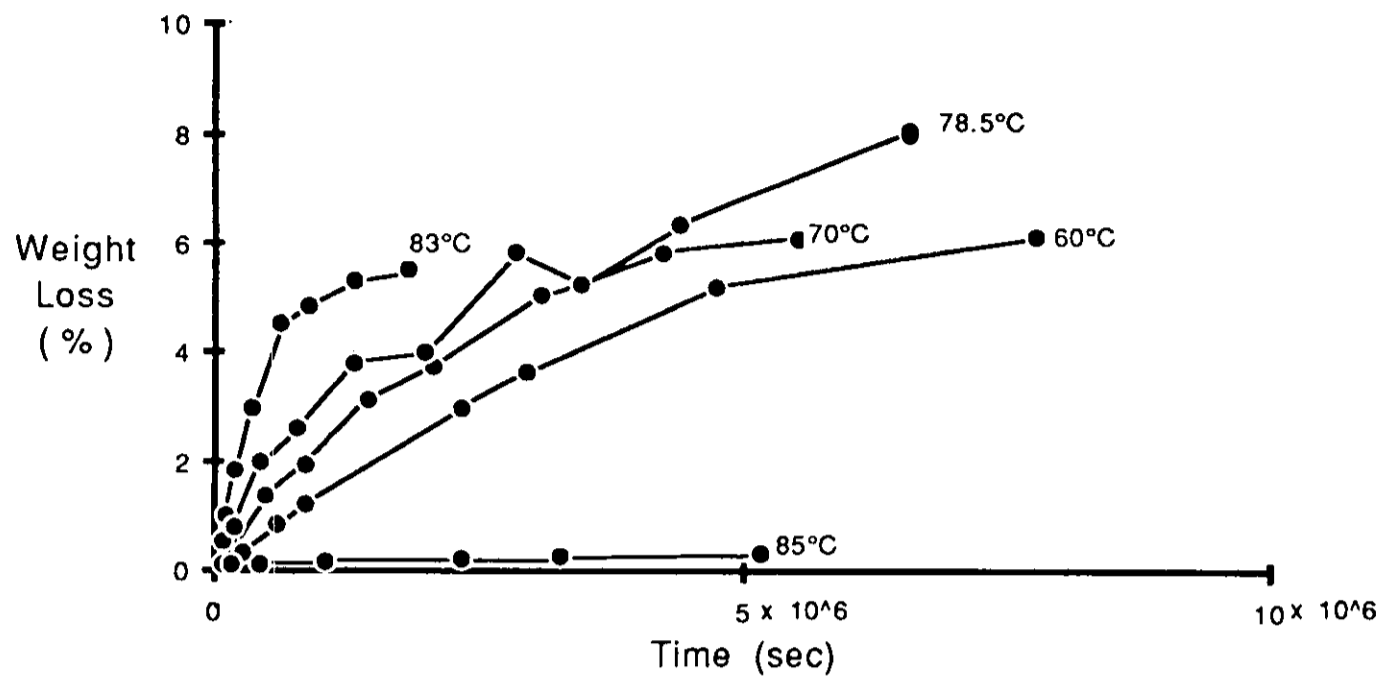


Fig. 1 Per cent weight loss of PVC insulation with time (results for 85°C are for PVC in air only).

If it is assumed that the outer PVC sheathing and the internal PVC sheathing are in intimate contact and that the diffusion of plasticiser from one sheath to another is unaffected by the boundary between them, the PVC cable sheathing used in these experiments can be approximated to a solid cylinder. Crank's Equation 5.25 [11] can be used to describe diffusion controlled plasticiser migration as shown in Eq. 1.

$$\frac{Q}{S_i} = \frac{4}{\pi^{1/2}} \cdot \left(\frac{Dt}{a^2}\right)^{1/2} - \frac{Dt}{a^2} - \frac{1}{3\pi^{1/2}} \cdot \left(\frac{Dt}{a^2}\right)^{3/2} + \dots \quad (1)$$

where Q = mass of plasticiser lost in kg
 S_i = mass of plasticiser lost at infinite time in kg
 D = diffusion constant in m^2/s
 t = time in s
 a = the radius of the cylinder in m

To simplify Eq. 1 for small time intervals, the first term in the expansion is used to give Eq. 2 which is equivalent to the equation used by Quackenbos [12] to describe the diffusion controlled migration of plasticiser through PVC sheet.

$$\frac{Q}{S_i} = \frac{4}{\pi^{1/2}} \cdot \left(\frac{Dt}{a^2}\right)^{1/2} \quad (2)$$

Fig. 2 shows a plot of Q/S_i versus square root of (t/a^2) for the data in Fig. 1. In this case S_i is assumed to be the total plasticiser content. It can be seen that initially the plot is linear, but at about 15-20% plasticiser loss the lines start to deviate from linearity. Diffusion coefficients were calculated at each temperature from Fig. 2 by drawing a line through the linear sections of the data and are shown in Table 1. The values are of the same order as those reported by Quackenbos for DOP (TABLE 1). Some differences are to be expected because of differences in the composition of the PVC used in each experiment and the presence of extender in the PVC used in this work.

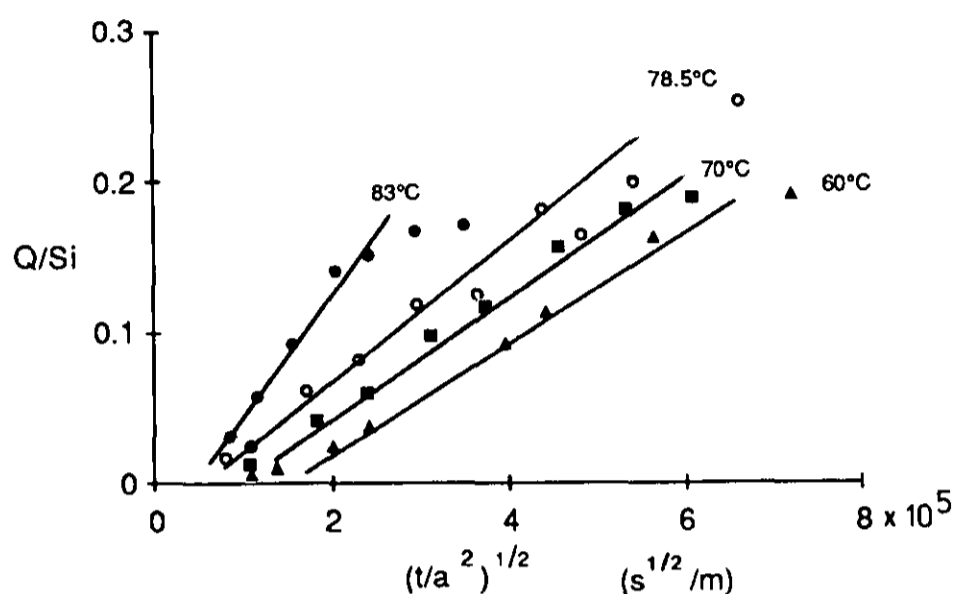


Fig. 2 Plot of Q/S_i : Versus square root of (t/a^2)

Table 1 Diffusion Coefficients

Temperature °C	Diffusion coefficient from Fig. 2 m^2/s	Diffusion coefficient from Quackenbos[12] m^2/s
60	2.5 E-14	2.5 E-14
70	3.1 "	8.1 "
78.5	3.9 "	14.4 "
83	12.5 "	19.8 "

The similarity of the diffusion constants measured here and the literature values for DOP suggests that, initially, plasticiser is being removed from the surface of the PVC at a faster rate than diffusion of plasticiser to the surface. The deviation from linearity seen at approximately 20% plasticiser loss indicates that the initial rate of plasticiser build-up in the film of plasticised polystyrene which forms around the cable is rapid, but it slows to eventually become rate limiting.

A linear relationship between \ln diffusion constant and the reciprocal of absolute temperature has been reported for diffusion of di-octyl phthalate into PVC [1]. Fig. 3 shows the plot of $\ln D$ versus inverse temperature for the results shown in Fig. 2. Eq. 3 which is derived from the slope and ordinate intercept of the regression line though the data in Fig. 3 can be used to estimate the diffusion constant at various temperatures.

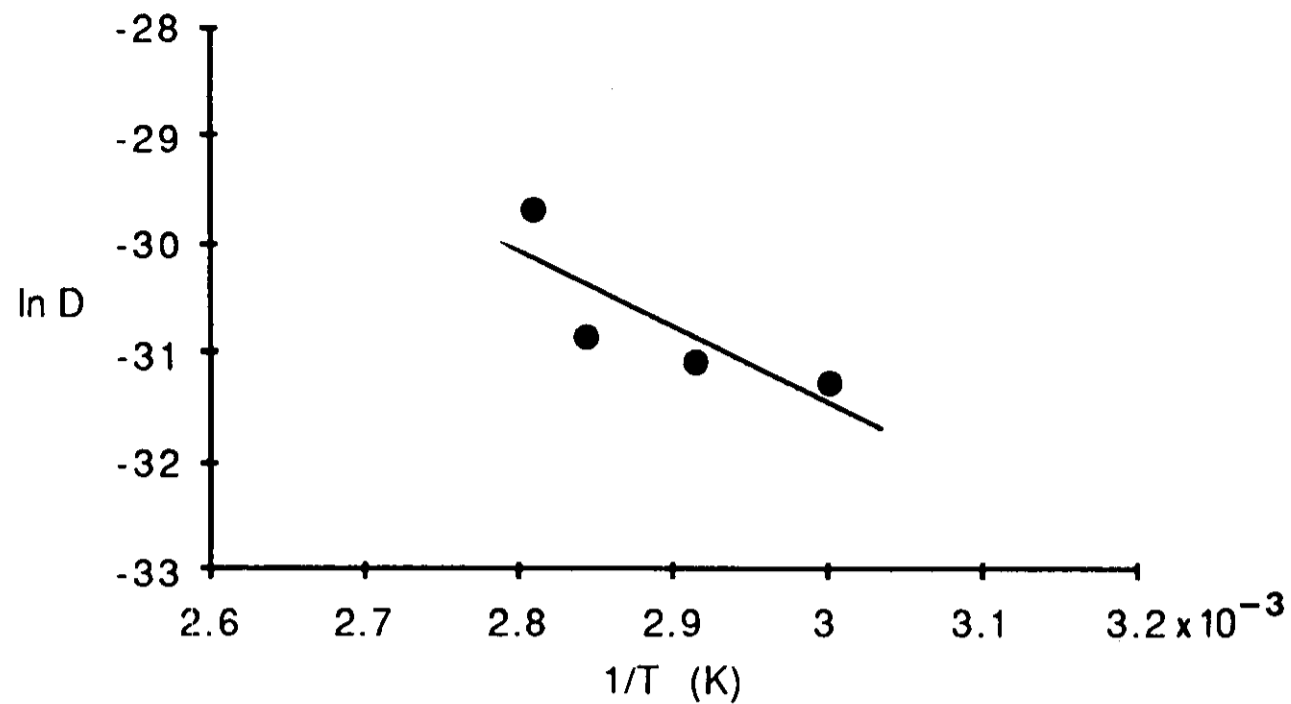


Fig. 3 Reciprocal of absolute temperature versus ln D

$$D' = e^{(-10.9 - 6867/T)} \quad (3)$$

where D' = diffusion constant at temperature T (K).

Eq. 4 which follows from Eq. 2 can be used to obtain an estimate of the time required for a set percentage of plasticiser to migrate at a given temperature.

$$t = a^2 \left(\frac{P}{100D' \cdot 2.26} \right)^2 \quad (4)$$

where t = time for percentage (P) plasticiser loss at temperature T
 a = cylinder thickness

The use of this equation will result in underestimates of the time for a set percentage loss of plasticiser as it ignores the lag phase seen at the start of the curves in Fig. 2 and the reduction in rate occurring at 15-20% plasticiser loss.

The percentage loss of plasticiser that can be considered as failure of the cable has not been determined, but cable samples which had lost 82% of their plasticiser content showed no cracking either at room temperature or at 4°C when bent around a mandrel, even though the PVC insulation had hardened and the cable diameter had shrunk by 17%.

IN-SERVICE TEMPERATURE OF PVC SHEATHED CABLE

An electrical cable carrying current generates heat in proportion to the square of the current. In an uninsulated building wall or ceiling cavity the heat generated is able to dissipate readily. Where the cavity contains insulation the dissipation of heat is impeded. The heat build-up in a typical cavity was measured.

Procedure

A 900 x 900 x 100mm timber frame was constructed and sheathed with 12mm plywood on one side and 9mm gypsum plasterboard on the other. A 2.2m length of twin-plus-earth cable was run through the centre of the cavity. A copper-constantan thermocouple was embedded in the cable between the outer sheath and the cable insulation. Voltage changes in the thermocouple were recorded using a Heathkit 10mV fullscale chart recorder. AC power was supplied to the cable using double staged Variac transformers. The actual current flowing through the cable was determined by measuring the voltage across a calibrated resistor. The apparatus was maintained at an external temperature of $20 \pm 2^{\circ}\text{C}$. Measurements of cable sheath temperature were made for different current values for the empty cavity and with the cavity filled with EPS or fibreglass insulation respectively.

Results

Table 2 shows the results of the experiments. The thermocouple voltage changes were converted to temperature changes using Table 55 in ASTM STP 470A [14].

The temperature expected for the cable used in real situations would be of the order of $20-60^{\circ}\text{C}$ above ambient as the cable is rated for 15 A. Table 3 shows the time, calculated from Eq. 4, required to lose 50% and 80% of the plasticiser in a 1.5mm twin-plus-earth PVC sheathed cable at various temperatures.

Table 2 Temperatures of current carrying PVC sheathed cable

cavity fill	AC current A	temperature rise above ambient (20°C)
none	10	10
	12.5	15
	15	21
	20	33
EPS	10	26
	12.5	43
	15	57
	20	106
fibreglass	10	29
	12.5	39
	15	64
	20	107

Table 3 Time for 50% and 80% plasticiser loss at various temperatures

temperature °C	time in years for plasticiser loss	
	50% loss	80% loss
40	110 years	282 years
50	56	144
60	30	76
70	16	42
80	9	24

DISCUSSION

A straight line from a square root of time versus plasticiser loss curve does not necessarily mean that a process is diffusion controlled or, if it is diffusion controlled, that diffusion from within the PVC is the rate-limiting or controlling process. Where the receiving material is polymeric (as in this case) the controlling process may be the diffusion of the plasticiser into this polymer. The diffusion constants calculated are, however, close enough to the reported values for DOP diffusion from PVC to suggest that initially, diffusion of plasticiser within the PVC is the rate-determining process for plasticiser loss. The deviation from linearity in Fig. 2 at such a low value of Q/S_i indicates that there is probably a change in the rate determining process. This could result from boundary effects between the two layers of PVC sheathing as the plasticiser in the outer sheathing is depleted, or between the outer sheath and the plasticised polystyrene layer as it forms. Diffusion of plasticiser into this layer could also become rate determining. The EPS beads should act as a sink which is large in comparison with the plasticiser reservoir. In practice it appears that the plasticised layer of polystyrene becomes increasingly less efficient at absorbing more EPS beads and acts as a finite sink for the plasticiser.

The estimates of plasticiser loss obtained from Eqs. 4 and shown in Table 3 are worst case estimates. The values are calculated assuming the initial rate of plasticiser loss is maintained over the exposure period, when in practice the rates slow after about 20% plasticiser loss. The lag observed before the linear portion of the curves in Fig. 2 also result in an over-estimation of plasticiser loss. The presence of the lag may be due to the requirement for the cable and beads to reach the experimental temperature, or to delays caused as the initial layer of beads in contact with the cable are dissolved to form plasticised polystyrene. The estimate of 24 years to lose 80% of the plasticiser at 80°C will be conservative. At this level of plasticiser loss, electrical cables in building cavities are unlikely to fail unless they are subject to regular flexing. The loss of plasticiser from electrical cable sheathing ducted through rigid EPS block, or blown into cavities with adhesive, will be reduced by the tendency of the EPS to "shrink away" from the PVC as the plasticiser dissolves the material in contact with the cable.

CONCLUSIONS

Plasticiser migration is not expected to reduce the service life of PVC sheathed cable plasticised with di-octyl phthalate to less than 30 years when it is in contact with EPS under New Zealand conditions.

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