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THE INFLUENCE OF AIR FLOW RESISTANCE ON THE ACOUSTIC ABSORPTION PROPERTIES OF POLYURETHANE FOAMS

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1 Introduction

It has been suggested by several authors e.g.[1,2,3] that the degree to which a foam will be an effective acoustic absorber is governed by many of its easily measurable material characteristics. These properties include airflow resistivity, loss tangent, storage modulus and density. It has further been suggested [8] that there is an optimum value of flow resistance 3 $\rho_0 c$, where $\rho_0 c$ is the acoustic impedance of air (412 Rayl at 20 ^{o}C). Unfortunately there has been little discussion of what is meant by optimum acoustic performance and there is little evidence given in the literature of systematic experimental studies. This investigation looks at how changes in air flow resistance affects absorption; all other factors remaining relatively constant. Two methods of varying air flow resistance are considered, both employ changes in the degree of reticulation within a foam.

2.The foams structure

By definition, a foam is a light cellular solid, created by the solidification of a liquid containing many bubbles. Two basic components are used in the manufacture of polyurethane foam, an isocyanate and a polyol. Other chemicals such as fire retardent, blowing agents are also added to fine tune the structure and properties of the finished foam. The polymerisation reaction that forms foam is exothermic. This energy generated in the heat of formation is used to expand gases trapped in the chemical mixture creating bubbles. When the bubbles are large enough they contact each other, distorting the shape of the bubble from spherical to a dodecahedron. Where the bubbles contact, pentagonal windows are created. With further expansion the windows can be made to break leaving just the outer struts shared by two pentagons see fig. 3,4. The degree of burst windows in a foam is called the amount of reticulation and can be controlled in manufacture. A large amount of windows form a highly unreticulated foam. As the foam is manufactured, it is constricted by a three sided forming enclosure, the foam expands to the constrained dimensions. Due to the nature of this constraint, and the heat trapped internally, variation occurs across the foam. Some methods of polyurethane foam manufacture are more susceptible to variation than others.

One of the primary characteristics that affects acoustic absorption is resistance to the passage of air through the material (airflow resistance). When a sound pressure wave is incident upon a material, the movement of the air through the material dissipates energy as heat. Losses are due to friction as air passes through the material matrix and the air flow turbulence. If the material has minimal air flow resistance then the acoustic wave will pass through the sample with negligible attenuation. Conversely, if the material is too resistant to the passage of air, then the acoustic wave will be reflected from the surface and any acoustic losses will be slight and due to compressive movement of the material.

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3. Objectives

Many studies of the relationship between acoustic absorption and air flow resistance have been undertaken ie [1,4]. All of these studies use different samples to obtain variation in the air flow resistance hence will cause changes in other material properties. The objective of this work is to minimise changes in material characteristics by using the same sample, or samples cut within close proximity from one sheet of material. Hence the following two experiments have been devised. One involving an acoustic grade foam the other a flexible closed polyurethane foam.

4. Experimental.

4.1 Experiment 1 - A sheet of polyurethane foam (62.0 x 54.0 x 2.6 cm) was chosen at random from normal production stock, the type of foam selected is described by the manufacturer as suitable for acoustic use. From this sheet 12 samples were cut and labelled as in fig. 1. The air flow resistance of each sample was measured. A contour map of constant air flow resistance was then drawn (fig 2), each contour representing a constant airflow resistance. Assumptions made to create the contour map were that the airflow acted through the centre of the sample and that variation vertically or horizontally between two adjacent centres could be described linearly. Full normal incident absorption data were obtained for samples A1, A4, B2, B3, C1 & C4 (fig 5). These were chosen after evaluation of flow resistance data (data is given in table I). They represent pairs of maximum, minimum and median flow resistance. To ascertain whether flow resistance and acoustic absorption are the only material characteristic that vary across the sheet, electron micrographs (figs 3,4), density and dynamic properties were also measured.

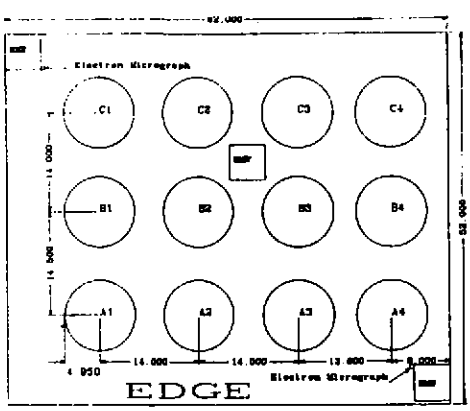

Fig 1

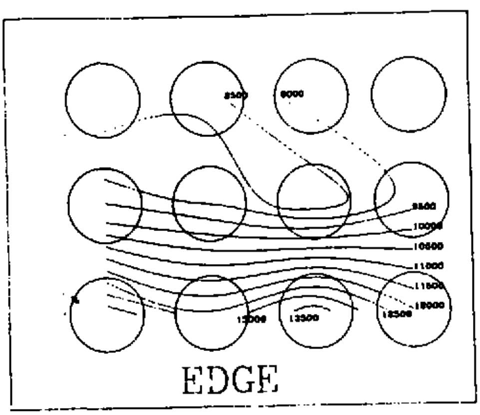

Fig 2

4.2 Experiment 2 - A highly non-reticulated (closed cell) foam was selected. Due to the high non-reticulation the material had high airflow resistance. By partially crushing the foam some of the cell windows were broken and hence the air flow resistance decreased. Between each crushing, measurements of airflow, mass and normal incident absorption were taken. Effects of crushing on other material properties (i.e. dynamic modulus and damping) were also investigated. After each crushing the foam was left for at least 48 hours in a warm oven (50° C). It was found that 48 hours was the minimum time required for full dimensional recovery. To assess dimensional recovery height was measured and general shape judged visually with the sample placed in the standing wave tube sample holder.

4.3 Crushing Techniques - Originally, the samples were crushed using a 'Mayes', normally used for ascertaining the properties of concrete. These initial investigations showed this linear compression technique unsuitable. After recovering from a compression of approximately 3.2×10^{6} Pa, there was little change in the air flow resistance. A pinch compression between two steel rollers did produce a marked change in air flow resistance *. The number of times the sample passed through the pinch rollers and the distance between the rollers gave an indication of the degree of cell window removal, and hence the change in air flow resistance.

* This technique did not lend itself to accurate measurements of the forces involved but did achieve the prime objective of varying the degree of reticulation and hence the air flow resistance.

4.4. The samples - As variation in material properties are expected across any sample of polyurethane foam, samples were cut so that airflow resistance and acoustic absorption measurements could be taken on the same piece of foam. The B&K standing wave tube uses a 99mm diameter sample. Modifications were made to the airflow measuring equipment so that it could accept the same sample.

4.5. Sound Absorption - The normal incident sound absorption was measured using a B&K type 4002 standing wave tube in accordance with ASTM C385. Calculations of normal incident absorption take into consideration tube attenuation as described in [5] and the end effect of the probe as described in [6]. Measurements were made at third octave band centres in the range 100Hz to 3150Hz. Frequencies less than 100Hz have wavelengths too long for the tube, and frequencies greater than 3150Hz create lateral standing waves which interfere with the measurement of the normal standing waves. A 29mm diameter tube was available to measure absorption at higher frequencies, but as the nature of the investigation was to use the same sample for airflow and normal incident absorption across the sheet, the extra information obtained from this tube would not have been advantageous.

4.6. Air Flow Resistance - Air flow resistance was measured in approximate accordance with BS 4443 pt. 6. The variation from this standard was in sample size, justification for the new sample size is given in section 4.4. It should be noted that BS 4443 pt. 6 is for static air flow resistance whereas acoustic pressure involves dynamic pressures. The static values can be used to give an indication of the dynamic values. Craggs [7] suggested the following relationship between static, dynamic air flow resistance and angular frequency.

$$R_e=R_s(0.6+0.55(\omega/R_s)^{1/2})$$

where Re=dynamic airflow resistance, Rs=static airflow resistance.

4.7. Dynamic Mechanical Measurements - All dynamic tests were carried out using what is commonly known as the "BMW" test method [9]. A sample of size 5.0x5.0 cm and height dependent on the sheet from which it is cut, has two accelerometers, one attached to each large face. The bottom accelerometer measures a sinusoidal input and the upper accelerometer measures transmitted forces. When the input is varied over a frequency range, a plot of the samples resonance can be obtained. From the height, width and frequency of the resonance peak the dynamic modulus and loss tangent at a resonance frequency are obtained.

4.8. Electron micrographs - Electron micrographs can be used to show important details in foam structures, cell size distributions and degree of reticulation.

5. Results and Analysis

All twelve circular samples in experiment 1 (Foam I) were weighed and density calculated (see fig.1 for details of sample positions). The maximum variation in either the horizontal or vertical direction was 1 %. This could be attributed to measuring and cutting error. Three samples were taken at different positions in the sheet (top left, centre and bottom right as shown in fig. 1) and dynamic measurements made. All three measurements gave the same values for the loss tangent ($\tan\delta = 0.21$) and the storage modulus of 4.35×10^7 Pa. No appreciable difference in cell size or structure can be seen between figs 3 and 4. Both micrographs were taken at the same magnification (18 times). The position from which samples for the micrograph have been taken are shown in fig 1.

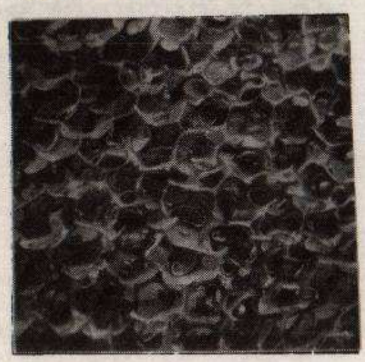

Fig. 3

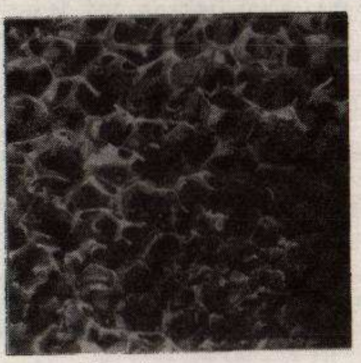

Fig. 4

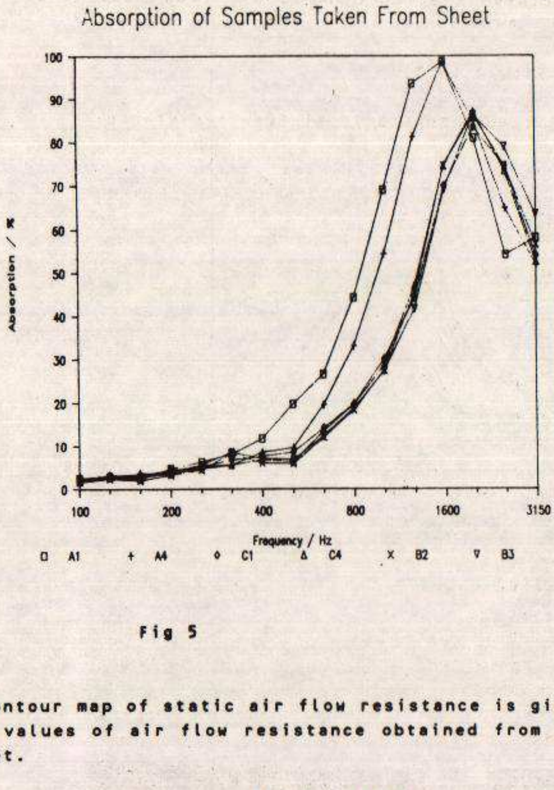

Fig 5

A contour map of static air flow resistance is given in fig 2. Table I gives the values of air flow resistance obtained from the samples taken from the sheet.

TABLE I (FOAM I)
Specific Air Flow Resistivity in MKS Rayls m^{-1}

	1	2	3	4
A	13900	12600	13800	12000
B	9300	9000	9100	9300
C	8200	8400	9300	9300

The graph in fig 5 gives the results for normal incident acoustic absorption measured on samples A1,A4,B2,B3,C1,C4.

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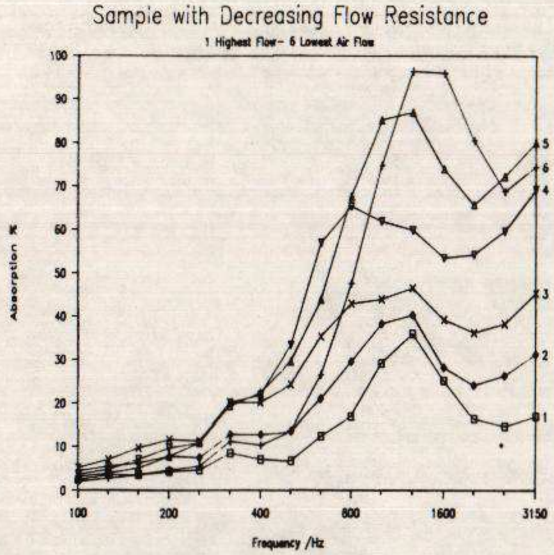

Fig. 6

Fig. 7

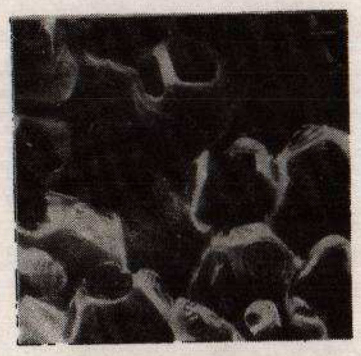

Fig. 8

The normal incident absorption coefficients on one sample of foam II after six levels of crushing are shown in fig.1. The corresponding changes in static air flow resistivity are given in Table II. As anticipated, the resistance to air flow falls as the amount of crushing increases.

TABLE II (FOAM II)

No of crushings	R1 /MKS Rayls m^{-1}
0	infinite
1	187000
2	69000
3	55000
4	34000
5	13000

After crushing there was no change in the mass of the test sample. The density of the material was 30.4 kg m^{-3}. The micrographs (fig. 7&8) show the destruction of cell windows after crushing. Cell struts and general cell structure are unaltered by the crushings.

Table III shows the changes in loss tangent and storage modulus brought about by degrees of crushing. The sample used to obtain dynamic information was not the same as had been used for acoustic measurements but was cut from the same sheet very close to the acoustic samples. The difference between the flow resistance of the two test pieces was not unexpected because of the lack of control on the crushing process.

TABLE III

No of Crushings	R1 /MKS Rayls m^{-1}	Loss Tangent	Storage Modulus /10^7 Pa
0	infinite	0.51	2.08
1	31740	0.51	1.81
2	27400	0.59	1.40
3	21850	0.52	1.68
4	13621	----	----

6.Discussion

Experiment 1 showed that the static air flow resistance and normal incidence acoustic absorption of a commercial foam were point specific but other material properties (E′ and tan δ) were constant. An increase in the normal incident absorption was observed as the flow resistance of the 26mm thick test pieces increased from 221 Rayls to 338 Rayls. Although experiment 1 gave promising results the range of flow resistances available did not allow us to investigate the conditions needed for optimum acoustic absorption. However it did show that the performance of this acoustic grade foam was less then optimum.

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Experiment 2 provides a wider range of flow resistances (about to 5800 Rayls) and although the loss tangent remains approximately constant the storage modulus showed a decrease (as a result of the reticulation process). which might be significant. The data showed that the maximum in absorption increases monotonically with decreasing resistance to air flow. The frequency of maximum first decreased and then increased.

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AIR ABSORPTION IN ACOUSTIC SCALE MODELS AND THE SUBSTITUTION OF NITROGEN

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Acoustic scale modelling is a useful tool for assisting the design of buildings with specific acoustic requirements.

A major problem in the modelling process however, involves the correct scaling of air absorption. For perfect scaling a linear increase of air absorption with frequency is required whereas the actual increase is considerably faster than this. As a result, large corrections must be applied to measurements made in air and the range of measurement is restricted. One well-established method of overcoming this problem has been to reduce the air absorption to the desired level by de-humidifying the air in the model; an expensive process. Nitrogen has been proposed as a cheaper alternative and has been adopted by several researchers.

Tests have been carried out in a 1:10 scale model reverberation chamber using nitrogen. The results indicate the suitability of nitrogen as a medium for modelling full-scale air absorption. Tests are now being conducted in the model in order to gain an insight into changes in the absorption of people at various packing densities.

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THE EFFECT OF LOADING ON THE IMPACT SOUND INSULATION OF CONCRETE FLOORS WITH A FLOATING RAFT ON A RESILIENT LAYER

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REASONS FOR RESEARCH

In the Institute of Environmental Health Officers' Annual Report of 1984/5 a graph was included showing the number of noise complaints received over the past 14 years. It showed a considerable increase in the number of complaints due to domestic noise (see Fig. 1).

Langdon, Buller and Scholes [2] gave a breakdown of the major sources of noise nuisance in flats. It was found that footstep noise from flats above was the greatest contributor. Therefore, if separating floors and walls are specified constructions as, for example in the Building Standards (Scotland), it is disturbing that there should be so many complaints. Could it be that the impact sound insulation of a floor reduces with ageing?

To investigate this, research is currently being undertaken in the Department of Building at Heriot-Watt University concentrating on party concrete floors using resilient layers underneath a floating raft.

INTRODUCTION

In most of the impact sound insulation tests carried out in flats and maisonettes in Scotland, the floors are either totally new or have just recently been refurbished. Very little is known about how the sound insulation fairs after a number of years when the floor has been loaded with domestic appliances or furniture which will cause the resilient layer to compress. Although a resilient layer will only compress a given amount for an applied load, if that load is maintained for a long time (as is obviously the case with domestic loads) further compression may take place due to creep. The aim is therefore to provide information for the construction industry on what type of floor materials give the most satisfactory long term impact sound insulation. Also, it is hoped impact sound insulation tests will be carried out on floors which have been wetted to show how moisture ingress from, for example, an overflowing bath or washing machine can affect impact sound insulation.

Only floating timber rafts on a pre cast hollow core concrete base are being considered (see Fig. 2) although it may be possible in the future to investigate floating screeds and timber floors.

METHODS

The tests are in three sections. The information obtained from tests i) and ii) will indicate what loads should be placed on the floor to simulate ageing. Impact sound insulation tests using the standard impact method will then be carried out (test iii)).

i) Constant Load Tests -
According to BS 6399 [4] an imposed load on a floor can be assumed depending upon the intended occupancy or use of the premises. For self contained apartments, the distributed load is assumed to be 1.5 kN/m^2 which approximately

provides for the effects of normal use. This infers the floor is capable of laterally distributing the load which will not happen with sharply focussed point loads such as a chair leg. These will be discussed later. However, the purpose of the constant load test is to simply assess whether creep deflection will take place in a given resilient material over a period of time. Therefore uniformly distributed loads only need be considered. Each resilient material is placed under a 0.5m x 0.5m square of flooring on 45mm x 45mm battens at 400mm centres. This is loaded with a paving slab giving an effective pressure of approximately 1.5 kN/m² (see slide 1). The deflection is then measured at different positions from a reference frame (see slide 2). Each test will be left for 6 months to determine the effects of creep deflection. If creep does take place, a curve of deflection against time will be drawn. From this, estimates of creep deflection over longer time periods (e.g. 5 years) will be made.

ii) Variable Load Tests -
The variable load tests will be carried out on 1m x 1m squares of chipboard flooring on 45mm x 45mm battens at 450mm centres. As with the constant load tests, resilient material will be placed under the section of flooring but this time the load will be increased in steps with deflection measurements being made for each load increase (see slide 3). This will give the load/deflection characteristics for each material.

The knowledge obtained in tests i) and ii) will then be used to determine what load should be placed upon the main floor for impact sound insulation tests.

iii) Impact Sound Insulation Tests -
These measurements will be made in the vertical transmission suite within the Department of Building. A range of floating raft constructions with different resilient materials will be placed upon the concrete floor for testing. A standard tapping machine will be used for the impact sound source with the sound pressure level being monitored in source and receiving rooms. The floor area is 4m x 3m.

DEFLECTION TESTS

Quick tests have been carried out on small 50mm x 36mm samples of 25mm quilt using a compression testing machine to measure the load/deflection characteristics. 8 different samples were used and the results can be seen in Table 1.

This data is used for the variable load test results in the example below but this is just a short term measure. In our main tests the results from the 1m x 1m sections of flooring will be used.

The following example sums up the way in which we intend to deal with the test data. The constant load test results are contrived as the experiments have only just been set up.

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EXAMPLE

To determine the effectiveness of a quilt for impact sound insulation when it has been installed for 5 years.

Creep deflection tests with a steady load of 1.5 kN/m² gave the following results:

Time (months)	1	2	3	4	5	6
Defl (mm)	4.7	5.1	5.4	5.67	5.77	5.83

A curve can be drawn and the deflection after 5 years extrapolated.

Fig. 3 shows the curve of the 6 month data. Fig. 4 is a logarithmic curve of the same data but the extended X axis allows an estimate to be made of what the creep deflection will be after 5 years. At present we are unsure of which method of extrapolation will be used depending on the nature of the data. If we can usefully employ a method of curve fitting then we will. However, this may not prove any more accurate than an extrapolation 'by eye' which for brevity, is the method used in Fig. 4.

The creep deflection after 5 years is estimated at 5.85mm. The results of the quick test are now examined to find out what the pressure/deflection characteristics are for this material. The following table is the averaged set of results.

Pressure (kN/m²)	0	1.1	2.2	3.3	4.4	5.5	6.6	7.7
Deflection (mm)	0	4.2	5.4	6.0	6.4	6.7	6.9	7.0

N.B. The load values above are different to those in Table 1 as they have been adjusted to account for the load upon the whole floor rather than just on the material (see Appendix). Fig. 5 is the graph of these results.

By interpolation of Fig. 5 the load required to give a deflection of 5.85mm is 2.92 kN/m².

An impact sound insulation test in the main transmission suite with a load on the floor of 3 kN/m² can now be carried out. This will approximately simulate the response of a 5 year old floor.

These tests are fine for loads which are distributed over a large area. However most domestic loads are not like that. Further impact sound insulation measurements will therefore be carried out with point loads simulating chairs, wardrobes, beds, etc. Attention will be given to the position of the point load in relation to the battens.

MATERIALS

All tests will be carried out on a hollow core reinforced concrete slab 150mm thick and weighing 300 kg/m². This complies with The Building Standards (Scotland) Amendment Regulations 1987 and is commonly used in short span floors (i.e. approx. 5m) 18mm chipboard flooring on 45mm x 45mm battens, and a number

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of propriety, continuous layer resilient materials including polyethylene foams, glass fibre and rock fibre quilts will be used. Battens on resilient foam strips will also be used in combination with the continuous layers.

PRELIMINARY RESULTS

Experiments have been carried out by a final year undergraduate student using a tapp ing machine (conforming to the standard impact method of testing as in BS 2750) on a 1.2m x 600mm section of chipboard on battens with various resilient flooring configurations. The board was placed on the concrete floor of the vertical transmission suite and sound pressure level measurements were made in the source room and receiving room below. 6 different measurements were taken for each configuration. In each case the board and microphones (on rotating booms) were moved to new positions.

Loads were applied to each corner of the boards (see slide 4). Table 2 shows the relationship between loading and L'nT,w values assuming the load is uniformly distributed.

Tests have also been carried out by Fothergill [5] at the Building Research Establishment on airborne and impact sound transmission in raft timber floors using 13mm (density = 36 kg/m^2) and 25-30mm (density = 80 kg/m^2) quilts with a load of 1 kN/m^2 on the floor. Results showed a 6 dB reduction in the weighted normalised impact sound pressure level (Ln,w) for the 13mm quilt whereas the 25mm quilt gave a 2 dB reduction.

CONCLUSIONS

These results give a good indication that the performance of a resilient material depends upon the load imposed upon it. Due to the fact that older floors have been exposed to loading for longer periods it is reasonable to assume that the impact sound insulation will reduce in time. We hope to elaborate on this in the near future.

ACKNOWLEDGEMENTS

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Load (kN)	Deflection Measurements (mm) 1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0
0.02	3.1	4.0	4.0	4.0	4.5	4.8	5.1	4.5
0.04	4.4	5.1	5.1	5.2	5.5	5.8	6.0	6.2
0.06	5.1	5.7	5.8	5.8	6.1	6.3	6.5	6.7
0.08	5.6	6.0	6.2	6.2	6.5	6.7	6.9	7.0
0.10	6.0	6.3	6.5	6.5	6.7	6.9	7.1	7.2
0.12	6.3	6.5	6.7	6.7	7.0	7.1	7.3	7.4
0.14	6.5	6.7	6.9	6.9	7.1	7.2	7.4	7.5

TABLE 1 LOAD DEFLECTION CHARACTERISTICS OF 13MM QUILT

CONFIGURATION	L'nT,w (dB) For Each Load 0 kN/m²	0.27 kN/m²	0.55 kN/m²	1.1 kN/m²	2.2 kN/m²
Bare Concrete Floor	77				
Plain Batten on 70mm Fibre Glass Quilt	50	52	51	53	54
Resilient Batten (Type 1-Closed Cell)	58	60	61	63	63
Resilient Batten (Type 1-Closed Cell) on 25mm Quilt	51	51	52	57	58
Resilient Batten (Type 2-Closed Cell)	59	60	61	63	63

TABLE 2 WEIGHTED STANDARDISED IMPACT SOUND PRESSURE LEVELS FOR RESILIENT MATERIALS WITH VARYING LOADS

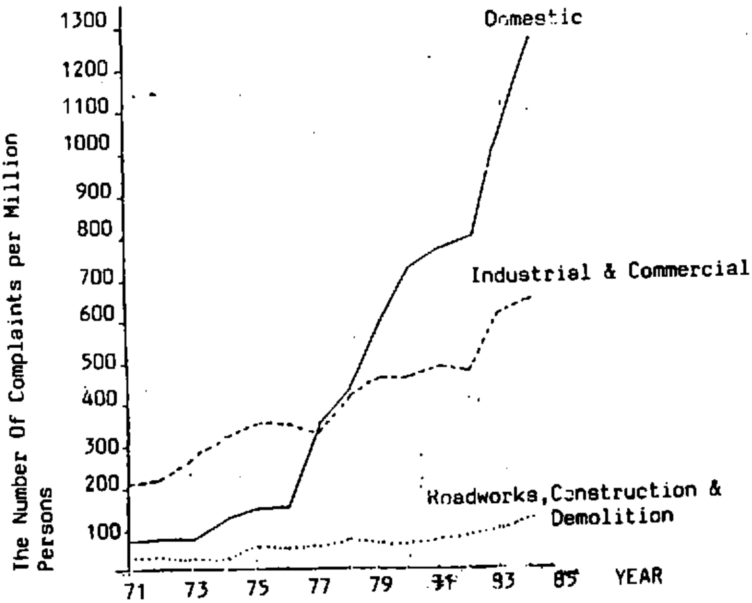

FIG 1 (ref 1) The Number Of Complaints per Million Of The Population Within The Local Authorities Making A Return To The Institute Of Environmental Health Officers.

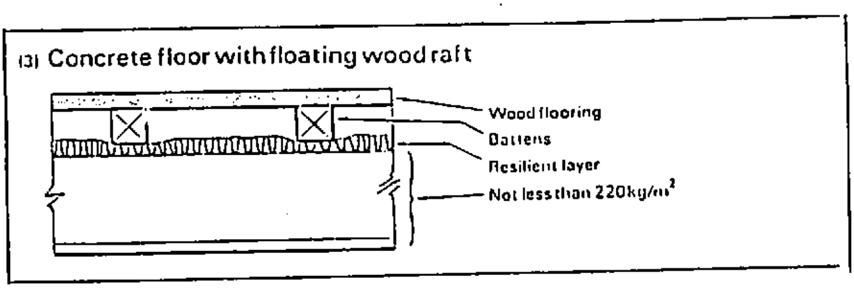

Fig. 2 : Detail of Concrete Floor With Floating Wood Raft (ref 3)

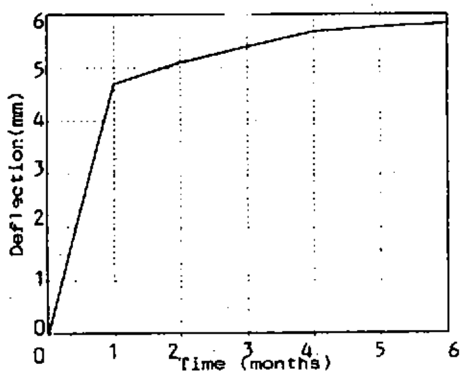

FIG 3 HYPOTHETICAL CREEP DEFLECTION OF A 13mm QUILT

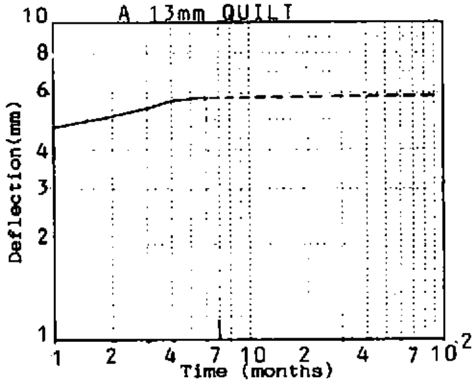

FIG 4 HYPOTHETICAL CREEP DEFLECTION OF A 13mm QUILT ON A LOG SCALE

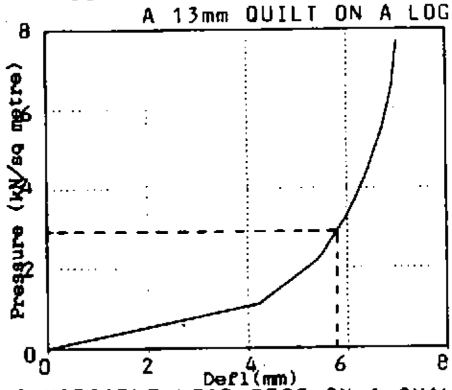

FIG 5 VARIABLE LOAD TEST ON A SMALL SAMPLE OF QUILT

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APPENDIX

The measurements made in Table 1 were on 50mm x 36mm samples of quilt. The pressure can be calculated by:

$p = w/A$ (w = load (kN), A = loaded area (kN/m^2))

Load (kN)	0	0.02	0.04	0.06	0.08	0.10	0.12	0.14
Pressure (kN/m^2)	0	11.1	22.2	33.3	44.4	55.6	66.7	77.8

TABLE A

For the variable load tests, 1m x 1m of chipboard flooring is being examined. Therefore the above pressures have to be changed to take into account this area of flooring. The $1m^2$ of board has an effective area of $1.35m^2$ because on a real floor the battens will be supporting half the span to the next batten. Therefore to give a pressure of 1 kN/m^2 a load of 1.35 kN needs to be applied to the board. However, this load is supported by the 3 battens alone which is an area of (0.045 x 1) x 3. Thus a load of 1.35 kN will give a pressure on the resilient layer beneath the batten of

$$1.35/[(0.045 \times 1) \times 3] = 10\ kN/m^2$$

If the values of pressure in Table A are divided by 10 this will give the pressure on a 1m x 1m square of flooring. This has been done in the text example.