ACOUSTICAL PROPERTIES OF FIBROUS ABSORBENT MATERIALS

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(Received: 28 August, 1969)

SUMMARY

Results are presented of an investigation into the acoustical properties of a range of fibrous absorbent materials. Measured values of characteristic impedance and propagation coefficient are shown to normalise as a function of frequency divided by flow-resistance and can be represented by simple power-law functions. Absorption coefficients of thin layers of material over a range of flow-resistance values are also shown. Supplementary data provide a basis for estimating the flow-resistance of a material from its bulk density.

INTRODUCTION

In general, propagation of sound in an isotropic homogeneous material is determined by two complex quantities, the characteristic impedance $Z_0 = R + jX$ and the propagation coefficient $\gamma = \alpha + j\beta$.

The fibres of many of the available absorbent materials are layered, causing such materials to be anisotropic; also variation in the fibre size and in the distribution of bonding agent is inherent in the manufacturing process. However, most available materials are sufficiently homogeneous for practical purposes, and by considering only plane-wave propagation in a given direction the isotropy requirement may be relaxed. A convenient physical parameter for their assessment is then the specific flow-resistance per unit thickness σ (henceforth referred to as the flow-resistance); this depends mainly on the bulk density and fibre size (and, for anisotropic absorbents, on the direction of flow relative to the layered fibres).

Using transmission-line analysis, the acoustical characteristics of a number of fibrous absorbent materials covering a wide range of σ-values have been measured under plane-wave conditions by the impedance-tube method over the frequency

Applied Acoustics (3) (1970)—© Elsevier Publishing Company Ltd, England—Printed in Great Britain

range of practical interest. These data normalise in terms of the dimensional variable (frequency/flow-resistance) and can be adequately represented in terms of power-law relations.

It has been shown[1] that analysis of these normalised data yields values for derived material parameters which characterise this type of absorbent and are capable of physical interpretation. Moreover, comparison with results for an idealised model using established theoretical analysis[2, 3, 4] serves to justify the normalisation procedure but cautions against extrapolation.

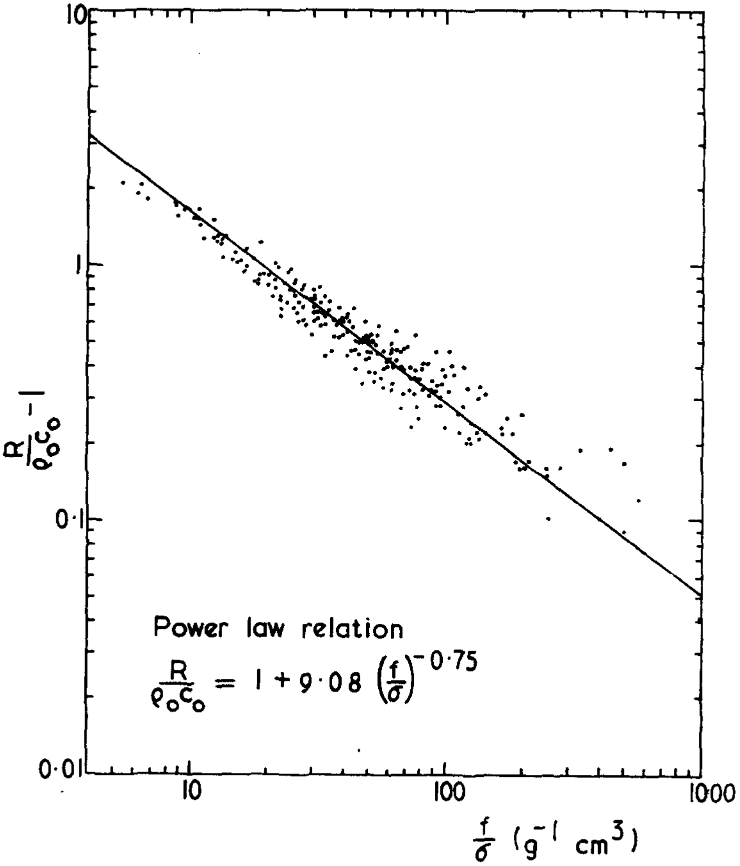

Fig. 1. Normalisation of the real component of characteristic impedance as a function of frequency/flow-resistance.

The empirically normalised relations presented here will prove useful in the general evaluation of absorbents and their application to free-field rooms, room acoustics, noise control measures, the design of linings for ventilation ducts etc.

It should be noted that the empirical relations require only a knowledge of the flow-resistance of the material, which can be readily determined from sampling measurements using simple apparatus, and that the need for tedious routine acoustic measurements is considerably reduced.

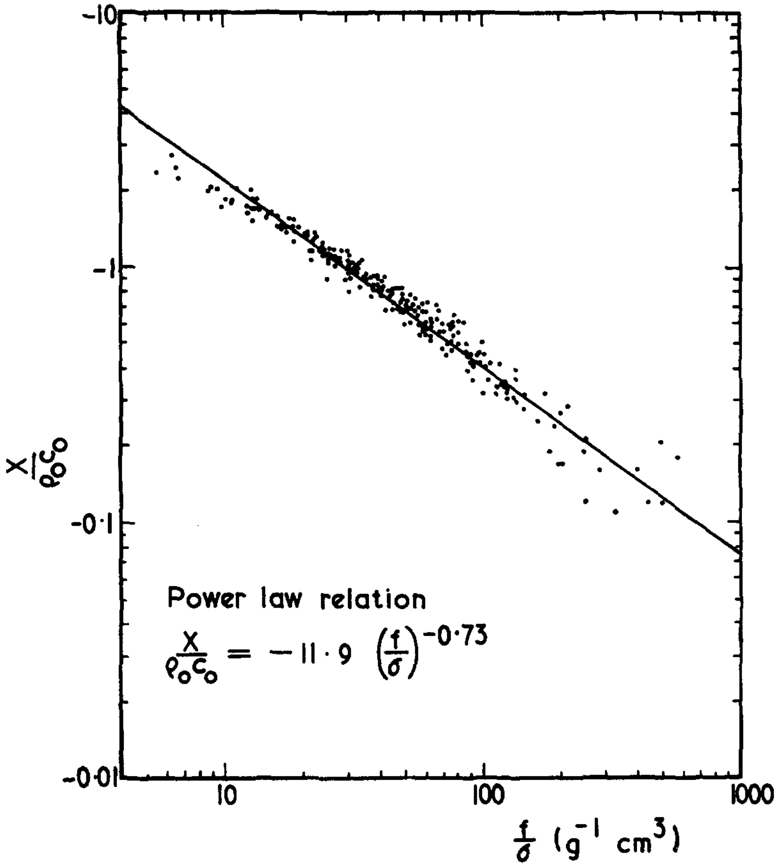

Fig. 2. Normalisation of the imaginary component of characteristic impedance as a function of frequency/flow-resistance.

MEASUREMENT TECHNIQUE

Samples were selected from a range of commercial fibrous absorbents, including various grades of glass-fibre and mineral-wool materials. Each sample was mounted in an impedance tube and the axial sound pressure distribution explored using a long probe microphone; at each frequency $f(=\omega/2\pi)$, measurements were made first with rigid backing and then with the sample backed by an air space of calculable acoustic impedance, *e.g.* a quarter-wave termination. Two impedance tubes were available for these measurements, one 8·9 cm diam. and nearly 2 m long, the other 4·5 cm diam. and 1 m long. Values of Z_0 and γ were calculated using a digital computer, allowance being made for the effects of attenuation within the tube.

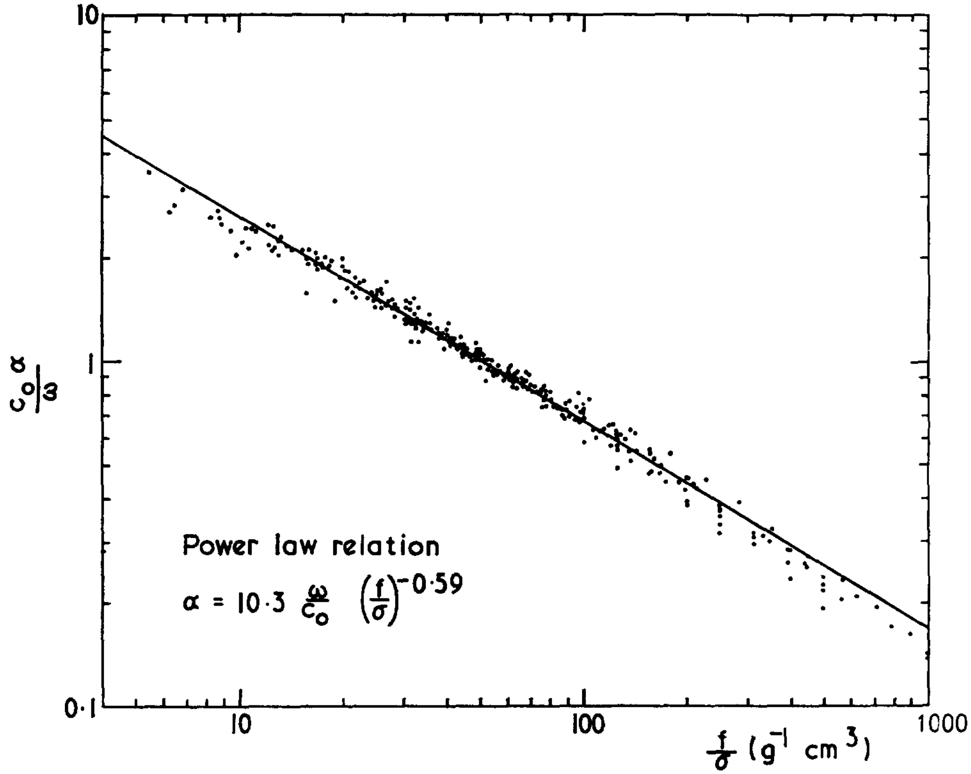

Fig. 3. Normalisation of the real component of propagation coefficient as a function of frequency/flow-resistance.

The flow-resistance σ was obtained from direct measurement of the pressure developed across the sample for known volume velocity of steady air flow passing through it. For each variable some 200 separate data points in the frequency range 250–4000 Hz were obtained on materials having flow-resistance values between 2 and 80 CGS units (g s^{-1} cm^{-3}).

A further 20 data points for characteristic impedance were derived from direct measurements on long samples in the impedance tube. An additional 80 points for propagation coefficient were derived from direct measurements of rate of attenuation and phase change by passing a probe microphone into long samples of material. Materials having flow-resistance values between 8 and 45 CGS units were used for these measurements.

For both characteristic impedance and propagation coefficient the results obtained from the different techniques were in good agreement and have been combined.

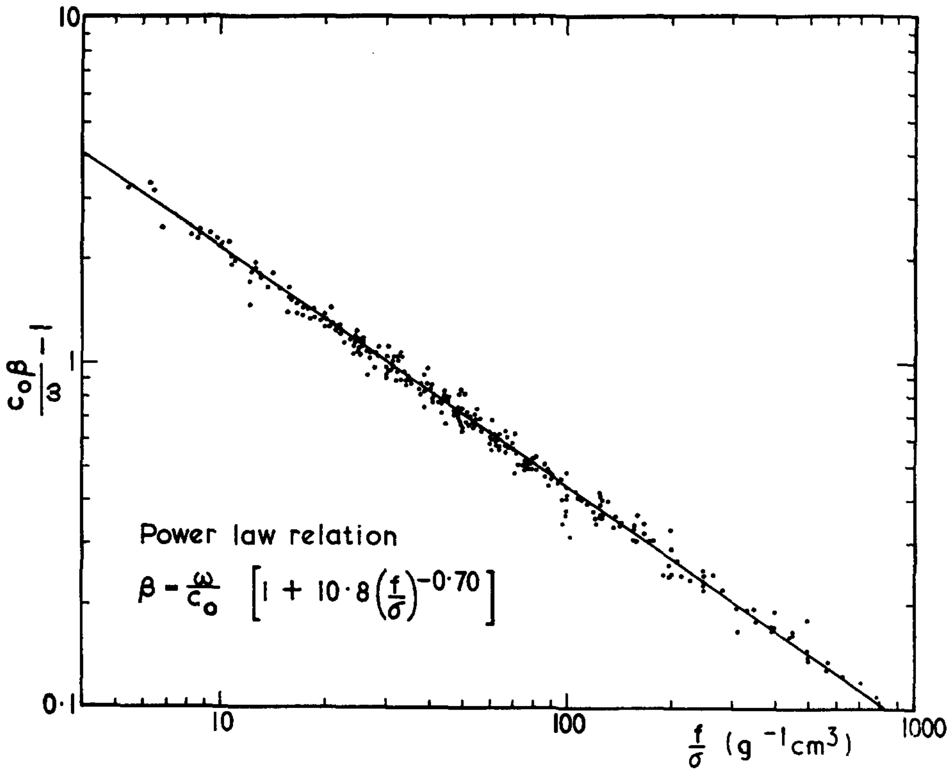

Fig. 4. Normalisation of the imaginary component of propagation coefficient as a function of frequency/flow-resistance.

PRESENTATION OF DATA

In presenting these data, the common practice of expressing impedances in the non-dimensional form Z/ρ_0c_0 is adopted, where ρ_0 is the density, c_0 is the velocity of sound and ρ_0c_0 is the characteristic impedance of air.

Figures 1–4 show that $(R/\rho_0c_0) - 1$, X/ρ_0c_0, $\alpha c_0/\omega$, and $\beta c_0/\omega - 1$ each normalise as functions of the dimensional variable f/σ and that for most practical purposes they can be adequately represented by simple power-law relations. The plane-wave normal-incidence pressure-reflection coefficient and the energy absorption coefficient for a semi-infinite thickness of material also normalise, experimental data agreeing well with the curve calculated from the power-law relations shown in Figs. 1 and 2, but for clarity the experimental data have been omitted from Fig. 5. Dispersion generally increases towards higher values of f/σ but in every case is within the limitations of experimental error, typically ±0·1 dB on measurements of relative sound pressure level and ±0·1 cm on measurements of distance; precision in the latter case is not limited by instrumental shortcomings but by the inherent uncertainty in the position of the surface of the absorbing material. The dispersion also tends to be particularly marked in Fig. 1 because the quantity plotted as ordinate is $(R/\rho_0 c_0) - 1$ whilst the primary quantity measured is $R/\rho_0 c_0$; the percentage error therefore increases rapidly as $(R/\rho_0 c_0) - 1$ tends to zero.

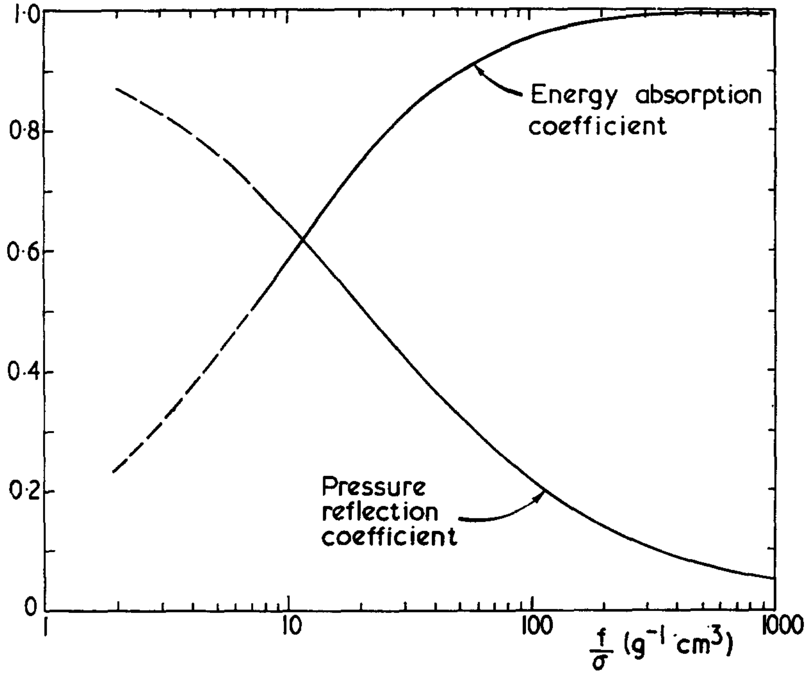

Fig. 5. Normal-incidence pressure-reflection coefficient and energy absorption coefficient as functions of frequency/flow-resistance for a semi-infinite layer.

Whilst the scatter of the data points results primarily from the inherent limitations of the measuring techniques available, the variability of most production materials is such that even if higher precision were achieved it would have little practical significance. Indeed, use of the normalised curve in conjunction with an accurate determination of σ probably achieves a higher overall precision in the characteristic quantities than could be hoped for from an individual acoustic determination using stationary-wave techniques.

The empirical curves may be used with confidence within the interpolating range $10 \leq f/\sigma \leq 1000$ but extrapolation outside this range is not advisable. At both lower and higher values of f/σ there are theoretical reasons for expecting the data for rigid materials to normalise to other power-law relations, with progressive departure from the empirical relations shown. Moreover, at the lower values of f/σ it is known from experimental measurements that many materials exhibit significant structural non-rigidity and under these circumstances simple normalisation is not possible. However, the range covered by the data includes most materials and frequencies in common use and should find widespread application. For convenience in use, Tables 1 and 2 give values of R/ρ_0c_0, X/ρ_0c_0, α, β, as functions of f and σ; these have been calculated from the empirical relations.

Note that $c_0\beta/\omega$ is equal to c_0/c, the ratio of the velocity of sound in air to that in the bulk material. Thus from Fig. 4 it can be seen that at high frequencies and/or for low flow-resistance materials the velocity in the material approaches c_0,

TABLE 1

CHARACTERISTIC ACOUSTIC IMPEDANCE OF FIBROUS ABSORBENTS DERIVED FROM EMPIRICAL POWER-LAW RELATIONS (IN UNITS OF ρ_0c_0)

Frequency (Hz)	*Flow-resistance σ (CGS units)*				
	2	5	10	20	50
125	1·40−*j*0·58	1·80−*j*1·13	2·35−*j*1·88	—	—
250	1·24−*j*0·35	1·48−*j*0·68	1·80−*j*1·13	2·35−*j*1·88	—
500	1·14−*j*0·21	1·28−*j*0·41	1·47−*j*0·68	1·80−*j*1·13	2·60−*j*2·21
1000	1·08−*j*0·13	1·17−*j*0·25	1·28−*j*0·41	1·48−*j*0·68	1·95−*j*1·33
2000	1·05−*j*0·08	1·10−*j*0·15	1·17−*j*0·25	1·28−*j*0·41	1·56−*j*0·80
4000	—	1·06−*j*0·09	1·10−*j*0·15	1·17−*j*0·25	1·33−*j*0·48
8000	—	—	1·06−*j*0·09	1·10−*j*0·15	1·20−*j*0·29

TABLE 2

PROPAGATION COEFFICIENT $\alpha + j\beta$ OF FIBROUS ABSORBENTS DERIVED FROM EMPIRICAL POWER-LAW RELATIONS (NEPER cm^{-1})

Frequency (Hz)	*Flow-resistance σ (CGS units)*				
	2	5	10	20	50
125	0·020+*j*0·037	0·035+*j*0·049	0·052+*j*0·065	—	—
250	0·027+*j*0·063	0·046+*j*0·078	0·069+*j*0·098	0·11+*j*0·13	—
500	0·035+*j*0·11	0·061+*j*0·13	0·092+*j*0·16	0·14+*j*0·20	0·24+*j*0·29
1000	0·047+*j*0·21	0·081+*j*0·23	0·12 +*j*0·26	0·18+*j*0·31	0·32+*j*0·43
2000	0·062+*j*0·40	0·11 +*j*0·43	0·16 +*j*0·46	0·24+*j*0·52	0·42+*j*0·67
4000	—	0·14 +*j*0·80	0·21 +*j*0·85	0·32+*j*0·93	0·56+*j*1·10
8000	—	—	0·28 +*j*1·61	0·43+*j*1·70	0·74+*j*1·92

whereas for low values of f/σ the velocity in the material may be less than one-third of c_0.

The fibrous materials considered in this paper all had porosity factors near unity (the porosity factor is defined as the ratio of the volume of air in the pores to the total volume). For materials with lower porosity it would be necessary to modify the normalising procedure. It is also of interest to note that the non-dimensional normalising parameter $\rho_0 f/\sigma$ may be used provided appropriate adjustments are made to the power-law relations.

APPLICATIONS

The normalised data for the characteristic impedance, propagation coefficient, reflection and absorption coefficients (presented above) find direct application when a sufficiently large thickness of material is to be used. For many applications, however, the performance of a relatively thin layer is required. For example, the impedance Z of a rigidly-backed layer of thickness l may be calculated from the equation

$$Z = Z_0 \coth \gamma l$$

using appropriate values of Z_0 and γ from Figs. 1–4. The normal-incidence energy absorption coefficient α_n is derived from the impedance and is defined by

$$\alpha_n = 1 - \left| \frac{Z - \rho_0 c_0}{Z + \rho_0 c_0} \right|^2$$

The absorption coefficients of 2·5- and 5-cm-thick layers of rigidly-backed material have been computed and are shown in Figs. 6 and 7; for each thickness the effect of varying the flow-resistance of the material is indicated. In Figs. 8 and 9 the effect of varying the thickness of a given material is shown for flow-resistance values of 20 and 50 CGS units respectively.

For applications to problems in room acoustics, when the sound field can be considered to be reverberant, the statistical absorption coefficient may be required and this can be obtained from the impedance using established formulae.[5]

In most applications, then, a knowledge of the flow-resistance of a material permits the relevant acoustical quantities to be derived, although care must be taken to ensure that a representative value of flow-resistance is used, as many practical materials are subject to considerable variation between and within batches. However, for many purposes high accuracy is not required—for instance, in the initial design stages where selection of a potentially suitable absorbing material is the objective. Unfortunately, maufacturers do not usually include data on flow-resistance in their technical literature. Now the main factors influencing the flow-resistance of fibrous materials are the fibre size and the bulk density, and it is known that for given fibre size the relation between bulk density and flow-resistance approximates closely to a simple power law. Whilst data on a range of

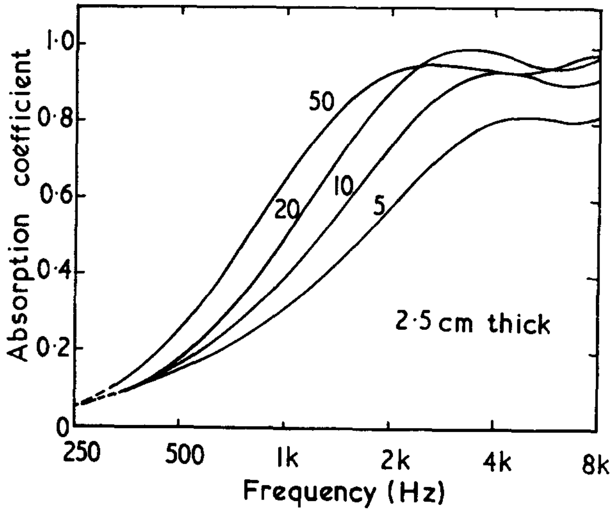

Fig. 6. Normal-incidence energy absorption coefficient of a 2·5-cm layer of fibrous absorbent (parameter is flow-resistance, CGS units).

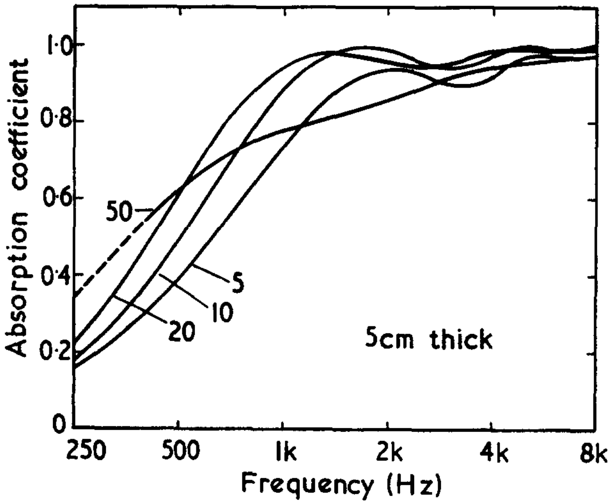

Fig. 7. Normal-incidence energy absorption coefficient of a 5-cm layer of fibrous absorbent (parameter is flow-resistance, CGS units).

materials of American manufacture are available in the literature,[6] data on materials commonly available in Great Britain are not so readily available. For this reason we give in Fig. 10 some results of measurements made at the National Physical Laboratory over a period of years. Although currently available materials may differ

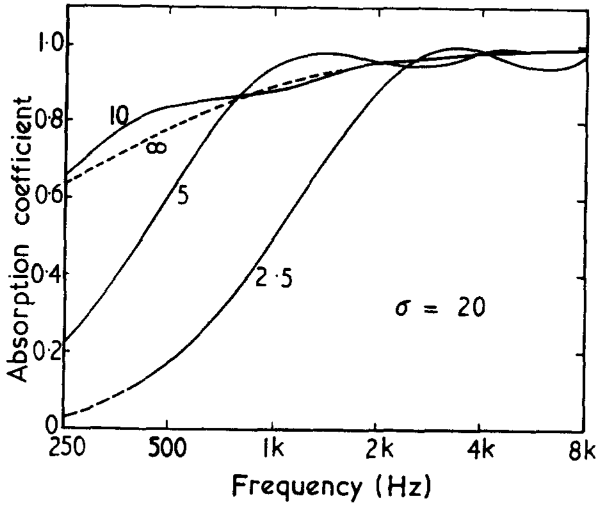

Fig. 8. Normal-incidence energy absorption coefficient for a material with flow-resistance of 20 CGS units (parameter is thickness of layer in cm).

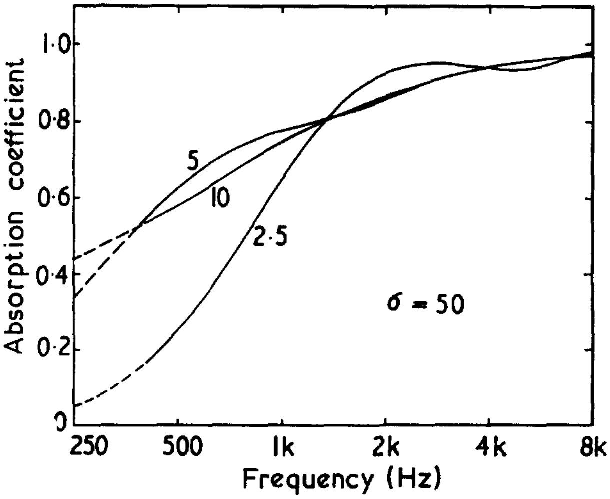

Fig. 9. Normal-incidence energy absorption coefficient for a material with flow-resistance of 50 CGS units (parameter is thickness of layer in cm).

somewhat due to change in manufacturing processes and grades of material produced, Fig. 10 indicates the wide range of flow-resistance likely to be encountered in practice and should form a good basis for selection. It should be noted that the range of bulk density indicated for each material does not imply that the material is normally available in such a range of densities; on the contrary, in most cases samples were compressed in order to increase the range of effective density.

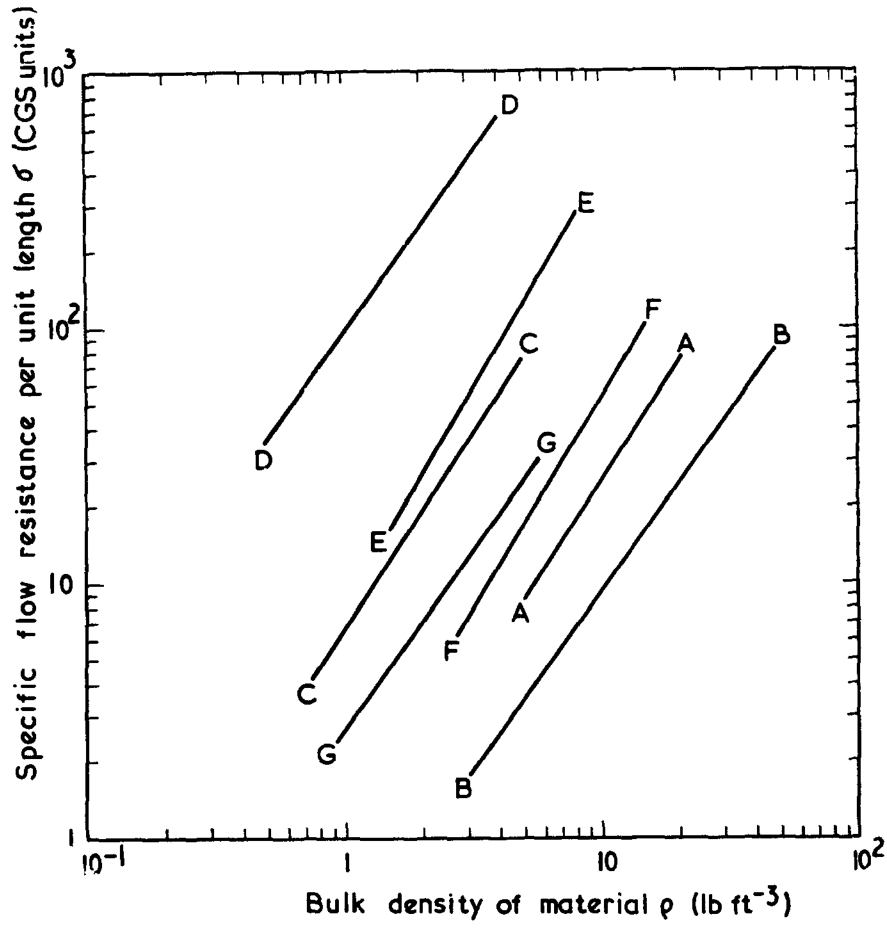

Fig. 10. Typical variation of flow-resistance with bulk density for various fibrous materials: (A) Fibreglass white wool (1948), (B) Fibreglass resin-bonded (1950), (C) Fibreglass Crown fibre (1959), (D) Fibreglass aircraft insulation (1962), (E) Cotton wool (1968), (F) Stillite type SR mineral wool (1968), (G) Rocksil resin-bonded rockwool (1969).

It is emphasised that the purpose of Fig. 10 is solely to provide an indication of the order of magnitude of the flow-resistance to be expected for a given material.

Manufacturers do not necessarily control the flow-resistance of their product and it will usually be necessary to sample-test a specific material before final evaluation.

ACKNOWLEDGEMENT

The work described has been carried out as part of the Research Programme of the National Physical Laboratory.

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