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BUILDING ACOUSTICS MEASUREMENTS

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1 INTRODUCTION

Building acoustics measurements can be classified into four main groups:

- Group 1: Material properties
  Laboratory measurements (e.g. dynamic stiffness, airflow resistance)

- Group 2: Building element performance
  Laboratory measurements (e.g. sound reduction index, impact sound pressure level)

- Group 3: Connected building element performance
  Laboratory measurements (e.g. normalised flanking level difference, vibration reduction index)

- Group 4: Complete building performance
  Field measurements (e.g. standardised level difference)

Groups 1, 2 and 3 facilitate the comparison of products and allow designers to specify the use of building products such that they satisfy the complete building requirements that can be tested using group 4 measurements. There are two main developments related to the laboratory measurements in groups 1, 2 and 3:

- The Construction Products Directive (CPD). This is intended to remove technical barriers to trade and increases the importance of laboratory test data that is used to describe the acoustical properties of construction products.

- The calculation of the complete building performance using Statistical Energy Analysis[1] (SEA) or SEA based models[2]. Input data for these models is derived from one or more of the laboratory measurement groups 1, 2 and 3. New European standards for the estimation of sound insulation between dwellings increases the usefulness of group 2 laboratory measurements because the measured data can be directly incorporated into the models.

Increasing emphasis on laboratory measurements and the introduction of innovative building products has highlighted the limitations of different laboratory tests. The quest for repeatability and reproducibility in and between laboratories has also meant that the relevance and usefulness of measurements on some elements has been overlooked. For any laboratory measurement, there will be uncertainty in the application of the data for at least one construction scenario that can be found in real buildings. However, the complexity of many building elements creates an inextricable link between measurement and prediction such that one is of little use without the other. The laboratory therefore remains a valuable tool in the estimation of sound insulation in the field and allows an assessment of building elements that cannot be determined accurately with field measurements (e.g. low frequency transmission loss). This paper gives an overview of the four measurement groups.

2 Group 1: Material properties

There are three factors that make this group of particular importance.

- Availability of prediction models for absorption, airborne sound transmission and structural transmission that require material properties as input data.
- Difficulty in assessing the influence of individual components of a building element measured in the transmission suite (i.e. assessing wall ties in a masonry cavity wall).
- Variation in the material properties of products that are described using generic names.

This last point is important because material specification using generic names can also hinder innovation. Constructions in Approved Document E currently describe suitable building materials using a generic material name, density and physical dimensions. The use of a generic material name provides no incentive for the building materials industry to develop new products and improve the acoustic/dynamic properties of existing generic products. Problems can also occur when material properties are altered or production is ceased. A solution may exist in the use of acoustic/dynamic material specification parameters for the benefit of both regulators and industry.

2.1 Wall ties

Wall ties that are used in UK masonry cavity walls are an example of a product for which it is useful to identify alternatives to the generic butterfly tie that are nominally identical in terms of their dynamic stiffness[3]. Table 1 shows measured dynamic stiffness data for generic butterfly ties.

Table 1: Dynamic stiffness data[3] for wall ties (50mm spacing)

Type of wall tie	Dynamic Stiffness Mean value (MNm^{-1})	Dynamic Stiffness Standard deviation (MNm^{-1})	Number of samples
Butterfly (2.6mm Stainless steel)	1.7	0.1	6
Butterfly (3.15mm Galvanised steel)	1.7	0.1	6

A suitable specification for alternative wall ties to the butterfly tie can be based on butterfly tie dynamic stiffness data with reference to vibration transmission between cavity wall leaves. Wall tie dynamic stiffness as an acoustic specification parameter for regulatory purposes is more robust than the comparison of wall ties using sound insulation measurements of masonry cavity walls in a transmission suite. This is due to variations in the sound insulation for nominally identical cavity walls built in the laboratory and the unknown strength of transmission between the two wall leaves via the sound field in the cavity. The dynamic stiffness parameter allows a wall tie of equivalent dynamic stiffness to the butterfly tie to be identified without involving unknown variables for the field construction such as cavity damping and foundation coupling. It also allows independent assessment of the wall tie without needing to test the many different cavity wall constructions in which the ties can be used. A suitable alternative wall tie to the butterfly tie could be defined as one with a mean dynamic stiffness value from six samples that is less than or equal to $1.7MNm^{-1}$.

2.2 Plasterboard

Plasterboard is another example of a product with a generic material name. The material composition varies between manufacturers across Europe and is typically one of two types, (A) or (B).

(A) A blend of flue gas gypsum (main component) and natural gypsum
(B) Natural gypsum

Product B typically has a higher density than product A. When field sound insulation tests were carried out to provide data on which to base Approved Document E in the 1970s and early 1980s, the majority of plasterboard used in dwellings was type (B). The main properties of plasterboard sheets that affect sound transmission are density, dimensions, longitudinal wavespeed and the internal loss factor. Data on the latter two properties are not commonly available, although both can be investigated experimentally. The results are shown in Table 2 in order to discuss differences between plasterboard (A) and (B). (NB These plasterboard properties are only representative of one batch of (A) and (B) from one plasterboard manufacturer.) A t-test for equality of means has been carried out which indicates a significant difference between plasterboard (A) and (B) (using 5% significance level) for both longitudinal wavespeed and internal loss factor data.

Table 2: Plasterboard properties

Type	Number of sheets	Thickness (mm)	Surface density (kgm^{-2})	Measured longitudinal wavespeed (ms^{-1})	Calculated critical frequency (Hz)	Estimate of η_{int} (100Hz – 1kHz)
A	4	12.5	8.5	1814 (σ=45)	2899	0.0125 (σ=0.0009)
B	4	12.5	10.8	1490 (σ=31)	3530	0.0141 (σ=0.0004)

Longitudinal wavespeed data can be used to determine the bending stiffness of plasterboard sheets and hence the critical frequency. The measurement used the time of flight of a longitudinal impulse[4] along the plasterboard.

The internal loss factor quantifies the transfer of vibrational energy into heat energy. Reverberation time measurements can be used to determine the total loss factor, which consists of internal losses, losses due to structural coupling and radiation losses. Loss factor measurements of the internal loss factor of plasterboard therefore require the structural coupling and radiation losses to be negligible. To minimise the coupling losses, each sheet under test was suspended vertically by two loops of elastic cord. The radiation losses from the plasterboard sheet are inherent, but because plasterboard does not radiate efficiently until frequencies close to the critical frequency, there is a wide frequency range below the critical frequency in which the internal losses dominate. In strict terms, these reverberation time measurements only provide an estimate of the internal loss factor. Shaker excitation was used with a Maximum Length Sequence (MLS) signal. This had an advantage over steady state noise or hammer excitation in that very low excitation levels could be used to minimise whole body motion of the plasterboard sheet. The measured loss factor varies with frequency and therefore a suitable frequency range was required to determine a frequency average loss factor. The frequency range, 100Hz - 1kHz was used to prevent the use of any frequencies which might be affected by the high radiation losses in the vicinity of the critical frequency.

Plasterboard type (A) is shown to have lower density, lower internal damping and a lower critical frequency in comparison with plasterboard type (B). A degree of caution is needed with any generalisation, however, the effect of density, damping and critical frequency can be considered from a generalised viewpoint of two different transmission mechanisms, non-resonant and resonant. This approach is only used to give a basic assessment of the relative importance of density, internal damping and the critical frequency for plasterboard sheets. Many plasterboard constructions are particularly complex in terms of their vibro-acoustic behaviour due to stiffening elements and the variability in the connections between the individual sheets.

For airborne sound insulation controlled by non-resonant transmission[5], it is appropriate to consider only the mass of the plasterboard. Using a sheet with the density of type (B) instead of type (A) leads to a calculated improvement of 1.7dB - 2.1dB in the airborne sound insulation.

Stiffness, damping and mass are relevant when the airborne sound insulation is controlled by resonant transmission. Consider the case for airborne sound insulation controlled by resonant transmission where the total loss factor of a plasterboard sheet in a construction is dominated by the internal losses (i.e. coupling losses and radiation losses are negligible). Using a sheet with the internal damping of type (B) instead of type (A) would lead to an improvement of 0.5dB in the airborne sound insulation.

The critical frequencies are representative of the isolated sheets of plasterboard and the longitudinal wavespeed is therefore useful for material specification purposes. The critical frequencies calculated from the mean longitudinal wavespeed data indicate that the critical frequency of (A) falls in the lower part of the 3.15kHz third octave band and the critical frequency of (B) falls in the upper part of the 3.15kHz third octave band. Use of the 95% confidence intervals for the longitudinal wavespeed data indicates that the mean critical frequency could fall in the 2.5kHz third octave band for (A) and the 4kHz third octave band for (B). A shift in the critical frequency can affect the single number quantity (BS EN ISO 717) when there are adverse deviations due to high radiation in the vicinity of the critical frequency. Small shifts in critical frequency are now covered by the introduction of single number quantities with spectrum adaptation terms that include third octave bands up to 5kHz. When the sheets are connected to form building elements, it is also necessary to consider any potential change to the stiffness of the plasterboard and any orthotropism that may be introduced.

Comparing plasterboard (A) and (B), the density can generally be considered to be of most importance. Differences in the stiffness and damping will affect the performance of some constructions although there will also be a strong dependence upon the connection points and other stiffening elements. The complexity of plasterboard constructions means that a combination of group 1 and 2 measurements along with prediction tools will often be necessary to verify any differences between different types of plasterboard.

3 Group 2: Building element performance

This group commonly contains transmission suite measurements of airborne and impact sound insulation. These measurements are prone to significant differences between laboratories. Advances in instrumentation mean that more measurement tools are now available with which more accurate and 'meaningful' transmission parameters can be determined. Three measurement tools that have made a significant impact are sound intensity, MLS signals and the determination of short structural reverberation times using time reversal.

3.1 Structural reverberation times

It has been recognised for approximately sixty years[5,6,7] that the sound insulation of solid concrete/masonry elements is dependent upon the total loss factor. However, laboratories rarely ever measure and quote the total loss factor with the sound reduction index (SRI). Above the critical frequency, the total loss factor can allow the comparison of SRI data of a nominally identical test element from different laboratories. It can also allow an estimate[2] to be made of the performance of the wall in the field situation through estimation of the total loss factor in the field. One obstacle has been the measurement of short structural reverberation times to determine the total loss factor. Advances in signal processing mean that this can now be overcome with the use of time reversal[8] and backward integration with either shaker MLS excitation or impulse excitation from a hammer strike.

In order to compare SRI data from different laboratories using the total loss factor, transmission across the solid homogenous test element must be dominated by resonant transmission and both laboratories must not have significant power flow from any of the transmission suite walls/floors into the test element. For a test element with different boundary conditions in laboratories A and B, the sound reduction indices are R(A) and R(B) and the total loss factors are η_A and η_B (linear values). Using the total loss factor data, R(A) can be converted to R(B) and is denoted R(A,B).

$$R(A,B) = R(A) + 10\lg\left(\frac{\eta_B}{\eta_A}\right)$$

The total loss factor (linear value) is calculated from the structural reverberation time, T_s in seconds.

$$\eta = \frac{2.2}{fT_s}$$

An example is shown for a 215mm masonry blockwork wall (2000kgm^{-3}) with 13mm plaster on both sides. The critical frequency of the test element was below 100Hz and it was assumed that resonant transmission was dominant above the critical frequency. The plaster on both sides of the test element effectively sealed the blocks and mortar joints to remove any non-resonant transmission through air paths. The direction average intensity SRI, R_I (dB) for the nominally identical 215mm wall with plaster finish in laboratories A and B is shown on Figure 1. It also shows the SRI data that has been converted from laboratory A to laboratory B to give R(A,B). Good agreement exists between R(B) and R(A,B) in both the single number quantity and the third octave band data for 315Hz-3.15kHz. This shows that without the total loss factor, differences ≤3dB between masonry elements may not give an indication of better or worse performance.

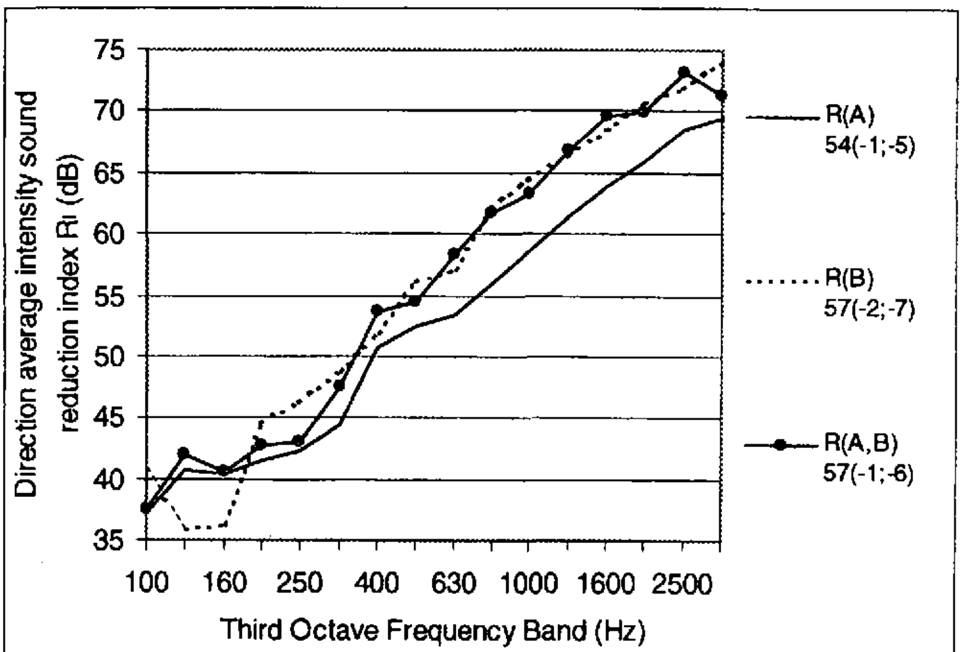

Figure 1: 215mm masonry wall (2000kgm^{-3}) with 13mm plaster both sides. $R_w(C;C_{tr})$

Recent 'round robin' data from Germany[9] indicates that the differences can be even higher. For airborne sound insulation on a masonry wall, the range of measured sound reduction indices on a nominally identical wall was 7dB. Use of the total loss factor should eventually allow a fairer comparison of the acoustic performance of concrete/masonry products in promotional literature. The example also indicates that the concept of a 'mass law' curve determined from many different laboratory measurements over the past few decades could be considered meaningless without total and internal loss factor data. This is part of the reason for the different 'mass law' curves that exist across Europe.

Measurement of the total loss factor is currently being considered for introduction into the ISO 140 series as a separate part rather than an informative annex in ISO 140-3. However, although there is considerable potential in the use of total loss factor measurements with concrete/masonry elements, it is not a panacea. There are three main problems. Firstly, the use of the total loss factor in transmission suites can be confounded if there is significant flanking transmission[7]. Secondly, measured data for the internal loss factor are still required (although not easily measured) for the SRI to be 'portable' to the many different field situations. Thirdly, there are 100mm masonry walls where the critical frequency occurs in third octave bands 160Hz - 400Hz which means that the total loss factor cannot strictly be used below the critical frequency without accounting for the non-resonant transmission using theoretical calculations.

3.2 Sound intensity

There are two significant advantages of sound intensity. Firstly it can be used to determine the radiated sound power in the presence of flanking transmission and secondly, it allows more accurate sound reduction indices to be determined at low frequencies. ISO standards are currently being drafted for the laboratory determination of airborne sound insulation using sound intensity methods[10,11]. At low frequencies, traditional ISO 140 sound pressure measurements overestimate the 'true' sound reduction index due to underestimation of the radiated sound power. Sound intensity overcomes this problem by direct determination of the radiated power and removes the need for low frequency reverberation time measurements, which can also be problematic. To increase the accuracy and reproducibility of low frequency measurements, draft ISO/WD 15186-3[11] is intended for low frequency applications in the range 50Hz –500Hz. A reverberant source room is used with fixed microphone positions that are <20mm from the test element surface.

Sound intensity is used in the receiving room with the back wall covered with absorbent material.

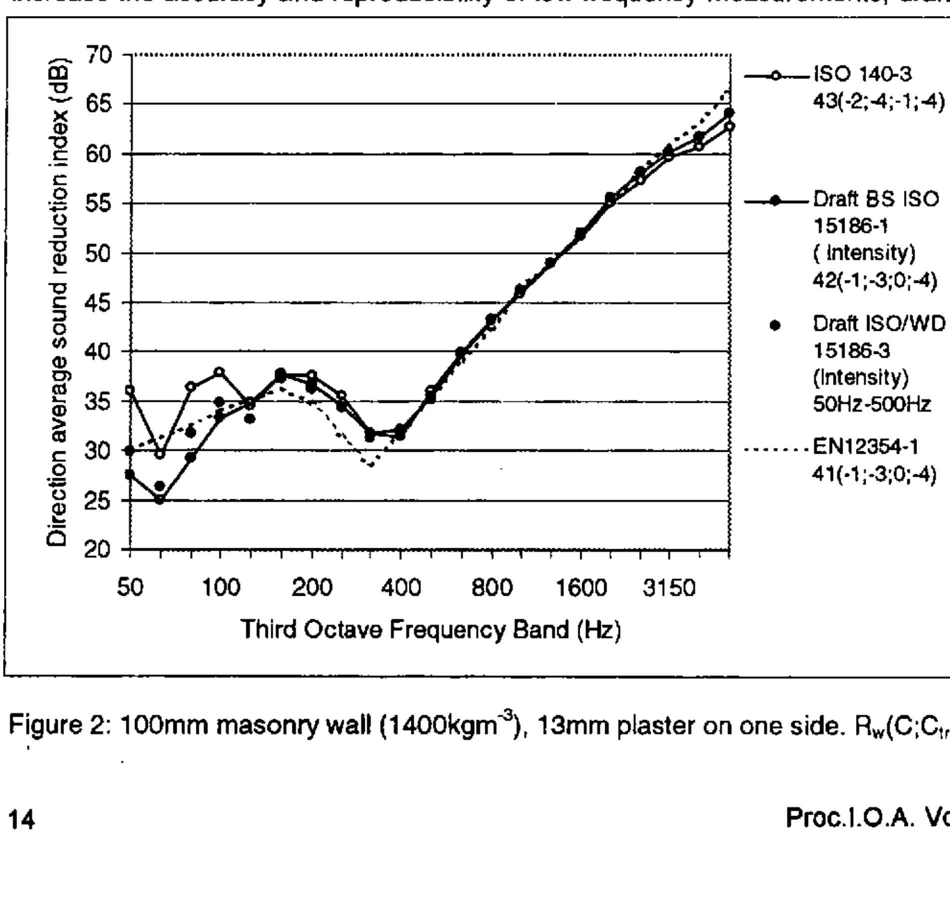

Figure 2: 100mm masonry wall (1400kgm^{-3}), 13mm plaster on one side. $R_w(C;C_{tr};C_{50\text{-}5000};C_{tr,50\text{-}5000})$

Figure 2 shows an example of ISO 140-3 and draft ISO sound intensity measurements used to determine the sound reduction index of an element. The test element was a 100mm masonry wall (1400kgm^{-3}) with 13mm plaster on one side. Predicted SRI data is also shown that used measured input data for the total loss factor and the longitudinal wavespeed. The measured data illustrates the differences between sound pressure and sound intensity measurements. At low frequencies (50Hz – 100Hz), sound pressure measurements overestimate the sound reduction index. At high frequencies (2.5kHz – 5kHz), the sound pressure measurements underestimate the sound reduction index due to flanking transmission. The low frequency intensity measurements show satisfactory agreement with the predicted data at low frequencies (50Hz – 100Hz). Discrepancies exist between measured and predicted data near the critical frequency with good agreement between measured and predicted data above the critical frequency (400Hz – 3.15kHz).

The low frequency intensity method has been used to investigate differences between solid separating walls with different surface finishes as shown in Figure 3. Plasterboard on dabs has a lower sound reduction index than the fair faced wall near 200Hz due to the mass-spring resonance. A comparison of the surface finishes indicates that the plaster finish has a higher sound reduction index than plasterboard on dabs.

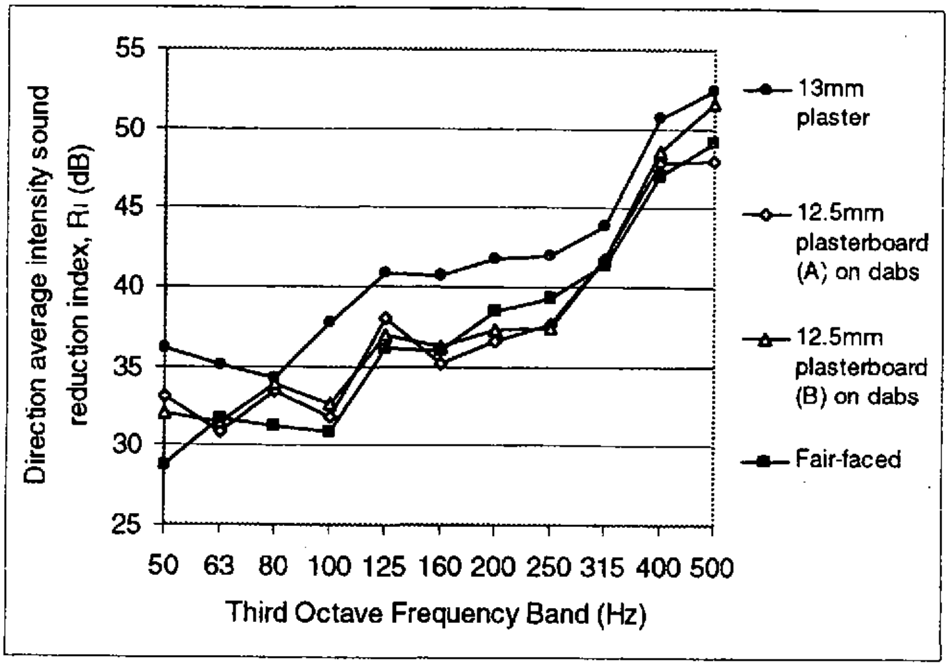

Figure 3: 215mm masonry wall (2000kgm^{-3}). Fair-faced or with surface finishes on both sides.

4 Group 3: Connected building element performance

Flanking transmission is often significant in buildings such that group 3 measurements allow a laboratory assessment of the complete building performance and enable the determination of transmission parameters for energy flow between connected elements. Suspended ceilings and access floors can be seen as connected elements from the viewpoint of flanking transmission, although there are a multiplicity of other constructions for which sound or vibrational energy flow between elements is important. Approved Document E allows a flanking laboratory to be used in the evaluation of new building constructions. Flanking laboratory test constructions consist of both separating and flanking elements that define at least two pairs of rooms. It allows the combination of direct and flanking transmission to be determined in the laboratory and comparison of the sound power radiated from separating and flanking elements[12] using sound intensity measurements.

Laboratory measurements[13] have been carried out to assess the potential for using concrete/masonry elements that were free-standing upon a concrete floor to determine the vibration reduction index[2], K_{ij}. The free-standing measurement scenario is problematic as K_{ij} is not a situation invariant parameter for elements which have modal overlap factors that are less than unity. It may be that K_{ij} measurement with concrete/masonry elements is better suited to flanking laboratories where the coupling losses are higher than with free-standing test constructions.

5 Group 4: Complete building performance

The importance of group 4 measurements is sometimes overshadowed by the lower accuracy associated with them. Generally, there have been more developments in measurement techniques for the laboratory rather than in the field. An important development for field measurements has been the availability of MLS signals to allow the measurement of sound pressure and reverberation times in the presence of background noise. This is also useful for measuring high performance walls and floors in the field. Sound intensity can also be used to compare the sound power radiated from the separating and flanking elements although it is often difficult to satisfy laboratory measurement criteria in the field situation.

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