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THE ACCURACY OF SOUND ABSORPTION MEASUREMENTS

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1 INTRODUCTION

The Australian Standard [1] on the measurement of sound absorption coefficients in a reverberant room and its ISO equivalent [2] have been criticised because of apparent differences in the results obtained, on nominally the same materials, in different laboratories testing to the standard. The issue appears to be one of commercial advantage or legal duty rather than of science. Contracts worth millions of dollars for ceiling tiles in buildings are won and lost on the basis of small (acoustically insignificant) differences in the sound absorption characteristics of tiles. A measurement made on a tile, to AS 1045, in one laboratory is not the same as one made in another laboratory and never can be unless the laboratories are identical and even then there may be differences due to equipment and procedures.

There are several reasons for discrepancies between the results obtained. The size and shape of laboratories vary and the properties of the absorbing materials are not identical unless the same sample is tested in each laboratory (manufacturers admit to variations of the order of ± 10% in density and porosity in different batches for instance). Even the way in which the materials are mounted in the reverberation room as well whether the mounting frame is left in or taken out of the room when the empty room reverberation time is measured are important. These factors cannot be closely specified because conditions in existing laboratories cannot easily be changed.

From a mensuration viewpoint there are two ways of addressing the issue of the reproducibility of sound absorption measurements, but in the present climate of funding for universities and CSIRO and the attitude of material manufacturers and suppliers, neither is likely to be undertaken and so alternatives need to be considered. The two "scientific" ways of dealing with the reproducibility of results are:

- Undertake an investigation into how the standard could be tightened up so that all laboratories measure the same values within an acceptable error margin and apply that standard. This would probably require the determination and control of the diffuseness of the acoustic field in the reverberation room, with and without absorbing material present. There is at present no standardized or widely accepted method of measuring the diffuseness of acoustic fields although there is a requirement in AS 1045 that diffusers be progressively added until no further change in the absorption coefficient is measured.

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- Carry out "round robin" testing of several absorbing materials, with a range of absorption characteristics, in all laboratories undertaking absorption measurements and apply correction factors to achieve agreement or quote confidence limits based on these differences.

One of the dangers in these approaches is that measurements are made with ever-smaller confidence limits but the differences may still be commercially exploited. Alternative approaches are:

- Estimate the confidence limits of measurements using existing data.

- Educate commercial users about the meaning and significance of confidence limits.

- Quote values of the absorption properties of materials in broad classes (rather than the absorption coefficients to the nearest 0.05) based on the uses to which results are to be put. One difficulty with this approach is that the uses may not be known. In the case of ceiling tiles this is unlikely to be an issue.

Basically these approaches are about the recognition that there are inherent errors in any measurement, that measurements are rarely required to be made to more than two significant figures when human perception is involved and that the acoustic and legal professions have yet to adopt sensible ways of expressing and using inexact measurements (There seems to be a world of difference between the understanding of those who write standards and those who apply the results obtained using the standards.).

The approach used in this paper is to address, in simple terms, three issues:

1 How accurate do the measurements of α need to be?
2 How accurately can measurements of α be made using AS 1045?
3 Do laboratories comply with AS 1045?

This paper, while focussing on sound absorption, is about the realistic representation of measured and predicted data where there is insufficient information on which to calculate confidence limits and how to present this uncertainty in a way that can be understood and not exploited either commercially or legally. The issues are far from new but are worth another look.

2 WHAT ACCURACY IS NEEDED?

The issue of matching of measurement precision with subjective responses has recently been addressed by Dodd [3]. The use to which absorbing materials are put and the effect that absorption measurement errors have on the conditions for which the materials are to be used should be a factor in determining the accuracy of a standard. For example, if the change in noise level or reverberation time in a room with ceiling tiles having an α or NRC value of 0.5, rather than 0.6, is within the difference limen for these quantities there is little point in requiring measurements to be made to 0.01.

What are absorption coefficients used for and how accurate do they need to be? Two of the main uses for absorption coefficients values of materials are to calculate reverberation times and sound levels in rooms and enclosures. To do this within the difference limens for reverberation time and sound level for furnished rooms requires absorption coefficient data to be expressed to approximately ± 20% as demonstrated below. Manufacturers and suppliers though have exploited differences in absorption coefficients of less than 0.05 (<± 10%) in the performance of their product compared with that of an alternative supplier's product.

If there are many materials that comprise the finishes of a room then positive errors in some materials should be compensated by negative errors in other materials. An analysis of a commercial office where ceiling tiles are used may serve to illustrate the need for very limited accuracy in the absorption performance of materials. Consider several cases from the most critical (where the ceiling tiles are the only significant absorbent material in a room) to the other extreme where the ceiling tiles contribute a negligible amount of absorption to the total (a very dead room due to carpet and other furnishings).

Within this range there will be differences in the accuracy required for the absorption measurements. A change in absorption coefficient from 0.1 to 0.2 in a near-critical case will produce a difference in RT of 100% (a very significant change given the just noticeable difference (JND) is approximately 10%) and a change of 3 dB in the reverberant field sound level (a small but noticeable change). It should be noted though that such a situation (only one material absorbing sound and that with a low absorption coefficient) is unlikely and the room acoustics would be unsatisfactory whether the α value was 0.1 or 0.2. On the other hand a change from 0.8 to 0.9 in the absorption coefficient results in a reverberation time difference which is only just noticeable and a sound level difference of 0.5 dB which is less than the difference limen.

Near the other extreme (an acoustically dead room) a change of 100% in the absorption coefficient of one surface will have no noticeable effect on the RT or on the sound level, whatever the absorption coefficient of the material is.

More realistically, acoustic tiles are used in offices where there is carpet on the floor and there are other furnishings. The ceiling tiles could be expected to contribute up to half the total absorption in a room and the tiles will typically have an NRC value greater than 0.5. In this situation a change of 20% in the absorption coefficient will produce about a 10% change in the reverberation time and less than 0.5 dB change in the sound level ie a 20% change in the absorption coefficient of a ceiling tile is not noticeable to most occupants.

The above analysis is simplistic in that no account is taken of the variation of absorption with frequency is considered and there are situations involving absorbing materials other than ceiling tiles in offices which may be more critical. Nevertheless the analysis puts us in the right ballpark. In most situations where human habitation and perception are involved an absorption coefficient result to within ±20% is satisfactory and accuracies greater than ±10% cannot usually be justified.

Another assessment of the accuracy that is required of sound absorption measurements can be obtained from the work of Nannariello [4]. Nannariello has shown that not only can the reverberation times in auditoria can be calculated to within the difference limen at low, mid and high frequencies, using only three broad categories for the absorption of surfaces, but that such calculations give better agreement with measured values than either Sabine's equation or values obtained using Odeon software [5].

While Nannariello shows that absorption coefficients need not be closely specified this is only the case if Nannariello's neural network approach is used. The same type of analysis that was carried out above, using Sabine's equation, could also be applied using Nannariello's three absorption categories. Where there are many different materials and furnishings in a room the errors involved in using "crude" categories will not result in rooms having unacceptably high or low reverberation times. The errors in this analysis are unlikely to be large compared with other assumptions made such as the absorption coefficients of furnishings and that the sound field is diffuse.

If a three absorption category system were considered too crude then an alternative would be to use the ISO six-category system [6], recently adopted by Standards Australia [7]. This six-category approach could be extended to cover each frequency band as well. That is, there would be a determination of the absorption coefficient to the nearest 0.2 (or thereabouts) rather than 0.05.

3 THE ACCURACY OF SOUND ABSORPTION MEASUREMENTS

The only known assessments of the repeatability and reproducibility of sound absorption measurements in Australasia are those carried out by CSIRO [8] [9] on "round robin" testing of a fibrous absorbing material in Australian and New Zealand laboratories (This forms the basis for Appendix B in AS 1045) and a confidential report to the AV/4 Committee of Standards Australia [10]. (Information on the materials from this second report will therefore not be identified other than that the samples were commercially available ceiling tiles.)

The CSIRO reports are comprehensive but they deal with one material only (a rockwool product called Silan) and one thickness (50mm) and the work was undertaken to the 1971 version of AS 1045. Consequently it is difficult to draw well-based generalised conclusions from the work. The second report [9] is concerned with ceiling tiles only and there is too little data available in to justify the calculation of confidence limits. Nevertheless there is much useful data that can be obtained from these reports.

The CSIRO reports show that even in the better laboratories (ones which comply with AS1045 in that they have adequate volume and diffusion and optimum sample size) there were average absorption coefficients obtained of 1.1 and maximum values of 1.15 measured by CSIRO staff at mid-frequencies (around 500 Hz) ie errors of 10 to 15% as the material could be expected to have an absorption coefficient of about unity at these frequencies. The approximate 95% confidence limits were between ±0.15 at mid-frequencies and ±0.30 at low frequencies. For non-optimal situations the errors/confidence limits were even greater.

The AV4 document [10] reports on absorption measurements on ceiling tiles, with a 400mm air-gap, where the absorption coefficients are lower than those for the Silan. Because of the limited data available (2 products tested in 3 laboratories and one product tested in 4 laboratories) the statistical analysis results can perhaps best be called "anecdotal statistics".

The trends in the data are far from clear and about as much as can be said is that the 95% confidence limits range from ±0.3 to ±0.4 at low frequencies, ±0.1 to ±0.2 at mid-frequencies and ±0.2 to ±0.3 at high frequencies for absorption coefficients ranging from about 0.3 at low frequencies to about 0.6 at high frequencies. The NRC 95% confidence limits are in the range ±0.1 to ±0.15. These confidence limits are slightly higher than those obtained using the Silan sample. Also, perhaps not surprisingly as the confidence limits are large, the normal incidence absorption coefficients, measured on tiles without an air-gap, using an impedance tube, are within the 95% confidence limits of the reverberation room measurements.

Importantly, if the NRC is expressed to the nearest 0.2 for four types of ceiling tiles with a 400mm air-gap, then irrespective of which laboratory the tiles were tested in and which method (frame in or out), the same NRC value was obtained in all but one case. The one outlying case was for one laboratory when the frame was left in the room for the empty room measurement. A lower NRC category was obtained in this case but the measurement is to some extent confused because tiles for two of the laboratories came from a different factory on a different continent to the tiles used in the other three laboratories.

So far absolute errors in α have been discussed. It is worth considering whether percentage errors or absolute errors should be specified. Interestingly, AS 1045 indirectly specifies a constant absolute error of 0.05 (as measurements must be quoted to this figure) even though, in Appendix B of AS 1045, the absolute errors are not constant. With only one material tested thoroughly and the low absorption coefficient values coinciding with low frequencies one shouldn't speculate on whether it is better to specify an absolute or percentage error but it is worth pointing out that the percentage error at low frequencies is very large (expressed as 95% confidence limits it is approximately ±250% at 100Hz) while at mid-frequencies it is more like ±15%. It is clear then that absolute error specification is more appropriate as there is only about a 2:1 change in it over the frequency range used.

There is a case for needing smaller percentage errors for more reflective materials, as pointed out in the analysis in the previous section. While materials with low absorption coefficients will be measured more accurately than materials with high absorption coefficients because they will disturb the sound field less there must be a sufficient change in the reverberation time of room, with and without the sample, to enable the absorption coefficient to be calculated accurately. Though it is rare that a material with an absorption coefficient of less than 0.1 is submitted for testing perhaps a limit on the minimum absorption coefficient that can be measured using AS 1045 should be stated. How this could be done without first undertaking an impedance tube assessment of the normal incidence absorption coefficient is not clear. A limit of 20Hz on the lowest frequency at which measurements should be made would also seem prudent.

4 DO LABORATORIES COMPLY WITH MEASUREMENT STANDARDS?

This question of whether laboratories comply with measurement standards is difficult to answer because, although it is easy to assess whether a laboratory can comply with a standard, it is more difficult to determine whether the provisions of a standard are followed. For instance, in AS 1045, there is a requirement to determine how many diffusers are required to achieve an "acceptable diffusivity". This is a lengthy procedure and there is no need to state whether it has been carried out but only to state the number and size of diffusers. Presumably too, "short-cuts" are sometimes used, even if a laboratory is NATA registered.

In the second CSIRO study [9] measurements were carried out by laboratory and CSIRO personnel with different equipment and procedures in different laboratories, but complying with the standard. There were differences in the measured absorption coefficients but whether this was because of equipment or procedural differences cannot be determined. The differences obtained can however be used as an indication of compliance with a standard measuring procedure. In the best case situation (diffuser area/floor area > 1.4 and a sample area of $10.5m^2$) the differences obtained on the Silan sample, in three laboratories where the measurements were made by CSIRO and laboratory staff the results were not significantly different. For other diffuser ratios and sample sizes the differences in reported values was greater with differences in α of up to 0.75 at a particular frequency. It would seem likely that a laboratory which obtains a value of α=1.75 (or α values greater than 1.2) is not complying with the standard (Perhaps the standard should specify a maximum measured absorption coefficient on a material in order to comply.) but the laboratory staff presumably thought they were complying with the standard!

As a result it can probably be said that if laboratories comply with the diffusion procedure in Appendix A of AS 1045 they are likely to comply with the standard's other provisions and measurements of absorption coefficients can be made to confidence limits of ±0.15.

5 DISCUSSION

The need for assessing and representing the accuracy of acoustic measurements and predictions is not confined to sound absorption. It applies to transmission loss, environmental noise assessments and sound power measurements for instance. I was recently asked to review the noise section of the Environmental Impact Statement [11] in which the sound power level from a "large dozer" (no make or model given or how it was to be used) was quoted as 113.7 dB(A) for the purposes of calculating residential noise levels, over a kilometre away, to 0.1 dB(A). Even under laboratory conditions the sound power of a source cannot be measured with this precision. Sound level meters can't be calibrated to this degree of accuracy either and, in my experience, different standard methods of measuring the sound power of a source, such as a domestic appliance, give sound power level differences of the order of 3 dB(A). The sound power level of a large dozer doing unspecified activity in the field would be far less precise. AS 2436 [12] on noise control from construction and demolition sites recognizes this and gives the "typical" sound power level of a large dozer as >120 dB(A).

Why are measurements and predictions quoted to such precision? The answer appears to be that by quoting precise values improved credibility is given to the measurements and commercial advantage follows from this. Unfortunately, by stating that measurements of α should be stated to the nearest 0.05, AS 1045 gives the impression that the reproducibility of the measurements is much better than it is. Measurements of α, at best, should be quoted to the nearest 0.2.

Results should be presented in such a way that they are more difficult to misinterpret or misrepresent. The argument has been used that if a standard only ensures that measurements are accurate to the nearest 0.2 then there is the unacceptable situation that one laboratory may measure a sample, which had a nominal absorption coefficient of 0.3, as 0.2 and another laboratory would measure it as 0.4. The same argument applies whatever the level of accuracy of the measurement method unless the accuracy of each laboratory's measurements can be determined and confidence limits applied and the results understood by the users.

One way of presenting results which may be less confusing and less open to exploitation is to calculate α values to the nearest 0.05 and add and subtract 0.15 to give the "expected range" within which the absorption coefficient is expected to lie. If this expected range for one material overlaps with the expected range of another material then the absorption performance of the two materials should be considered to be the same.

If measurements are not required to an accuracy of 0.05 (as suggested in this paper) then the any standard that ensures an accuracy of 0.05 is too stringent. AS 1045 is contradictory on this matter as the significance of the smallest graduation on a scale is that it represents the repeatability or reproducibility of a measurement. In Appendix B of the standard it is clearly stated that an accuracy of 0.05 cannot be achieved.

6 CONCLUSIONS AND RECOMMENDATIONS

This paper does not present anything new but it does put a few issues together which may help avoid the stupidities brought about in the past by implying that the accuracy of the measurements of sound absorption are greater than they actually are. The argument produced here, based on the need for accurate absorption data, obviates the need to tighten up the standard on absorption measurement of materials used in the building industry.

The following recommendations are made as a result of the present work:

- Six broad categories of absorbers (represented by α values of 0.0, 0.2. 0.4, 0.6. 0.8 and 1.0) are all that is practically justified. Three categories would probably be sufficient. Measurements should not be quoted to the nearest 0.05 as required in AS 1045. The categorisation of absorbing materials into one of six groups does not totally overcome specification problems because some materials will always fall into different categories depending on the laboratory in which they are measured.

- The six categories (A to E and "not classified") in AS ISO 11654 – 2002 do not seem to be appropriate in that the range of α_w values for each category do not take into account the reproducibility of the absorption measurements.

- A better method of presenting absorption coefficients would be to specify the maximum and minimum values of a measurement based on reproducibility 95% confidence limits rather than an "average" value**.** This should not only be a requirement of the standard but a requirement for any presentation of product data. (Failing this the 95%confidence limits should be required to be specified to ensure compliance with AS 1045.)

- Practitioners need to be educated about the use of confidence limits and understand that if the range of measurements, on two materials, overlap then the materials should be considered to have the same absorption properties.

- That NRC value of a material can be satisfactorily measured using AS1045 if it is calculated from 1/3 octave measurements rounded off to the nearest 0.2. Alternatively the NRC value should also be specified as a maximum and minimum value.

- Within the limits of the measurement accuracy it appears of no importance whether the frame is left in or taken out for the empty room measurements on materials.

- On the basis of the available absorption data on ceiling tiles it appears to be a waste of time making measurements in a reverberation room as normal incidence absorption coefficient measurements on the same tiles without any backing air-gap, using an impedance tube, fall within the 95% confidence limits of the reverberation room measurements.

Other comments are:

- One should question why a standard should be prescriptive rather than performance based. Why shouldn't the absorption measurement standard be written in such a way that compliance is based on the measurements on a number of samples with different absorption characteristics being "correct" within certain limits? Why should the size and shape of the room etc be specified when it is not known how these factors influence the measurements?

- There is a perceived need to specify acoustic quantities precisely. This gives the impression that the result of any calculation can be relied on. The problem of measurement accuracy is not just one that laboratories and Standards Australia must face but also lawyers, designers and consultants.

- Another approach to this issue should be to study the legal issues and precedents to see whether there have been cases involving the accuracy of absorption coefficient or other acoustic measurements (It would seem highly unlikely that there have been cases concerning absorption measurements.). Certainly the legal duties of a testing or standards authority need to be understood.

- In designing for noise control it is common practice to design conservatively by about 5dB. Inaccuracies of ±20% in absorption coefficient values are therefore of little consequence. Designers of room acoustics and in other areas where absorption coefficients are used could be taught to use the same technique.

- More comparative measurement results are required if the reproducibility of absorption measurements in AS 1045 are to be accurately specified.

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